Longitudinal Lung Function Surveillance in the South Australian Metropolitan Fire Service: Trajectory Analysis and Participant Experience

Catherine Ann Pendergrast

B App Sci (Ex & Sport Sci), Grad Cert Resp Sci, CRFS, ACP – Respiratory

A thesis submitted for the degree of

Master by Research (Human Movement)

Allied Health and Human Performance

University of South Australia

January 2023

Table of Contents

Table of Contents		i
Appendices		iii
List of Figures		iv
List of Tables		v
Table of Abbreviations		vi
Summary		viii
Declaration		x
Dedication		xi
Acknowledgements		xii
Publications and Presentations		xiii
Chapter 1	**Introduction and Background**	**1**
1.1	Exposure - Risk to Lung Health in the Fire Service	2
1.2	Monitoring Firefighter Lung Health	3
1.3	Considerations for Longitudinal Lung Function Analysis	5
1.4	Lung Function Surveillance in Firefighter Workplace Health and Safety Programs	7
1.5	Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) Study: History, Methodology and Findings	8
1.6	Research Aims	10
1.7	References	11
Chapter 2	**Longitudinal Lung Function in Urban Firefighters: A Group-based Multi-Trajectory Modelling Approach**	**18**
2.1	Abstract	19
2.2	Introduction	20
2.3	Methods	21

Table of Contents

2.4	Results	23
2.5	Discussion	25
2.6	Declarations	29
2.7	References	31
2.8	Supporting Information	36
Chapter 3	**Urban Firefighter Experiences of and Attitudes towards Lung Function Surveillance**	**46**
3.1	Abstract	47
3.2	Introduction	48
3.3	Methods	49
3.4	Results	51
3.5	Discussion	61
3.6	Declarations	63
3.7	References	65
Chapter 4	**Discussion**	**68**
4.1	Main Findings	69
4.2	Implications of the Research Program Findings	70
4.3	Strengths of the Research Program	72
4.4	Limitations of the Research Program	73
4.5	Future Opportunities	74
4.6	Conclusion	74
4.7	References	76

Appendices

Chapter 2

2.1	Statement of Authorship	79
2.2	Published Manuscript	81
2.3	Manuscript Visual Abstract	88

Chapter 3

3.1	Statement of Authorship	89
3.2	Manuscript Under Review	91
3.3	Interview Guide	115

List of Figures

Chapter 1

Figure 1 Timeline of RFMS-SAMFS data collection and published outputs 9

Chapter 2

Figure 1 Graphical representation of the five trajectory groups of spirometry parameter z-scores in the urban firefighter cohort from 2007 to 2019 25

Figure S1 Fit Criteria Assessment Plot 39

Chapter 3

Figure 1 Identified themes, interactions and categories regarding the value, benefits of, and barriers to participating in a lung health surveillance program 53

List of Tables

Chapter 2

Table 1	Baseline Characteristics of Participants According to Lung Function Trajectories	26
Table S1	Exposure Variable Description	36
Table S2	Model Fit Indices of 1 Through 6 Class Unconditional GBTM Models of Spirometry Parameter z-scores	40
Table S3	Model Fit Indices of 4 and 5 Class Unconditional GBMTM Models of Spirometry Parameter z-scores	41
Table S4	Comparison of the Main Baseline Characteristics for Those Included and Excluded in the RFMS-SAMFS cohort	42
Table S5	Indices of Goodness of Fit and Model Adequacy for the 5 Trajectories of the selected GBMTM model of FVCz, FEV_1z, FEV_1/FVCz (11111/11111/11111)	43
Table S6	Description of Group Trajectory Labels	43
Table S7	Comparison of Baseline Characteristics for those Included by Number of Wave in the RFMS-SAMFS cohort	44
Table S8	Comparison of Trajectory Group Membership Between Original Model and Model Including Covariates	45

Chapter 3

Table 1	Participant Characteristics	52

Table of Abbreviations

ACP	Accredited Clinical Physiologist
AIC	Akaike Information Criteria
AJC	Professor Alan J Crockett
APPA	Average Posterior Probability of Assignment
ATS/ERS	American Thoracic Society / European Respiratory Society
BIC	Bayesian Information Criteria
COPD	Chronic Obstructive Pulmonary Disease
COREQ	Consolidated Criteria for Reporting Qualitative Research Framework
CP	Cathy Pendergrast
CRFS	Certified Respiratory Function Scientist
FEV1	Forced Expiratory Volume in the First Second
FEV1/FVC	Ratio of FEV1 and FVC
FVC	Forced Vital Capacity
GBMTM	Group-based Multi-trajectory Modelling
GBTM	Group-based Trajectory Modelling
GLI	Global Lung Initiative
GRoLTS	Guidelines for Reporting on Latent Trajectory Studies
HRQOL	Health-Related Quality of Life
KJ	A Professor Kylie Johnston
LLN	Lower Limit of Normal
MAR	Missing at Random
PF	Deputy Chief Officer Paul Fletcher
PPE	Personal Protective Equipment
RFMS-SAMFS	Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service
SAMFS	South Australian Metropolitan Fire Service
SCBA	Self-contained Breathing Apparatus

Table of Abbreviations

SD	Standard Deviation
TSANZSRS	Thoracic Society of Australia and New Zealand and Australian and New Zealand Society for Respiratory Science
VOC	Volatile Organic Compound
WHS	Workplace Health and Safety
z	z-Score

Summary

Firefighters are routinely exposed to an environment that presents a hazard to health and safety. Risks to lung health are well documented and include the potential for inhalation exposure to noxious gases and particulates. Serial spirometry measurement is a method of monitoring changes in lung health in the occupational setting. Despite multiple cohort studies undertaken over the last fifty years, it is still unclear if urban firefighting results in long-term decrements in spirometry parameters due to repeated exposures and respiratory insults.

In 2007 the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study began collecting occupational, health, lifestyle and spirometry measurements. Data collection ended in 2019 after six waves. The program of research described in this thesis aims to (1) perform a longitudinal analysis of the entire dataset to investigate if there are groups of firefighters whose lung function trajectories diverge from others and (2) explore the perceptions of urban firefighter participants on the facilitators, barriers and value of lung health surveillance.

This thesis consists of an introductory chapter, two studies in manuscript form, followed by a discussion chapter.

Chapter One introduces the research program by providing a background to the respiratory burden of firefighting. It then reviews pertinent aspects of longitudinal lung function analysis, the place of health surveillance within workplace health and safety programs, and summarises the RFMS-SAMFS study and its outcomes. Finally, the chapter concludes with the aims of the research program.

Chapter Two presents a contemporary longitudinal analysis of six waves of spirometry data from the RFMS-SAMFS study using group-based multi-trajectory modelling (GBMTM). On identifying distinct, biologically plausible trajectories, we then sought to determine if these trajectories were associated with the firefighters' occupational, health, or lifestyle characteristics.

Chapter Three reports a qualitative descriptive study that explored how urban firefighters, who participated in the RFMS-SAMFS study, perceived their involvement, particularly regarding the limiting and facilitating factors. We also aimed to describe the value they ascribed to their participation in lung function surveillance.

The fourth and final chapter summarises the overall findings of the research program and describes the implications of the works, outlines the program strengths and weaknesses, and suggests future research directions.

The body of work presented in this thesis delivers novel outcomes that will contribute to informing future firefighter lung health surveillance methods and work health and safety policy.

Declaration

I declare that this thesis presents work carried out by myself and does not incorporate without acknowledgement any material previously submitted for a degree or diploma in any university; to the best of my knowledge, it does not contain any materials previously published or written by another person except where due reference is made in the text, and all substantive contributions by others to the work presented, including jointly authored publications, is clearly acknowledged.



Catherine Pendergrast B App Sci (Ex & Sport Sci), Grad Cert Resp Sci, CRFS, ACP – Respiratory

Dedication

I would like to dedicate this thesis to

Professor Alan J Crockett

MPH, PhD, Grad Cert HE, CRFS, FANZSRS, PSM

who, through his leadership and passion within the fields of public health, evidence-based medicine, and respiratory physiology, has made outstanding contributions to policy, education and scientific understanding, most recently within the field of firefighter lung health.

Thank you, Alan. It has been a privilege to have the opportunity to learn from you and contribute to this important project.

Acknowledgements

This program of research was supported by an Australian Government Research Training Program Scholarship (Domestic Fee Offset Scholarship) and the University of South Australia Firefighter Lung Function Scholarship (Living Allowance Scholarship) funded by the South Australian Metropolitan Fire Service. I would like to acknowledge and thank Deputy Chief Officer Paul Fletcher for his support and assistance throughout my candidature.

There are many people whom I would like to thank for their part in helping me to complete this Research Training Program.

First and foremost, my sincerest gratitude goes to my supervisory team – Associate Professor Kylie Johnston, Dr Terry Boyle, Professor Alan Crockett and Professor Roger Eston. Thank you for the time you have dedicated to helping me learn the research skills required to complete this program of study and for sharing your knowledge and expertise.

I also would like to acknowledge the following people who have supported me along the way.

My Lung Lab crew, Jenny, Dee and Iain, who have taken up the slack whilst I stepped away from my role at work; my colleagues Sonya and David, who have always helped and encouraged me to believe in myself; my office buddies, Saraid, Elisio, Lisa, Lindy, Stuart, and the ALH team for your friendly company, support and advice.

Thanks also go to my family and dear friends, whom I can always rely on to provide love and encouragement.

Finally, to Graham, for which words will never be capable of expressing my love and gratitude.

Publications and Presentations

To date, the following peer-reviewed publications and conference presentations have arisen from this program of research:

Accepted publication

1. **Pendergrast, C**, Boyle, T, Crockett, AJ, Eston R, Johnston KN. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. *Respirology*. 2022. https://doi.org/10.1111/resp.14382

Publication under review

1. **Pendergrast, C**, Boyle, T, Crockett, AJ, Eston R, Johnston KN. Perceptions of Lung Function Surveillance in Urban Firefighters submitted to *Annals of Work Health and Exposures*.

Conference presentations

1. **Pendergrast C**, Boyle T, Crockett A, Eston R, Johnston K. Firefighter Lung Function Multi-Trajectory Analysis. 33rd International Congress of Occupational Health (Virtual Conference), 6 – 10 February 2022 (Oral presentation).
2. **Pendergrast C**, Boyle T, Crockett A, Eston R, Johnston K. Lung Function Trajectories in Urban Firefighters. TSANZSRS Annual Scientific Meeting 2022 (Virtual Conference), 31 March – 2 April 2022 (Poster presentation)

Upcoming conference presentations

1. **Pendergrast C**, Boyle T, Crockett A, Eston R, Johnston K. Firefighter Lung Function Multi-Trajectory Analysis. TSANZSRS Annual Scientific Meeting 2022, 31 March – 2 April 2023 (Poster presentation)

Chapter 1 Introduction and Background

This chapter begins by outlining firefighting exposures that pose a risk to lung health and some of the challenges associated with addressing those hazards. Evidence relating to firefighters' long-term rate of change in lung function (as an indication of lung health) is summarised, providing a background to some of the methodological and analytical factors that impact this evidence. This is followed by an introduction to health surveillance and the use of lung function measurements within fire service workplace health and safety programs. Finally, it provides a brief overview of the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study on which this program of research is based. The chapter concludes with an outline of the aims of my research program.

1.1 Exposure - Risk to Lung Health in the Fire Service

Urban firefighting is an inherently dangerous occupation where its incumbents are exposed to acute physical (thermal, chemical, ergonomic) and psychological hazards that have suspected and known effects on health and wellbeing (1–9). Occupational tasks include fighting fires, attending accident scenes, responding to hazardous materials leaks, and performing rescues. In addition to the hazards associated with acute exposure and catastrophic events (e.g. Twin Towers, Grenfell Tower, Notre Dame)(10–14), there is increasing evidence of long-term physical(15) and psychological (16) risks to health and wellbeing due to repeated exposures.

Firefighters are exposed to various toxic chemical substances in either gaseous or particulate form during their workday (e.g. carbon monoxide, polycyclic aromatic hydrocarbons, polyfluoroalkl substances, benzene, hydrogen cyanide, asbestos, fire retardants, and diesel exhaust). These exposures occur primarily as a result of combustion on the fireground, but may also occur at motor vehicle accident scenes, hazardous chemical incidents or at the fire station(17–22). Toxic substances can be absorbed into the body either through inhalation into the lungs or by absorption through the gastrointestinal tract and skin(15). Respiratory system impacts of exposures include acute airway hyper-responsiveness(23,24), reductions in lung function (25–27), and lung inflammation(24,26,28). Chronic lung inflammation is known to result in lung tissue damage via inflammatory response mediators in susceptible individuals(26,29).

Structure fire containment and suppression are the principal duties served by urban firefighters. The products of combustion pose a risk to lung health for those involved directly with active fire ‘suppression’, the first phase of extinguishing a fire. Firefighters undertaking this role routinely wear respiratory protective equipment in the form of self-contained breathing apparatus (SCBA), which provides an uncontaminated air supply. There are, however, risks of respiratory exposure outside the immediate fire zone for those who undertake ancillary roles such as Incident Control during suppression. When there are no longer visible flames on the fireground and smoke clears, firefighters conduct ‘overhaul’, examining the fireground to ensure reignition does not occur. Those undertaking ancillary roles during suppression and firefighters performing overhaul are less likely to use SCBA

(25,30,31). On leaving the fireground, possible respiratory exposure continues with the release of volatile organic compounds (VOCs) from contaminated personal protective equipment (PPE). VOCs that are trapped in PPE fibres during suppression begin re-aerosolising (off-gassing) once away from the fire scene(19,32).

Emergency response occupations, such as firefighting, tolerate higher risk than most workplaces. The most effective risk mitigation solutions listed in the hierarchy of controls (removing, replacing or isolating the hazard) are generally unavailable to the fire service when at an emergency scene(33). They are left with administrative controls (e.g. fire attack strategy, strategic positioning for rest and turnout gear doffing) and protective equipment (turnout gear, respiratory protection) to shield their employees from dangerous environments(33). These controls often require a dynamic approach to risk assessment by those responsible for managing the emergency, which, when paired with a changing environment and competing demands, are often unable to eliminate respiratory exposure completely(31). A recent exposure reduction intervention study by Burgess et al. showed the effectiveness of risk mitigation techniques (including SCBA, decontamination washdowns, and contaminated equipment isolation). Still, these did not completely eliminate exposure(34).

Direct quantification of firefighter exposure to hazards over the course of their working life is a difficult task. Complexities include the wide variety of substances, the range of variables affecting exposure levels (fire type, role, phase of work, intensity, weather conditions, exposure time), and ongoing improvements in safety standards that have occurred during the careers of firefighters taking part in lung health studies. Contributing to these difficulties are the long latency of lung disease and lifestyle factors such as tobacco smoking which may also impact lung health. Self-reported exposure data, respiratory protection use, and years of service are surrogate markers of exposure but are far from ideal(35). Changes to the methods of quantifying exposure will be required to elucidate if this occupational group has an accelerated decline in lung function related to workplace exposures.

1.2 Monitoring Firefighter Lung Health

Since the earliest firefighter lung health studies(36–40) in the 1970s, researchers have been working to determine if the respiratory exposures experienced by urban firefighters throughout their careers lead to an accelerated decline in lung function. These studies

predominantly use spirometry, a volitional lung function test that can be performed periodically, to determine if there are changes in firefighter lung health over time(41). Serial spirometry measurements provide information on lung volumes and airflow that decline in the presence of lung diseases such as chronic obstructive lung disease and untreated asthma.

A recent systematic review performed by Slattery et al. into the long-term rate of change in urban firefighter lung function reported conflicting findings from 16 studies (n=9581) that investigated the effect of routine firefighting on spirometry parameters over time (2–13 follow-up measures over 1–13 years). In summary, the authors suggested that most studies of non-smoking firefighters showed rates of change in lung function that were not significantly different from non-smokers in the general population(41). The review also reported on the quality of the studies, finding that those that were published more recently were of higher quality with less chance of bias. These later studies also used contemporary statistical analysis, such as mixed modelling approaches(41).

Since this review, only one new firefighter longitudinal study has been reported. A cohort study of 662 Virginian firefighters who underwent two spirometry tests five years apart suggested decrements 2 – 4 times greater than those expected compared to a reference cohort (42). The ongoing conflicting outcomes lead us to question if there are genuine differences in the studied firefighter cohorts or if the differing outcomes are due to methodological and analytical challenges.

These studies (41,42) indicate that longitudinal lung function measures in firefighters have been conducted in the US, UK, Australia and Korea over various time periods but there is limited information about whether lung function surveillance is a routine inclusion in firefighter work health and safety programs. Peer-reviewed reports that describe mandatory or voluntary lung function screening programs in firefighters are lacking. Spirometry for occupational health monitoring of firefighters is reported to be voluntary in Alberta, Canada and offered only by larger fire services(43).

The Australasian Fire Authorities Council (AFAC)(44) provided guidelines in 2006 for those conducting health assessments on firefighters in Australia and New Zealand. The guidelines prescribed that a health assessment (including spirometry) must be performed during recruitment to the fire service and strongly encouraged individual agencies to develop

ongoing programs for periodic health assessments. The National Fire Protection Association (NFPA), based in the US and Canada provides guidelines on the medical evaluation of candidates and members, suggesting that spirometry must be done at baseline and annually thereafter as part of a comprehensive medical assessment. Firefighters in Germany who use SCBA undertake a medical assessment every 3 years(45). Overall, information is limited regarding the implementation of ongoing lung health assessments for urban firefighters.

1.3 Considerations for Longitudinal Lung Function Analysis

Spirometry Measurement

Spirometry is a physiological test that measures the maximal volume of air that can be inspired and expired by an individual with maximal effort. The principal parameters derived from spirometry are the Forced Vital Capacity (FVC), the volume of air exhaled during an expiration made as forcefully and completely as possible starting from a full inspiration, and the FEV_1, which is the expiratory volume in the first second of an FVC manoeuvre. These two parameters and their ratio, FEV_1/FVC, are used when classifying physiological impairment and monitoring changes in lung health(46).

Spirometry is a volitional test that requires cooperation and motivation from the individual being tested. It also relies on a motivated and knowledgeable operator to ensure valid measurements (47). There is wide individual biological variability in spirometry measurements (dependent on height, age, ethnicity, and sex), and consequently, spirometry parameters are compared to population-based reference equations derived from healthy individuals. Historically, spirometry parameters have been expressed as a percentage of predicted with set cut points used to define impairment. Recently, interpretation guidelines were updated to address the bias of using this approach. It is now recommended that spirometry parameters be expressed as percentiles or z-scores (z), allowing consideration of the measurement variability and the biological characteristics of the subject (particularly in those individuals at the extremes of height and age)(46).

A single spirometry test is helpful to determine whether individuals have lung function below the lower limit of normal (LLN) (> 5^{th} percentile of healthy non-smokers of the same sex, ethnicity and height). While it can provide information on abnormal physiological patterns, due to wide biological variation, excessive decline may still have occurred in an individual with

results above the LLN. In the case of firefighters, pre-exposure spirometry is an essential reference for later comparison rather than comparing to a generic reference group.

Defining Excessive Lung Function Decline

Comparing an individual's successive lung function results over time provides information on changes in lung health. With advancing age, it is normal for lung function indices to decline due to decreased chest wall compliance, loss of lung parenchyma and diminished respiratory muscle strength(48). To monitor for an accelerated decline, a methodology that considers both the variability of the lung function parameter and the change that would be regarded as normal over the intervening period is needed(46,49,50). Using a fixed percentage change or volume per year is inappropriate as change over time has been demonstrated to depend on age, sex and baseline lung function(51,52). A decline in lung function that is observed over multiple measurements is also more likely to reflect meaningful change than one seen from two measurements, as it allows us to define individual biological variability(46).

Longitudinal Modelling of Lung Function Change

Many early studies of firefighter respiratory health reflect spirometry parameter change by averaging the absolute difference in each spirometry parameter across two-time points. This was then compared with a control or reference group's average change in lung function over the same period(41). Other studies used simple linear regression looking at the change in absolute spirometry parameters with age. These methodologies present limitations to firefighter spirometry analysis. Firstly, both methods analyse the firefighter cohort as a single group and do not account for the heterogeneity of the firefighter sample or the possibility that there are subgroups of firefighters that follow distinctive trajectories not identifiable based on pre-defined characteristics. Secondly, by using the absolute value, they do not consider the innate variability of the measurement or the effect of demographic factors when determining the expected decline in lung function with age.

Firefighters are a heterogeneous group whose work, health and lifestyle choices may cause a single averaged longitudinal trajectory to mask individual differences and lead to erroneous conclusions regarding lung health. Group-based trajectory modelling (GBTM) is a method that allows the identification of groups of individuals with similar trajectories over time. An extension to this method, group-based multi-trajectory modelling (GBMTM) provides a

method of analysing related parameters simultaneously (15). Combining parameters simultaneously when modelling changes in spirometry is particularly suitable as it is the combination of parameters that describes lung health status.

This evolution of the understanding of the interpretation of lung function and the application of contemporary statistical techniques may provide an opportunity to further our knowledge of firefighter lung health.

1.4 Lung Function Surveillance in Firefighter Workplace Health and Safety Programs

The overarching goal of workplace health and safety (WHS) programs is to proactively provide a workplace that is not detrimental to employee wellbeing. Firefighting is an occupation that, by its definition, places its workers in danger. Consequently, managing the hazards associated with firefighting and their effects on wellbeing is an important component of their operations.

As a part of WHS programs, surveillance is a method used to identify, monitor and control hazards that workers are exposed to with the aim of preventing injury, illness and accidents before they occur(53). Surveillance is divided into two categories, hazard surveillance and health surveillance. Hazard surveillance is a primary prevention tool that utilises approaches such as surveys, near miss and exposure registries, expert judgement and biomonitoring to prevent harm before it occurs(54). Health surveillance is considered a secondary prevention tool allowing early recognition, intervention and minimisation of harm. The National Occupational Health and Safety Commission defines health surveillance as 'the assessment of individuals for the purpose of identifying changes in health status due to occupational exposure to a hazardous substance'(55). Health surveillance is appropriate to include in a WHS program when there is an identifiable disease or adverse health outcomes which may be related to exposure. It is particularly beneficial when it is impractical to reduce exposure to hazards(53) further.

WHS programs are most successful when there is consultation with the employees who will be affected(56). Employees have unique insight into the aspects of their work that impact themselves and their co-workers. By providing an understanding of the lived experience of their workplace environment and workday tasks, they contribute vital information that adds value to a WHS program. Consultation and engagement between employers and employees on the design, implementation and amendment of workplace health and safety policy and

practice results in greater awareness, commitment and understanding of workplace safety priorities and goals(56,57). The RFMS-SAMFS cohort study provides a unique opportunity to consult with those involved in a lung function surveillance program. Findings from such a consultation would assist with future research and ensure that research focuses on issues that are relevant to those it affects.

1.5 Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) Study: History, Methodology and Findings

Following the 9/11 Twin Towers disaster, responding New York firefighters were shown to have significant changes in lung health(58). Recognition of the value of having baseline data for the New York firefighters before this extreme event prompted a collaboration between South Australian Universities and the South Australian Metropolitan Fire Service (SAMFS) to monitor the lung health of South Australian Urban Firefighters. The Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study commenced in 2007 under the leadership of Professor Alan J Crockett (AJM). Lung function, anthropometric, and self-reported occupational and respiratory health data were collected in 6 waves. The study concluded in 2019 with over 996 participants and 2780 spirometry measurements over 12 years.

The earliest data analysis from this study was cross-sectional and compared the lung function and health-related quality of life in SAMFS firefighters (n=501) and a general population cohort, participants of the North-West Adelaide Health Study (n=1,324). Schermer et al. showed that this cohort of firefighters had better general health, better lung health and similar mental health compared to this general population cohort. The authors also reported a dose-response relationship between self-reported exposure to dust, smoke and fire and lung function(59).

The first longitudinal analysis of the RFMS-SAMFS dataset was published in 2013. The results of the first two waves of data collection (n=281; duration between waves 2.9±0.3 years) showed that those firefighters who reported rarely or never using SCBA for fire suppression were 2.2 times more likely to have accelerated FEV_1 decline than those who used SCBA often or frequently. The odds of accelerated decline in those who smoked were four times greater than their non-smoking colleagues. Interestingly, this study reported increases in FEV_1 and



Figure 1. Timeline of RFMS-SAMFS data collection and published outputs.

FVC in younger firefighters less than 40 years of age, whilst population controls consistently showed a decline in all age groups(60).

A 2014 data analysis investigated the prevalence of chronic respiratory conditions in the SAMFS cohort and health-related quality of life (HRQOL). They found that approximately 10% of firefighters suffered from chronic respiratory conditions(61). There appeared to be an association between respiratory health and physical HRQOL in those who did not consistently use respiratory protection.

The most recently published output from the RFMS-SAMFS study investigated if the newly recommended Global Lung Initiative (GLI) spirometry reference equations(62) were suitable for use in this firefighter cohort, compared with a local South Australian reference set(63). It concluded that the GLI equations predicted similar outcomes as the Gore et al. reference set(64) and resulted in a lower incidence of obstruction in the RFMS-SAMFS cohort(63).

Prior to this program of research, there have been no published studies describing the longitudinal lung function of firefighters from the full RFMS-SAMFS dataset collected between 2007 and 2019.

1.6 Research Aims

This program of research aimed to address identified knowledge gaps in firefighter lung health by:

1. Completing a longitudinal analysis of the full RFMS-SAMFS dataset using contemporary methodological and statistical techniques.

We aim to identify distinct subgroups of spirometry trajectories in the firefighter data and to assess if baseline lifestyle, health and occupational factors were associated with trajectory group membership (**Chapter 2**).

2. Seeking to understand the lived experience of firefighters undertaking lung function measurement.

We aimed to explore the experiences and attitudes of South Australian Metropolitan Fire Service firefighters who participated in a longitudinal lung function surveillance study. Specifically, we examined their perceptions of the value, benefits of, and barriers to participating in a lung health surveillance program (**Chapter 3**).

1.7 References

1. Wagner SL, White N, Buys N, Carey MG, Corneil W, Fyfe T, et al. Systematic Review of Mental Health Symptoms in Firefighters Exposed to Routine Duty-Related Critical Incidents. Traumatology. 2021;27(3):285–302.
2. Macdermid JC, Lomotan M, Hu MA. Canadian career firefighters' mental health impacts and priorities. Int J Environ Res Public Health. 2021;18(23):12666.
3. Orr R, Simas V, Canetti E, Schram B. A profile of injuries sustained by firefighters: A critical review. International Journal of Environmental Research and Public Health. Multidisciplinary Digital Publishing Institute; 2019;16:3931.
4. Taylor NAS, Dodd MJ, Taylor EA, Donohoe AM. A Retrospective Evaluation of Injuries to Australian Urban Firefighters (2003 to 2012). J Occup Environ Med. 2015;57(7):757–64.
5. Horn GP, Kesler RM, Kerber S, Fent KW, Schroeder TJ, Scott WS, et al. Thermal response to firefighting activities in residential structure fires: impact of job assignment and suppression tactic. Ergonomics. 2018;61(3):404–19.
6. Walker A, Argus C, Driller M, Rattray B. Repeat work bouts increase thermal strain for Australian firefighters working in the heat. Int J Occup Environ Health. 2015;21(4):285–93.
7. Bos J, Mol E, Visser B, Frings-Dresen MHW. The physical demands upon (Dutch) fire-fighters in relation to the maximum acceptable energetic workload. Ergonomics. 2004;47(4):446–60.
8. Fent KW, Evans DE. Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. J Environ Monit. 2011;13(3):536–43.
9. Gainey SJ, Horn GP, Towers AE, Oelschlager ML, Tir VL, Drnevich J, et al. Exposure to a firefighting overhaul environment without respiratory protection increases immune dysregulation and lung disease risk. PLoS One. 2018;13(8).
10. Allonneau A, Mercier S, Maurin O, Robardet F, Menguy-Fleuriot A, Luu SC, et al. Lead contamination among Paris Fire Brigade firefighters who fought the Notre Dame Cathedral fire in Paris. Int J Hyg Environ Health. 2021;233:113707.

11. Peaslee GF, Wilkinson JT, McGuinness SR, Tighe M, Caterisano N, Lee S, et al. Another Pathway for Firefighter Exposure to Per- A nd Polyfluoroalkyl Substances: Firefighter Textiles. Environ Sci Technol Lett. 2020;7(8):594–9.

12. Vossbrinck M, Zeig-Owens R, Hall CB, Schwartz T, Moir W, Webber MP, et al. Post-9/11/2001 lung function trajectories by sex and race in World Trade Center-exposed New York City emergency medical service workers. Occup Environ Med. 2017;74(3):200–3.

13. Yip J, Webber MP, Zeig-Owens R, Vossbrinck M, Singh A, Kelly K, et al. FDNY and 9/11: Clinical services and health outcomes in World Trade Center-exposed firefighters and EMS workers from 2001 to 2016. Vol. 59, American Journal of Industrial Medicine. Wiley-Liss Inc.; 2016;59:695–708.

14. Stec AA, Dickens KE, Salden M, Hewitt FE, Watts DP, Houldsworth PE, et al. Occupational Exposure to Polycyclic Aromatic Hydrocarbons and Elevated Cancer Incidence in Firefighters. Sci Rep. 2018;8(1).

15. Demers PA, DeMarini DM, Fent KW, Glass DC, Hansen J, Adetona O, et al. Carcinogenicity of occupational exposure as a firefighter. Lancet Oncol. 2022;23(8):985–6.

16. Laroche E, L'espérance S. Cancer incidence and mortality among firefighters: An overview of epidemiologic systematic reviews. International Journal of Environmental Research and Public Health. 2021;18:1–32.

17. Horn GP, Kerber S, Fent KW, Smith DL. Management of Firefighters' Chemical & Cardiovascular Exposure Risks on the Fireground. Int fire Serv J Leadersh Manag. 2020;14:7–16.

18. Sparer EH, Prendergast DP, Apell JN, Bartzak MR, Wagner GR, Adamkiewicz G, et al. Assessment of Ambient Exposures Firefighters Encounter while at the Fire Station: An Exploratory Study. J Occup Environ Med. 2017;59(10):1017–23.

19. Fent KW, Evans DE, Booher D, Pleil JD, Stiegel MA, Horn GP, et al. Volatile organic compounds off-gassing from firefighters personal protective equipment ensembles after use. J Occup Environ Hyg. 2015;12(6):404–14.

20. Bolstad-Johnson DM, Burgess JL, Crutchfield CD, Storment S, Gerkin R, Wilson JR. Characterization of firefighter exposures during fire overhaul. Am Ind Hyg Assoc J. 2000;61(5):636–41.

21. Banks APW, Engelsman M, He C, Wang X, Mueller JF. The occurrence of PAHs and flame-retardants in air and dust from Australian fire stations. J Occup Environ Hyg. 2020;17(2–3):73–84.

22. Banks APW, Thai P, Engelsman M, Wang X, Osorio AF, Mueller JF. Characterising the exposure of Australian firefighters to polycyclic aromatic hydrocarbons generated in simulated compartment fires. Int J Hyg Environ Health. 2021;231:113637.

23. Chia KS, Jeyaratnam J, Chan TB, Lim TK. Airway responsiveness of firefighters after smoke exposure. Br J Ind Med. 1990;47(8):524–7.

24. Greven FE, Krop EJ, Spithoven JJ, Burger N, Rooyackers JM, Kerstjens HA, et al. Acute respiratory effects in firefighters. Am J Ind Med. 2012 Jan;55(1):54–62.

25. Burgess JL, Nanson CJ, Bolstad-Johnson DM, Gerkin R, Hysong TA, Lantz RC, et al. Adverse respiratory effects following overhaul in firefighters. J Occup Environ Med. 2001;43(5):467–73.

26. Gianniou N, Katsaounou P, Dima E, Giannakopoulou CE, Kardara M, Saltagianni V, et al. Prolonged occupational exposure leads to allergic airway sensitization and chronic airway and systemic inflammation in professional firefighters. Respir Med. 2016;118:7–14.

27. Gaughan DM, Piacitelli CA, Chen BT, Law BF, Virji MA, Edwards NT, et al. Exposures and cross-shift lung function declines in wildland firefighters. J Occup Environ Hyg. 2014;11(9):591–603.

28. Swiston JR, Davidson W, Attridge S, Li GT, Brauer M, Van Eeden SF. Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. Eur Respir J. 2008;32(1):129–38.

29. Gianniou N, Giannakopoulou C, Dima E, Kardara M, Katsaounou P, Tsakatikas A, et al. Acute effects of smoke exposure on airway and systemic inflammation in forest firefighters. J Asthma Allergy. 2018;11:81–8.

30. Austin CC, Dussault G, Ecobichon DJ. Municipal firefighter exposure groups, time spent at fires and use of self-contained-breathing-apparatus. Am J Ind Med. 2001;40(6):683–92.

31. Maglio MA, Scott C, Davis AL, Allen J, Taylor JA. Situational pressures that influence firefighters' decision making about personal protective equipment: A qualitative analysis. Am J Health Behav. 2016;40(5):555–67.

32. Banks APW, Wang X, He C, Gallen M, Thomas K V., Mueller JF. Off-gassing of semi-volatile organic compounds from fire-fighters' uniforms in private vehicles—a pilot study. Int J Environ Res Public Health. 2021;18(6):1–9.

33. Horn GP, Fent KW, Kerber S, Smith DL. Hierarchy of contamination control in the fire service: Review of exposure control options to reduce cancer risk. J Occup Environ Hyg. 2022;19(9):538–57.

34. Burgess JL, Hoppe-Jones C, Griffin SC, Zhou JJ, Gulotta JJ, Wallentine DD, et al. Evaluation of Interventions to Reduce Firefighter Exposures. J Occup Environ Med. 2020;62(4):279–88.

35. Abramson MJ, Glass DC. Trajectories of lung function in urban firefighters. Respirology. 2022:7–8.

36. Sidor R, Peters JM. Fire fighting and pulmonary function. An epidemiologic study. Am Rev Respir Dis. 1974;109(2):249–54.

37. Peters JM, Theriault GP, Fine LJ, Wegman DH. Chronic Effect of Fire Fighting on Pulmonary Function. N Engl J Med. 1974;291(25):1320–2.

38. Musk AW, Peters JM, Wegman DH. Lung function in fire fighters. A 3 yr follow up of active subjects. Am J Public Health. 1977;67(7):626–9.

39. Musk AW, Peters JM, Wegman DH. Lung function in fire fighters. II. A 5 yr follow up of retirees. Am J Public Health. 1977;67(7):630–3.

40. Musk AW, Smith TJ, Peters JM, McLaughlin E. Pulmonary function in firefighters: Acute changes in ventilatory capacity and their correlates. Br J Ind Med. 1979;36(1):29–34.

41. Slattery F, Johnston K, Paquet C, Bennett H, Crockett A. The long-term rate of change in lung function in urban professional firefighters: A systematic review. BMC Pulm Med. 2018;18(1):1–20.

42. Mathias KC, Graham E, Stewart D, Smith DL. Decreased Pulmonary Function Over 5 Years in US Firefighters. J Occup Environ Med. 2020;62(10):816–9.

43. Cherry N, Barrie JR, Beach J, Galarneau JM, Mhonde T, Wong E. Respiratory Outcomes of Firefighter Exposures in the Fort McMurray Fire: A Cohort Study From Alberta Canada. J Occup Environ Med. 2021;63(9):779–86.

44. Australasian Fire Authorities Council (AFAC) Medical Guidelines for Firefighters Summary Document October 2006.

45. Klatt S. An international comparison: Training standards and fireground safety [Internet]. Fire Engineering. 2020 [cited 2023 Apr 3]. Available from: https://www.fireengineering.com/health-safety/an-international-comparison-training-standards-and-fireground-safety-susanne-klatt/#gref

46. Stanojevic S, Kaminsky DA, Miller M, Thompson B, Aliverti A, Barjaktarevic I, et al. ERS/ATS technical standard on interpretive strategies for routine lung function tests. Eur Respir J. 2021;2101499.

47. Graham BL, Steenbruggen I, Barjaktarevic IZ, Cooper BG, Hall GL, Hallstrand TS, et al. Standardization of spirometry 2019 update an official American Thoracic Society and European Respiratory Society technical statement. Am J Respir Crit Care Med. 2019;200(8):E70–88.

48. Sharma G, Goodwin J. Effect of aging on respiratory system physiology and immunology. Clin Interv Aging. 2006;1(3):253–60.

49. Hnizdo E, Sircar K, Glindmeyer HW, Petsonk EL. Longitudinal limits of normal decline in lung function in an individual. J Occup Environ Med. 2006;48(6):625–34.

50. Hnizdo E, Yu L, Freyder L, Attfield M, Lefante J, Glindmeyer HW. The precision of longitudinal lung function measurements: Monitoring and interpretation. Occup Environ Med. 2005;62(10):695–701.

51. Nadri FR. Evaluation of Chronic Cough in a Tertiary Care Center in Tropics. Chest. 2003;124(4):136S.

52. Stanojevic S, Filipow N, Ratjen F. Paediatric reproducibility limits for the forced expiratory volume in 1 s. Thorax. 2020;75(10):891–6.

53. Koh D, Aw TC. Surveillance in occupational health. Occupational and Environmental Medicine. 2003;60:705–10.

54. Kauppinen T, Toikkanen J. Health and hazard surveillance - Needs and perspectives. Vol. 25, Scandinavian Journal of Work, Environment and Health. 1999; 25:61–7.

55. National Occupational Health & Safety Commission. Competencies for Health Surveillance. 1998.

56. Safe Work Australia. Work health and safety consultation , cooperation and coordination Code of Practice. Code of Practice. 2018:41.

57. NIOSH. Essential Elements of Effective Workplace Programs and Policies for Improving Worker Health and Wellbeing. 2008.

58. Aldrich TK, Vossbrinck M, Zeig-Owens R, Hall CB, Schwartz TM, Moir W, et al. Lung Function Trajectories in World Trade Center-Exposed New York City Firefighters over 13 Years the Roles of Smoking and Smoking Cessation. Chest. 2016 Jun 1;149(6):1419–27.

59. Schermer T, Malbon T, Morgan M, Briggs N, Holton C, Appleton S, et al. Lung function and health status in metropolitan fire-fighters compared to general population controls. Int Arch Occup Environ Health. 2010;83(7):715–23.

60. Schermer TR, Malbon W, Adams R, Morgan M, Smith M, Crockett AJ. Change in lung function over time in male metropolitan firefighters and general population controls: A 3-year follow-up study. J Occup Health. 2013;55(4):267–75.

61. Schermer TR, Malbon W, Morgan M, Smith M, Crockett AJ. Chronic respiratory conditions in a cohort of metropolitan fire-fighters: associations with occupational exposure and quality of life. Int Arch Occup Environ Health. 2014;87(8):919–28.

62. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. Eur Respir J. 2012 Dec;40(6):1324–43.

63. Slattery F, Schermer T, Esterman A, Johnston K, Crockett A. The Global Lung Function Initiative 2012 Equations Are as Well-Suited as Local Population Derived Equations to a Sample of Healthy Professional Firefighters. Can Respir J. 2017;2017.

64. Gore CJ, Crockett AJ, Pederson DG, Booth ML, Bauman A, Owen N. Spirometric standards for healthy adult lifetime nonsmokers in Australia. Eur Respir J. 1995;8(5):773–82.

Chapter 2 Longitudinal Lung Function in Urban Firefighters: A Group-based Multi-Trajectory Modelling Approach

The previous chapter outlined possible limitations methodologies previously used to analyse longitudinal firefighter spirometry. This chapter, presented in manuscript form, demonstrates the utility of using a Group-based Multi-trajectory Modelling approach. It is formatted to conform with requirements of the peer reviewed journal, *Respirology*.

The supporting information associated with this manuscript is presented in Chapter 2.7. A signed Statement of Authorship for this manuscript can be found in Appendix 2.1.

Citation

Pendergrast, C, Boyle, T, Crockett, AJ, Eston R, Johnston KN. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. *Respirology*. 2022. https://doi.org/10.1111/resp.14382

2.1 Abstract

Background and objectives:

Urban firefighters are routinely exposed to both physical and chemical hazards that can negatively impact lung health, but it is unclear if firefighters experience accelerated decline in spirometry parameters due to chronic exposure and acute insults. This study aimed to describe sub-groups of firefighters with differing spirometry trajectories and examine the relationship between the identified trajectories and demographic, lifestyle and occupational characteristics.

Methods:

Data from six waves of the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service Study (2007-2019) were used to identify spirometry parameter z-score trajectories, using group-based multi-trajectory modelling (GBMTM). Analysis of variance and chi-square statistics were used to assess trajectory group differences in baseline self-reported demographic, lifestyle, and occupational characteristics.

Results:

In the 669 included firefighters, we identified five trajectories for the combination of Forced Expiratory Volume in the first second z-score (FEV_1z), Forced Vital Capacity z-score (FVCz) and the ratio of FEV_1 and FVC z-score (FEV1/FVCz). There were three stable trajectories of low, average, and very high lung function and two declining trajectories of average and high lung function. Analysis of subgroup characteristics revealed no significant differences between expected and actual group proportions for the occupational characteristics of years of service and respiratory protection use. Significant differences were seen in respiratory health and body mass index.

Conclusion:

GBMTM defined distinct, plausible spirometry trajectory sub-groups. Firefighter longitudinal spirometry trajectory group membership was associated with body mass index and respiratory disease or symptoms but not with self-reported smoking history or occupational factors.

Keywords:

firefighter, occupational exposure, spirometry, longitudinal studies, group-based multi-trajectory modelling

2.2 Introduction

Firefighters are routinely exposed to both physical and chemical hazards that are associated with health risks, including increased rates of cancer(1,2), heart attack(3), musculoskeletal injury(4) and respiratory dysfunction(5). The acute responses of the respiratory system to inhalation of toxic gases and particulates are well documented(6,7). Exposures can lead to acute airway hyper-responsiveness(8), reductions in lung function(9–11) and lung inflammation(11,12), and repeated insults could result in long-term sequelae.

Serial spirometry is used to investigate the long-term rate of change in firefighters' lung health and determine if it is consistent with the general healthy population(5). A systematic review synthesising 22 studies of longitudinal spirometry measurement in cohorts of professional firefighters found that non-smoking firefighters who wore respiratory protection were likely to have a normal rate of lung function decline with age(5). Despite this review outcome, a more recent study of Virginian firefighters observed decreases in spirometry parameters two to four times greater than expected over five years(13). Alternate methodological approaches may be necessary to delineate if there are long-term decrements in lung health related to repeated exposures and respiratory insults in this at-risk group.

Urban fire services have seen significant changes in technology, procedures and training over the last four decades since the first evidence of accelerated spirometry decline was reported (14). Lower risk of accelerated decline in spirometry parameters has been demonstrated in those who frequently used respiratory protection(5), whilst weight gain and smoking history are associated with an increased rate of spirometry decline(5). Firefighters are a heterogeneous group whose work and lifestyle choices may cause a single averaged longitudinal trajectory to mask individual differences and lead to erroneous conclusions regarding lung health. Elucidation of sub-groups of firefighters following different spirometry trajectories and their characteristics may identify groups at risk of accelerated spirometry decline and those protective factors associated with the preservation of lung health.

Most longitudinal studies report changes in spirometry parameters in absolute terms (i.e. mL of volume change divided by the time between measurements)(5). Spirometry parameters and any associated changes are related to an individual's characteristics of age, height, gender, and ethnicity(15,16). Representation of spirometry parameters as a z-score (the number of standard deviations (SD) from the mean) allows standardisation of the measurement and minimises the effect of these characteristics during any comparison(17). Expressing firefighter spirometry as a z-score generated from Global Lung Initiative (GLI) reference values and examining z-score patterns over time is a contemporary approach to analysis that will build on existing knowledge in this field(18).

This study aimed to identify distinct subgroups of spirometry trajectories in longitudinal firefighter data, and to assess if baseline lifestyle, health and occupational factors were associated with trajectory group membership.

2.3 Methods

Study Design and Participants

Our study analysed data from the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study, conducted between 2007 and 2019 and included six waves of occupational, health, lifestyle and spirometry measurements (19–24). The observational study collected data biennially and was open to all SAMFS active firefighters and administrative staff (approximately 5%). Firefighting tasks were of a routine urban nature (structural, waste, car fire attendance with limited exposure to bushfire) and no catastrophic events were experienced throughout the period of data collection. The study used an open cohort design, allowing firefighters to participate in one, some or all rounds of surveillance. Of the 976 firefighters who took part in the study, our analysis focused on those who performed technically acceptable spirometry measurements at two or more waves and provided questionnaire data on their first wave(25).

Ethics approval was obtained from the University of South Australia Human Research Ethics Committee (Project no. 0000032662), and all participants gave written informed consent. We used the Guidelines for Reporting on Latent Trajectory Studies (GRoLTS) to inform our analysis and reporting(26).

Outcome Variables – Spirometry Parameters

Pre-bronchodilator spirometry was measured using a Masterscreen PFT spirometer (Vyaire, Würzburg, Germany) at each study wave attended by the firefighters according to the American Thoracic Society and European Respiratory Society guidelines(25). The FEV_1, FVC and FEV_1/FVC were converted to z-scores using the Global Lung Initiative (GLI) reference equations(17) that are validated for use in both the general Australian population (27,28) and the South Australian urban firefighter population(23).

Exposure Variables - Questionnaire Data

Data about lifestyle, respiratory disease and symptoms, length of service and respiratory protection use were collected at each firefighter's first attended wave and used to define baseline exposure variables (Table S1).

Lifestyle-related variables included body mass index (BMI) and smoking status. The height and weight measurements at the first spirometry test occasion were used to calculate BMI. Smoking status was based on self-report data, and firefighters were categorised as current smokers, ex-smokers, and never-smokers.

For respiratory disease, firefighters were grouped into the categories 'Nil', 'Asthma' or 'Chronic Obstructive Pulmonary Disease (COPD)' according to self-reported doctor diagnosis and/or symptoms as previously described by Schermer(19).

'Years of service' and 'Respiratory Protection Use' were calculated from self-report questionnaire baseline data to provide surrogate measures of occupational exposure.

Statistical Analyses

Baseline characteristics of participants were expressed as mean (SD) for continuous, normally distributed data and count (%) for categorical data.

We applied Group-Based Multi-Trajectory Modelling (GBMTM) to explore the presence of distinct subgroups of FEV_1z, FVCz and FEV_1/FVCz combinations within the cohort over the surveillance period. The spirometry parameters were considered to follow a censored normal distribution, and each participant's first wave attended was allocated as time equal to zero days.

Determination of the optimal number of trajectory groups was based on Growth Based Trajectory Modelling (GBTM) of individual spirometry parameters with the assistance of the Fit-Criteria Assessment Plot(29) (Appendix S1, Figure S1). A 5-trajectory model was deemed most appropriate, yielding the Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC) closest to zero, Average Posterior Probability of Assignment (APPA) greater than 0.7 and adequate sample sizes for each group (Table S2) (29,30). Subsequent application of GBMTM with stepwise analysis of polynomial significance led to the determination of a linear model shape. Model fit statistics (BIC, AIC, APPA), expert knowledge, and parsimony contributed to the final model determination (Table S3).

Assignment of an individual participant to a specific trajectory group was based on their highest posterior probability of group membership. Between-group differences for the lifestyle factors, respiratory status and occupational factors were tested using chi-square tests for categorical factors and analysis of variance for continuous factors.

As GBMTM analysis assumes that missing data are missing at random (MAR) (30), we performed a sensitivity analysis where we first investigated which baseline factors were associated with the number of waves participated in (i.e., those factors that help to predict missingness in the trajectory analysis). We then repeated the GBMTM analysis with those factors included as covariates and compared trajectory group allocation between the two models.

Data cleaning and regression analysis were performed using SPSS (version 26, IBM SPSS 26, Armonk, NY), and Stata (version 16, StataCorp LLC, College Station, TX) was used to perform the trajectory analysis(31).

2.4 Results

Firefighter Characteristics

Of the 976 firefighters that took part in the study, 669 performed spirometry testing in at least two waves and supplied baseline questionnaire responses allowing them to be included in this analysis. The included cohort was 98% male, had a mean age at baseline of 41.7 (SD=8.6) years, and had spent an average of 13.6 (6.6) years as a firefighter (Table 1).

At baseline measurement, mean firefighter lung function was within the normal range (FEV_1z: 0.44(0.97); FVCz: 0.90(0.89); FEV_1/FVCz: -0.70(0.88)). More than half of the group were non-smokers (57.7%), and 89% reported no respiratory disease diagnosis or symptoms. Characteristics of included firefighters were not significantly different from those who were excluded, except FEV_1z, which was, on average, higher in those included (0.44(0.97) vs 0.24(0.95), $P_{difference}$=0.003) and excluded firefighters were more likely to have missing data for smoking status, years of service and respiratory protection use (Table S4). Participants provided an average of 4(1) spirometry results for the analysis. Wave data points were an average of 670(57) days apart.

Trajectory Analysis

The selected model identified five spirometry trajectories (Figure 1) and performed well on all indexes of model fit (Table S5). Trajectory groups were labelled based on their relative differences from Group 2 (n=121, 18.7% of the included sample), which demonstrated stability over time in all spirometry parameters around the population mean. Group 1 displayed stable relatively low function (n=69, 10.3%), Group 3 displayed declining lung function around the population mean (n=208, 30.5%), Group 4 displayed relatively high but declining lung function (n=147, 22.3%) and Group 5 displayed very high stable lung function (n=124, 18.3%) (Table 1, Table S6).

Analysis of the characteristics of each trajectory group revealed no significant differences between the groups for the occupational characteristics of Years of Service and Respiratory Protection Use. However, significant differences were seen for Respiratory Status (p=0.006) and BMI (p=0.002). The stable, very high lung function group had a lower proportion (9%) of firefighters with a high BMI, whilst the stable, low lung function group had the highest proportion (18%) of firefighters with self-reported respiratory disease or symptoms (Table 1).

The sensitivity analysis found that BMI, Smoking Status, Years of Service and Respiratory Protection Use were associated with the number of waves participated in. Adding these variables to the trajectory analysis resulted in almost identical (99.1% agreement) trajectory group allocation to the original trajectory analysis (Table S7).

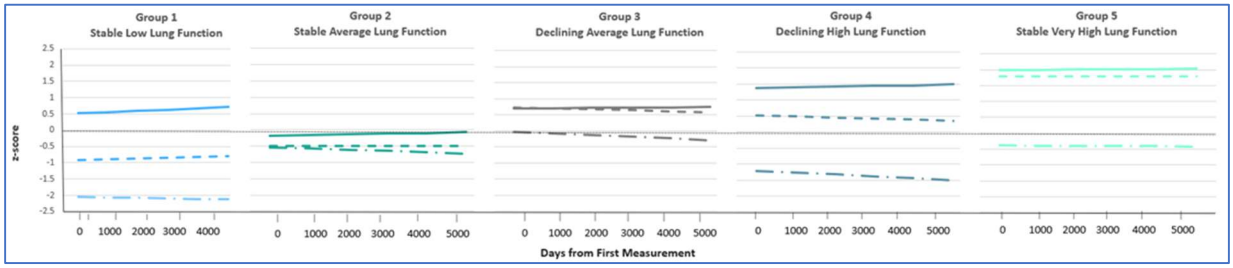


FIGURE 1 Graphical representation of the five trajectory groups of spirometry parameter z-scores in the urban firefighter cohort from 2007 to 2019. In each group FVCz is represented by a solid line, FEV_1z by a dashes and FEV_1/FVCz by a dash, dot line.

2.5 Discussion

This novel approach using GBMTM identified five distinct trajectories of spirometry parameter z-scores in an urban firefighter cohort. All trajectories for FVCz, FEV_1z and FEV_1/FVCz were above the lower limit of normal (z-score > -1.64) except the FEV_1/FVCz in Group 1 (Stable Low Lung Function trajectory). The analysis revealed that firefighters had average to very high FVCz that remained stable over the time of surveillance. The stable FVCz trajectories combined with either stable or declining FEV_1z trajectories resulted in stable or declining FEV_1/FVCz trajectories. This outcome contrasts with an earlier analysis of our dataset performed before the final wave of data collection (2019), which demonstrated that mean spirometry parameters in the whole study population remained stable over ten years (24).

The Stable Low Lung Function group displayed FEV_1z and FVCz within the normal range but a reduced FEV_1/FVCz, consistent with a dysanaptic pattern of spirometry parameters (32). It is unclear if dysanapsis (a reduced airway calibre relative to lung size) is a normal physiological phenomenon or a precursor to worsening obstructive lung disease(32). This firefighter cohort had characteristics comparable with those observed in a group of healthy people with a dysanaptic spirometry pattern (i.e. male sex, age < 55 years and FVC > 105% predicted), in contrast to people with dysanaptic spirometry and clinically confirmed obstructive lung disease(33). Recent studies of American and Canadian population cohorts suggest that those with dysanapsis have a predisposition for developing obstructive lung disease(34) and may be particularly susceptible to the long-term effects of air pollution(35). Levels of air pollution regularly encountered by firefighters are significantly greater than ambient air pollution so it is conceivable that risk of developing obstructive lung disease in later life is heightened further in firefighters with lower airway to lung size ratios(36,37).

Table 1. Baseline Demographic, Lifestyle and Occupational Characteristics by Spirometry Trajectory Group

	Overall	Group 1	Group 2	Group 3	Group 4	Group 5
	(n = 669)	Stable low lung function (n = 69)	Stable Average Lung Function (n = 121)	Declining Average Lung Function (n = 208)	Declining High Lung Function (n = 147)	Stable Very High Lung Function (n = 124)
Characteristics at Baseline						
Male (%)	656 (98%)	69 (100%)	119 (98%)	203 (98%)	144 (98%)	121 (98%)
Age (years)	41.7 (8.6)	39.7 (8.2)	42.3 (9.9)	41.5 (8.7)	41.6 (7.5)	42.6 (8.5)
BMI (kg/m^2)	27.3 (3.2)	27.8 (3.3)	28.2 (4.0)	26.9 (2.8)	26.9 (3.1)	27.0 (2.6)
< 25 kg/m^2	153 (23%)	14 (20%)	23 (19%)	54 (26%)	40 (27%)	22 (18%)
25 - 30 kg/m^2	406 (61%)	41 (60%)	66 (55%)	128 (62%)	80 (54%)	91 (73%)
>30 kg/m^2	110 (16%)	14 (20%)	32 (26%)	26 (13%)	27 (18%)	11 (9%)
Smoking Status*						
Non-smoker	386 (70%)	42 (61%)	65 (54%)	116 (56%)	90 (61%)	73 (59%)
Ex-smoker	117 (21%)	8 (12%)	28 (23%)	35 (17%)	20 (14%)	26 (21%)
Current smoker	46 (9%)	8 (12%)	7 (6%)	16 (8%)	8 (5%)	7 (6%)
Not Reported	120 (19%)	11 (16%)	21 (17%)	41 (20%)	29 (20%)	18 (15%)
Occupational Factors*						
Years of Service	13.4 (10.5)	12.16 (9.9)	14.8 (11.5)	13.0(10.4)	13.1 (9.6)	13.7 (10.7)
Respiratory Protection Use - Fire Task	0.49 (0.26)	0.45 $\pm$ 0.27	0.48 $\pm$ 0.25	0.50 $\pm$ 0.27	0.50 $\pm$ 0.28	0.49 $\pm$ 0.25
Respiratory Status*						
No reported diagnosis or symptoms	597 (89%)	57 (82%)	106 (88%)	192 (92%)	125 (85%)	117 (94%)
Asthma (diagnosis or symptoms)	10 (2%)	4 (6%)	0 (0%)	2 (1%)	4 (3%)	0 (0%)
Chronic bronchitis/emphysema (diagnosis or symptoms)	62 (9%)	8 (12%)	15 (12%)	14 (7%)	18 (12%)	7 (6%)
Spirometry						
FEV_1z	0.44 (0.97)	-0.89 (0.58)	-0.54 (0.47)	0.66 (0.50)	0.46 (0.52)	1.73 (0.54)
FVCz	0.89 (0.90)	0.57 (0.60)	-0.21 (0.48)	0.68 (0.49)	1.36 (0.56)	1.97 (0.65)
FEV_1/FVCz	-0.70 (0.88)	-2.07 (0.63)	-0.59 (0.63)	-0.08 (0.57)	-1.26 (0.61)	-0.43 (0.69)

Baseline Characteristics of participants according to lung function trajectories Data are n (%) or mean (SD). Denominators are shown where data are missing. Abbreviations: BMI, body mass index; COPD, chronic obstructive pulmonary disease; FEV_1z, forced expiratory volume in 1 second expressed as a z-score; FVCz, forced vital capacity expressed as a z-score; FEV_1/FVCz, ratio of FEV_1 and FVC expressed as a z-score. All spirometry parameter z-scores are based on the Global Lung Initiative reference values(44). * Denotes self-reported data.

As previously described(19,21–23), this firefighter cohort has higher than average spirometry, possibly due to selection into an active occupation and the healthy worker effect(38). Analysis techniques that average change in volume over time or use simple linear regression in the cohort, may result in those with above-average spirometry masking those firefighters whose spirometry is low, contributing to inconsistent study outcomes. Seventy-two percent of our cohort had FEV_1z and FVCz higher than the population average, and almost one fifth (19.5%) had z-scores above the 95th percentile. Group membership of declining trajectories was 50% and occurred in groups where lung function was at or greater than the population mean. Irrespective of the normality of baseline lung function results, accelerated lung function decline is associated with poor clinical outcomes(32). GBMTM allowed us to identify those groups within the cohort who may be susceptible to poor outcomes and define their associated characteristics.

Firefighter occupational characteristics of Years of Service and Respiratory Protection Use were not related to the prevalence of declining or low lung function in this analysis, with similar values observed in each of the trajectory groups. This result is consistent with previous studies that have failed to find a robust relationship between these occupational characteristics and lung function decline in routine urban firefighters (5). However, addressing whether occupational firefighting predisposes those on the frontline to accelerated spirometry decline has, and continues to be, a challenging problem. The long latency of possible lung disease from cumulative exposures, lack of pre-exposure baseline measurement, lifestyle confounders such as smoking history and weight gain, evolving improvements in work health safety and the healthy worker effect pose difficulties for researchers.

The Stable Very High Lung Function group had the lowest proportion of firefighters with a BMI greater than 30 kg/m^2. An increased BMI changes chest wall mechanics, lowering operating lung volumes, vital capacity and promoting airway narrowing and closure(39). Preserved spirometry in those with lower BMI is consistent with the evidence provided by previous longitudinal studies of firefighters(40,41) and non-firefighters(42). Unsurprisingly, the highest prevalence of self-reported respiratory disease or symptoms at baseline was seen in the Stable Low Lung Function (18%) and Declining High Lung Function (15%) groups. Whilst the

relationship between respiratory disease and lung function has not been investigated explicitly in firefighters, it is plausible that those with symptoms or diagnosed disease will demonstrate low or reducing lung function consistent with progression of disease-associated mechanical lung changes.

The study exclusion criteria and open cohort nature of the study may have contributed to selection bias in our analysis. Although excluded participants were similar to the included participants in terms of their reported questionnaire data (exposures), they were more likely to have missing questionnaire data (i.e., 'Not Reported' exposures). In addition, firefighters who were located at regional stations or those who suspected their health and fitness were compromised may have been less likely to participate and may be under-represented. This may limit the generalizability of our results.

The self-report nature of the data also introduced the risk of measurement error. Recall bias, breach of workplace policy and concern about data use in an occupational setting, reliant on health and fitness, may have negatively impacted exposure reporting. Ideally, objective measures of firefighter exposures and respiratory protection use, along with physician confirmed respiratory status at baseline would strengthen the methodology of studies in this occupational group.

The major strength of this study was the use of the contemporary methods of normalising and interpreting the spirometry data, consistent with the ATS/ERS recommendations(25). The use of absolute change over time and percentage of predicted in the analysis of spirometry and other lung function testing data are no longer recommended(32,43). Another strength of our study was the ability to explore undefined trajectories that were not based on an a priori hypothesis. By applying GBMTM, we were able to simultaneously analyse the combination of spirometry parameters that are clinically reflective of lung health. Despite the benefits of this type of analysis, there is currently no validated approach to determining the normal variation of z-scores over time(32) and hence if our declining trajectories are likely to represent clinical significance. We are currently limited to a purely descriptive outcome.

In conclusion, this study demonstrates that GBMTM was able to identify five distinct, biologically plausible firefighter spirometry trajectories. It failed to find evidence of an association between self-reported occupational factors and declining spirometry trajectories.

Despite this reassuring outcome, group membership of declining trajectories was > 50% and these were characterised by spirometry parameters that were at or greater than the population mean. This highlights the need for pre-exposure baseline screening of lung health in all firefighters, to ensure that decline in lung health can be identified, given the high risk of acute and chronic exposure.

2.6 Declarations

Acknowledgements

We wish to thank and acknowledge the generosity of the South Australian Metropolitan Fire Service (SAMFS) firefighters in contributing their time and effort to this study. The authors would also like to thank Deputy Chief Officer Paul Fletcher, SAMFS, for his communication, planning, and logistical assistance.

Research Funding

Catherine Pendergrast's research is funded by the University of South Australia Firefighter Lung Function Scholarship provided by the SAMFS and the Australian Government Research Training Program.

Disclosure Statement

The authors have no conflicts of interest to declare.

Author Contributions

Catherine Pendergrast: Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Project administration (lead); Visualisation (lead); Writing – original draft (lead); Writing – review & editing (lead). Terry Boyle: Conceptualisation (equal); Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Supervision (lead); Writing – review & editing (supporting); Alan J Crockett: Conceptualisation (equal); Data curation (supporting); Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting); Writing – review & editing (supporting). Roger Eston: Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting). Kylie N Johnston: Conceptualisation (equal); Investigation (supporting); Project administration (supporting); Supervision (lead); Writing – review & editing (supporting).

Data Availability Statement

The data that support the findings of this study are held by the corresponding author. Availability of the study data is at the discretion of the SAMFS upon application.

Human Ethics Approval Declaration

This study was performed in accordance with the Declaration of Helsinki. This human study was approved by the University of South Australia Human Research Ethics Committee (Protocol no. 0000032662). All participant provided written informed consent to participate in this study.

2.7 References

1. Jalilian H, Ziaei M, Weiderpass E, Rueegg CS, Khosravi Y, Kjaerheim K. Cancer incidence and mortality among firefighters. Int J Cancer. 2019;145(10):2639–46.

2. Laroche E, L'espérance S. Cancer incidence and mortality among firefighters: An overview of epidemiologic systematic reviews. Vol. 18, International Journal of Environmental Research and Public Health. 2021. p. 1–32.

3. Soteriades ES, Smith DL, Tsismenakis AJ, Baur DM, Kales SN. Cardiovascular disease in US firefighters: A systematic review. Cardiol Rev. 2011;19(4):202–15.

4. Nazari G, MacDermid J, Cramm H. Prevalence of musculoskeletal disorders among Canadian firefighters: A systematic review and meta-analysis. Journal of Military, Veteran and Family Health. 2020;6:83–97.

5. Slattery F, Johnston K, Paquet C, Bennett H, Crockett A. The long-term rate of change in lung function in urban professional firefighters: A systematic review. BMC Pulm Med. 2018;18(1):1–20.

6. Fent KW, Evans DE. Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. J Environ Monit. 2011;13(3):536–43.

7. Guidotti TL, Clough VM. Occupational health concerns of firefighting. Annual Review of Public Health. 1992; 13:151–71.

8. Chia KS, Jeyaratnam J, Chan TB, Lim TK. Airway responsiveness of firefighters after smoke exposure. Br J Ind Med. 1990;47(8):524–7.

9. Burgess JL, Nanson CJ, Bolstad-Johnson DM, Gerkin R, Hysong TA, Lantz RC, et al. Adverse respiratory effects following overhaul in firefighters. J Occup Environ Med. 2001;43(5):467–73.

10. Gaughan DM, Piacitelli CA, Chen BT, Law BF, Virji MA, Edwards NT, et al. Exposures and cross-shift lung function declines in wildland firefighters. J Occup Environ Hyg. 2014;11(9):591–603.

11. Gianniou N, Katsaounou P, Dima E, Giannakopoulou CE, Kardara M, Saltagianni V, et al. Prolonged occupational exposure leads to allergic airway sensitization and chronic airway and systemic inflammation in professional firefighters. Respir Med. ;118:7–14.

12. Swiston JR, Davidson W, Attridge S, Li GT, Brauer M, Van Eeden SF. Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. Eur Respir J. 2008;32(1):129–38.

13. Mathias KC, Graham E, Stewart D, Smith DL. Decreased Pulmonary Function Over 5 Years in US Firefighters. J Occup Environ Med. 2020;62(10):816–9.

14. Peters JM, Theriault GP, Fine LJ, Wegman DH. Chronic Effect of Fire Fighting on Pulmonary Function. N Engl J Med. 1974;291(25):1320–2.

15. Quanjer PH, Hall GL, Stanojevic S, Cole TJ, Stocks J. Age- and height-based prediction bias in spirometry reference equations. Eur Respir J. 2012;40(1):190–7.

16. Stanojevic S, Quanjer P, Miller MR, Stocks J. The Global Lung Function Initiative: Dispelling some myths of lung function test interpretation. Breathe. 2013;9(6):462–74.

17. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multı-Ethnıc Reference Values For Spırometry For The 3-95 Year Age Range: The Global Lung Functıon 2012 Equatıons: Report of the Global Lung Function Initiative (GLI), ERS Task Force to establish improved Lung Function Reference Values. Eur Respir J. 2012;40(6):1324–43.

18. Bui DS, Lodge CJ, Burgess JA, Lowe AJ, Perret J, Bui MQ, et al. Childhood predictors of lung function trajectories and future COPD risk: a prospective cohort study from the first to the sixth decade of life. Lancet Respir Med. 2018;6(7):535–44.

19. Schermer T, Malbon T, Morgan M, Briggs N, Holton C, Appleton S, et al. Lung function and health status in metropolitan fire-fighters compared to general population controls. Int Arch Occup Environ Health. 2010;83(7):715–23.

20. Schermer T, Malbon W, Newbury W, Holton C, Smith M, Morgan M, et al. Spirometry and impulse oscillometry (IOS) for detection of respiratory abnormalities in metropolitan firefighters. Respirology. 2010;15(6):975–85.

21. Schermer TR, Malbon W, Adams R, Morgan M, Smith M, Crockett AJ. Change in lung function over time in male metropolitan firefighters and general population controls: A 3-year follow-up study. J Occup Health. 2013;55(4):267–75.

22. Schermer TR, Malbon W, Morgan M, Smith M, Crockett AJ. Chronic respiratory conditions in a cohort of metropolitan fire-fighters: associations with occupational exposure and quality of life. Int Arch Occup Environ Health. 2014;87(8):919–28.

23. Slattery F, Schermer T, Esterman A, Johnston K, Crockett A. The Global Lung Function Initiative 2012 Equations Are as Well-Suited as Local Population Derived Equations to a Sample of Healthy Professional Firefighters. Can Respir J. 2017;5.

24. Slattery F. Longitudinal changes in South Australian metropolitan firefighter lung function [dissertation]. Adelaide: University of South Australia; 2019.

25. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A., et al. Standardisation of spirometry. Eur Respir J. 2005;26(2):319–38.

26. van de Schoot R, Sijbrandij M, Winter SD, Depaoli S, Vermunt JK. The GRoLTS-Checklist: Guidelines for Reporting on Latent Trajectory Studies. Struct Equ Model. 2017;24(3):451–67.

27. Thompson BR, Stanojevic S, Abramson MJ, Beasley R, Coates A, Dent A, et al. The all-age spirometry reference ranges reflect contemporary Australasian spirometry. Respirology. 2011;16(6):912–7.

28. Hall GL, Thompson BR, Stanojevic S, Abramson MJ, Beasley R, Coates A, et al. The Global Lung Initiative 2012 reference values reflect contemporary Australasian spirometry. Respirology. 2012 Oct;17(7):1150–1.

29. Klijn SL, Weijenberg MP, Lemmens P, Van Den Brandt PA, Lima Passos V. Introducing the fit-criteria assessment plot-A visualisation tool to assist class enumeration in group-based trajectory modelling. Stat Methods Med Res. 2017;26(5):2424–36.

30. Nagin DS, Odgers CL. Group-based trajectory modeling in clinical research. Annu Rev Clin Psychol. 2010;6(May):109–38.

31. Jones B, Nagin DS. A Stata Plugin for Estimating Group-Based Trajectory Models. 2012.

32. Stanojevic S, Kaminsky DA, Miller M, Thompson B, Aliverti A, Barjaktarevic I, et al. ERS/ATS technical standard on interpretive strategies for routine lung function tests. Eur Respir J. 2021;2101499.

33. Andreata LDS, Soares MR, Pereira CAC. Reduced FEV1/FVC and FEV1in the normal range as a physiological variant. Respir Care. 2019;64(5):570–5.

34. Smith BM, Kirby M, Hoffman EA, Kronmal RA, Aaron SD, Allen NB, et al. Association of Dysanapsis with Chronic Obstructive Pulmonary Disease among Older Adults. JAMA - J Am Med Assoc. 2020;323(22):2268–80.

35. Bourbeau J, Doiron D, Biswas S, Smith BM, Benedetti A, Brook JR, et al. Ambient Air Pollution and Dysanapsis: Associations with Lung Function and COPD in the CanCOLD Study. Am J Respir Crit Care Med. 2022;

36. Evans DE, Fent KW. Ultrafine and respirable particle exposure during vehicle fire suppression. Environ Sci Process Impacts. 2015;17(10):1749–59.

37. Baxter CS, Hoffman JD, Knipp MJ, Reponen T, Haynes EN. Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. J Occup Environ Hyg. 2014;11(7):85–91.

38. Li CY, Sung FC. A review of the healthy worker effect in occupational epidemiology. Occup Med. 1999;49(4):225–9.

39. Jones RL, Nzekwu MMU. The effects of body mass index on lung volumes. Chest. 2006;130(3):827–33.

40. Aldrich TK, Ye F, Hall CB, Webber MP, Cohen HW, Dinkels M, et al. Longitudinal pulmonary function in newly hired, non-world trade center-exposed fire department city of New York firefighters: The first 5 years. Chest. 2013;143(3):791–7.

41. Kim S, Jeon YE, Ryu H, Lee MY, Chung I. Related factors for preserving firefighter's pulmonary function. Ann Occup Environ Med. 2020;32(1).

42. Wang ML, Avashia BH, Petsonk EL. Interpreting longitudinal spirometry: Weight gain and other factors affecting the recognition of excessive FEV 1 decline. Am J Ind Med. 2009;52(10):782–9.

43. Graham BL, Steenbruggen I, Barjaktarevic IZ, Cooper BG, Hall GL, Hallstrand TS, et al. Standardization of spirometry 2019 update an official American Thoracic Society and European Respiratory Society technical statement. Am J Respir Crit Care Med. 2019;200(8):E70–88.

44. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. Eur Respir J. 2012;40(6):1324–43.

2.8 Supporting Information

Table S1. Exposure Variable Description

Exposure Variable	Survey Question	Exposure Variable Calculation	Exposure Variable Classification / Outcome
Smoking Status	Which of the following best describes your smoking status? 1 - Smoke daily; 2 - Smoke occasionally; 3 - Ex smoker; 4 - Tried but not smoked regularly and 5 – Never smoked.	1 & 2	Current Smoker
		3	Ex-Smoker
		4 & 5	Non-Smoker
Respiratory Status	1 - Have you ever been told by a doctor that you have asthma? Yes / No; 2 - Have you ever had an asthma attack? Yes / No; 3 - Have you had an attack of asthma in the last 12 months? Yes / No; 4 - Are you currently taking medicines for asthma? Yes/No; 5 - Have you ever been told by a doctor that you have any other respiratory problems? Yes / No; 6 - Do you usually cough up phlegm from your chest first thing? Yes / No; 7 - Do you cough up phlegm from your chest like this on most days - 3 month? Yes / No; 8 - Do you usually cough up phlegm from your chest rest of the day? Yes / No; 9 - Do you cough up phlegm from your chest like this on most days - 3 month? Yes / No	Answers 'Yes' to 1 & 2 or 1 & 4 or 2 & 4	Asthma Diagnosis or Symptoms
		Answers 'Yes' to 5 or 6 & 7 or 8 & 9	Chronic Obstructive Pulmonary Disease Diagnosis or Symptoms
		All others	None Reported
Years of Service	1 - For how many years have you been employed in this activity?; 2 - What year did you join the MFS?	Answer to 1	Number of Years of Service (years)
		Difference between the date of 1st wave attended and year joined the MFS	
Respiratory Protection Use - Task	For the Tasks: Knockdown; Overhaul; Fire Investigation, HazMat Investigation; Support/Command; Live Fire Training 1 - Have you been involved in <task> during the last 12 months?; 2 - How much time during <task> was spent using Respiratory Protection?	Exposure score (ES) was derived from the combination of the 2 questions. If not involved in the task an exposure score of '0' was assumed If involved in task and Respiratory Protection used:	Respiratory Protection Use
	NA	Frequently: ES - 0.1	Low Use: ES of 0.67 – 1.0
	Frequently: 80 - 100% of the time Often: 60 - 80% of the time	Often: ES – 0.3	
	Some of the time: 40 - 60% of the time	Some of the time: ES – 0.5	Medium Use: ES of 0.34 – 0.66
	Rarely: < 40% of the time	Rarely: ES – 0.8	
	Never: zero times	Never: ES – 1.0 ES of all fire tasks were averaged to one composite exposure score	High Use: ES of 0 – 0.33

S1 - Missing Data

There are a number of mechanisms for data missingness in our study. Firstly, the open cohort nature of the study allowed firefighters to enter those waves they wished and/or attend when conditions were conducive to participation. Recruitment involved communication of time-period of availability for data collection at several SAMFS sites. Participation was then reliant on firefighters' interest, awareness, availability and actively organizing attendance within their team. This study was fully supported by SAMFS who encouraged study participation by facilitating communication, availability, and backup of firefighters to travel to the testing sites during rostered hours. Despite this, some firefighters chose not to participate, and some were unavailable to participate due to physically not being able to be on-site whilst testing was available. Data on those who did not participate at any wave and their reasons for doing are unavailable and is a limitation of the study design.

Once recruited into the wave and attending, data may be missing due to the firefighter team being called away to an incident or incomplete questionnaire response.

Those who took part in two or more study waves and were included in the trajectory analysis were compared with those who were excluded due to only participating in one wave (Table S4). The differences between the two groups include a statistically significant difference in FEV_1z (but within normal test variability) and, more importantly, a significant difference in the number of participants missing health and occupational exposure variables.

Employer policy related to respiratory illness, smoking and respiratory protection use may have discouraged reporting on health and exposure indices. The nature of data missingness due to incomplete baseline exposure data in those who took part in 2 or more waves is explained further in Appendix S3.

S2 – Trajectory Modelling

Group-based Trajectory Modelling (GBTM)

We use GBTM and its extension GBMTM to identify subgroups of firefighters whose lung function parameters of FVCz, FEV_1z and FEV_1/FVCz follow similar patterns over time using the process below described by Andruff et al.(65). It was hypothesized that there were groups of firefighters within the cohort that would follow distinctive trajectories that could not be identified from the whole dataset. As our outcome measures are continuous data, the models are estimated using a censored normal distribution. Time = 0 was the date of the first wave attended. The final model was determined using a combination of fit statistics, model parsimony and knowledge of lung function interpretation.

GBTM for individual lung function parameters

We estimated models of between 1 and 6 groups for each lung function parameter using a quadratic model (cubic functions were not considered due to the relatively low number of time points and time frame of the study). The models were then re-run with the non-significant quadratic terms removed ($p>0.10$) leaving only the linear term (65). The outcome models of this analysis are presented in the table below with model fit criteria.

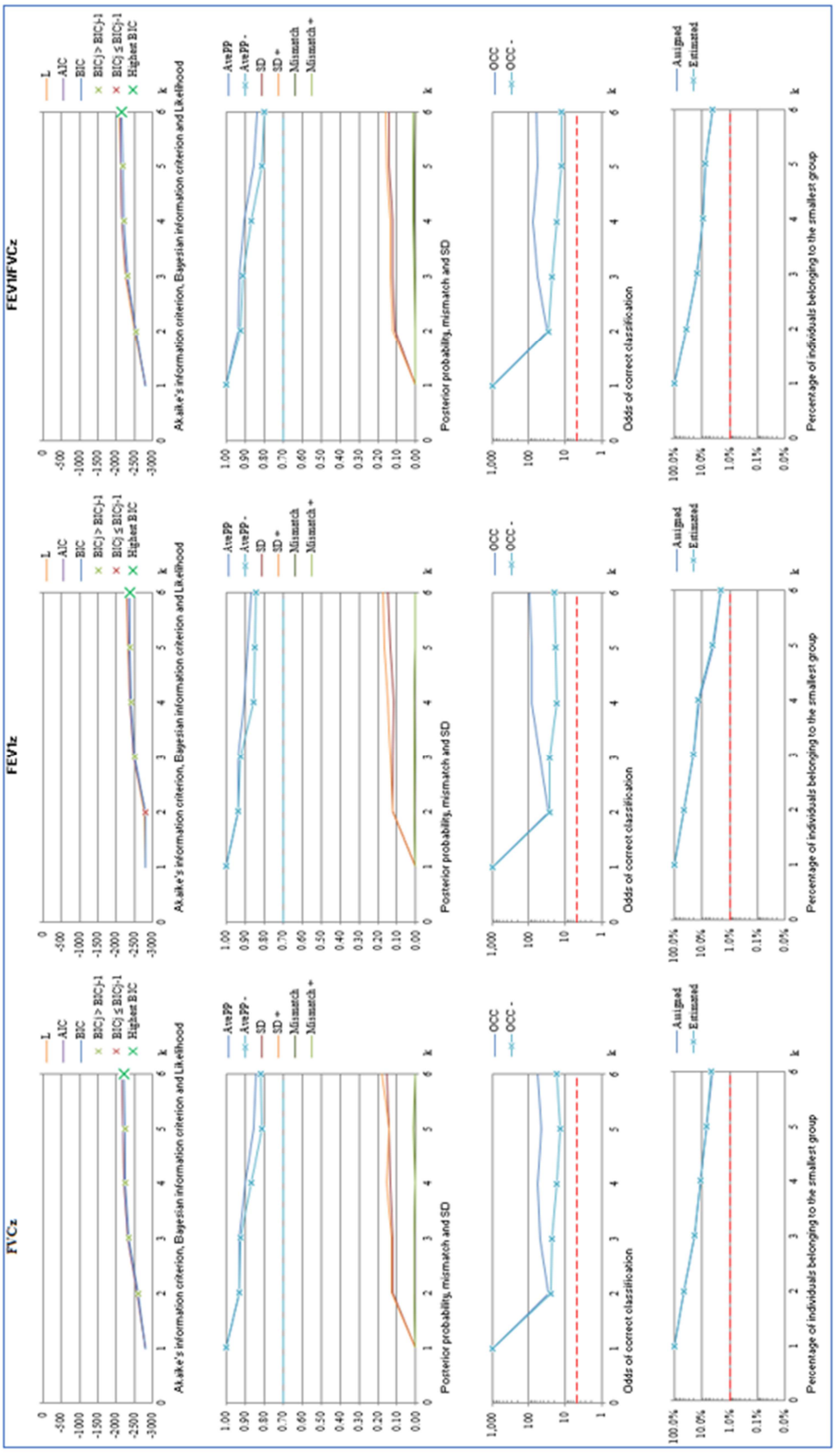


Figure S1 – Fit-Criteria Assessment Plot(2)
For all lung function parameters, as the number of groups increase, the Baysian Information Criteria (BIC) improves (the less negative number indicates a better fit) with the Bayes factor supporting a 6-group models as having very strong evidence (3). In models with 6 groups, some groups have predicted membership below the desired level of 5% (1). The 4 and 5 trajectory group models perform well on all tests of adequacy (odds of correct classification are above 7, actual and average posterior probabilities are higher than 0.8 and are assessed using group based multi-trajectory modelling (GBMTM).

Table S2. Model fit indices of 1 through 6 class unconditional GBTM models of Spirometry parameter z-scores.

		BIC (N=2318)	BIC (N=669)	AIC	Entropy	Predicted Probability of Group Membership					
						Groups					
						1.00	2.00	3.00	4.00	5.00	6.00
FVCz											
1 Group	1	-3060.04	-3058.17	-3051.41		100.00					
2 Groups	1 1	-2594.88	-2591.15	-2577.63	0.782	54.31	45.69				
3 Groups	1 1 1	-2350.08	-2344.49	-2324.21	0.843	29.05	52.74	18.21			
4 Groups	1 1 1 1	-2252.54	-2245.08	-2218.05	0.805	21.15	37.18	29.90	11.78		
5 Groups	1 1 1 1 1	-2233.15	-2223.83	-2190.04	0.764	18.18	30.05	30.37	14.57	6.83	
6 Groups**	1 1 1 1 1 2	-2211.36	-2199.56	-2156.75	0.776	4.80	20.02	32.46	27.13	10.98	4.60
FEV1z											
1 Group	1	-3294.29	-3292.42	-3285.67		100.00					
2 Groups	1 1	-2802.10	-2798.37	-2784.86	0.780	54.27	45.73				
3 Groups	1 1 2	-2503.34	-2497.13	-2474.60	0.857	27.19	52.16	20.65			
4 Groups	1 1 2 2	-2424.02	-2415.32	-2383.78	0.805	20.33	35.54	30.40	13.74		
5 Groups	1 1 1 2 2	-2382.05	-2371.49	-2333.19	0.808	4.26	22.15	36.08	24.78	12.73	
6 Groups**	1 1 1 2 2 1	-2362.99	-2350.57	-2305.51	0.801	4.14	21.53	34.12	25.42	12.58	2.20
FEV1/FVCz											
1 Group	1	-3008.87	-3007.01	-3000.25		100.00					
2 Groups	1 2	-2546.03	-2541.68	-2525.91	0.787	36.48	63.52				
3 Groups	1 2 2	-2298.09	-2291.26	-2266.47	0.836	15.52	54.32	30.16			
4 Groups	1 1 2 2	-2205.57	-2196.87	-2165.33	0.805	9.72	27.63	43.50	19.16		
5 Groups	1 1 2 1 2	-2174.71	-2164.14	-2125.84	0.752	7.71	19.03	35.08	26.75	11.44	
6 Groups**	1 1 1 2 1 2	-2165.92	-2153.49	-2108.44	0.748	4.18	9.61	23.00	34.44	20.79	7.98

* Lowest BIC

** Predicted probability of group membership below 5%

Table S3. Model fit indices of 4 and 5 class unconditional GBMTM models of Spirometry parameter z-scores.

GBMTM was performed for both 4 and 5 trajectory groups using the polynomials suggested from individual GBTM; purely linear models; and models including zero order trajectories when linear trajectory analysis showed no change over time. The results of this analysis are displayed in the Table 3. All models again performed well above the minimum thresholds in tests of adequacy. A 5-group model (1 1 1 1 1 / 1 1 1 1 1 / 1 1 1 1 1) was found to have the best fit and to be the most plausible in terms of representing patterns of lung function.

			BIC (N=6954)	AIC	Entropy	Predicted probability of group membership				
						Groups				
		FVCz FEV1z FEV1/FVCz				1.000	2.000	3.000	4.000	5.00
4 trajectories										
	Purely quadratic	2 2 2 2 2 2 2 2 2 2 2 2	-7408.930	-7265.140	0.878	20.122	31.624	26.995	21.260	
	Polynomials suggested by GBTM	1 1 1 1 1 1 1 2 2 2 1 1	-7374.190	-7335.560	0.878	20.132	31.783	26.867	21.218	
	As above, replacing NS linear functions with zero order	1 0 0 0 0 0 0 2 2 2 1 0	-7351.330	-7258.890	0.878	20.073	32.024	26.639	21.264	
	Purely Linear	1 1 1 1 1 1 1 1 1 1 1 1	-7369.400	-7266.700	0.878	20.047	31.642	27.123	21.188	
	As above, replacing NS linear functions with zero order	1 0 0 0 0 0 0 1 1 1 1 0	-7342.290	-7263.550	0.878	20.001	31.912	26.854	21.233	
5 trajectories										
	Purely quadratic	2 2 2 2 2 2 2 2 2 2 2 2 2 2 2	-7140.750	-6962.730	0.884	18.924	10.332	30.166	22.638	17.940
	Polynomials suggested by GBTM	1 1 1 1 1 1 1 1 1 2 1 1 1 1 2	-7102.530	-6930.010	0.885	14.982	26.683	27.438	18.593	12.304
	As above, replacing NS linear functions with zero order	1 1 0 0 0 0 0 1 0 2 1 1 1 0 2	-7076.400	-6966.840	0.878	14.709	26.087	26.290	19.368	13.546
	Purely linear*	1 1 1 1 1 1 1 1 1 1 1 1 1 1 1	-7085.160	-6958.490	0.884	10.205	18.939	30.360	22.461	18.034
	As above, replacing NS linear functions with zero order	0 0 0 0 0 0 0 1 1 0 0 0 1 1 0	-7040.430	-6951.420	0.886	10.092	18.920	30.864	22.121	18.003

Table S4. Comparison of the main baseline characteristics for those included and excluded in the RFMS-SAMFS cohort

	1 wave only (n=307)	2 or more waves (n=669)
Characteristics at Baseline		
Male (%)	303 (98.7)	656 (98.1)
Age (years)	41.5 (10.4)	41.7 (8.6)
Height (m)	180.7 (6.0)	180.5 (10.5)
Years of Service	9.2 (11.2)	13.4 (6.6)
Body Mass Index (kg/m^2)		
< 25	68 (22.1)	153 (22.9)
25 - 30	183 (59.6)	406 (60.7)
> 30	49 (16.0)	110 (16.4)
Not reported	7 (2.3)	0 (0.0)
Smoking Status		
Non-smoker	156 (50.8)	386 (57.7)
Ex-smoker	36 (11.7)	117 (17.5)
Current smoker	23 (7.5)	46 (6.8)
Not reported	92 (29.9)	120 (17.9) *
Years of Service (years)		
< 1, n (%)	33 (10.7)	90 (13.5)
1 - 3, n (%)	32 (10.4)	80 (12.0)
3 - 6, n (%)	26 (8.5)	82 (12.3)
> 6, n (%)	133 (43.3)	410 (63.1)
Not reported	83 (27.0)	7 (1.0) *
Respiratory Protection Use - Fire Task		
Low Use	34 (11.1)	166 (24.8)
Medium Use	37 (12.1)	235 (35.1)
High Use	40 (13.0)	213 (31.8)
Not reported	196 (63.8)	55 (8.2) *
Respiratory Status		
Asthma (diagnosis / symptoms)	4 (1.3)	10 (1.5)
Chronic bronchitis/emphysema (diagnosis / symptoms)	21 (6.8)	62 (9.3)
No reported diagnosis / symptoms	282 (91.9)	597 (89.2)
Spirometry	n=299	n=669
FEV_1 z	0.24 (0.95)	0.44 (0.97) *
FVC z	0.79 (0.90)	0.89 (0.90)
FEV1/FVC z	-0.82 (0.88)	-0.70 (0.88)

Data are n (%), n/N (%), or mean (SD). Denominators are shown where data are missing. * Significant difference p<0.05.

Table S5. Indices of goodness of fit and model adequacy for the five trajectories of the selected GBMTM of FVCz, FEV1z and FEV1/FVCz (1 1 1 1 1 / 1 1 1 1 1 / 1 1 1 1 1)

Trajectory Group	Average Posterior Probability of Assignment (APPA)	Standard Deviation of Group Membership Probabilities (SD-GMP)	Odds of Correct Classification (OCC)	Estimated Group Probability (%)	Proportion assigned to group according to the maximal Posterior Probability Assignment rule (%)
1 - Stable Low Lung Function	0.94	0.12	147.1	10.3	10.3
2 - Stable Average Lung Function	0.95	0.11	81.2	18.7	18.1
3 - Declining Average Lung Function	0.91	0.14	23.5	30.5	31.1
4 - Declining High Lung Function	0.92	0.14	38.4	22.3	22.0
5 - Stable Very High Lung Function	0.96	0.10	103.9	18.2	18.5

Table S6. Descriptions of Group Trajectory Labels

Label	Range of FVC, FEV1 and FEV1/FVC z-scores
Very Low	< -1.64
Low	-0.9 to -1.64
Average	0.9 to -0.9
High	0.9 to 1.64
Very High	>1.64

Appendix S3 - Sensitivity Analysis

Further investigation of the Missing at Random assumption was performed. Baseline characteristics data included in the Group Based Multi-trajectory analysis was stratified according to number of waves participated in. Chi-squared and ANOVA were used to ascertain between group differences and their level of significance.

Table S7 Comparison of Baseline Characteristics for those Included by Number of Waves in the RFMS-SAMFS Cohort

	2 waves (n=193)	3 waves (n=167)	4 waves (n=154)	5 waves (n=114)	6 waves (n=41)	P value
Characteristics at Baseline						
Male (%)	190 (98.4)	165 (98.8)	150 (97.4)	111 (97.4)	40 (97.6)	0.914
Age (years)	42.9 (9.8)	40.4 (8.7)	41.9 (7.9)	41.0 (7.6)	42.2 (7.5)	0.264
Height (m)	180.2 (6.3)	181.3 (7.0)	179.9 (6.9	18.8 (6.1)	179.7 (6.2)	0.504
Body Mass Index (kg/m2)						0.04*
< 25	34 (17.6)	35 (21.0)	33 (21.4)	37 (32.5)	14 (34.1)	
25 - 30	118 (61.1)	107 (64.1)	94 (61.0)	64 (56.1)	23 (56.1)	
> 30	41 (21.2)	25 (15)	27 (17.5)	13 (11.4)	4 (9.8)	
Not reported	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)	
Smoking Status						0.02*
Non-smoker	115 (29.6)	93 (55.7)	86 (55.8)	64 (56.1)	28 (68.2)	
Ex-smoker	30 (15.5)	29 (17.4)	23 (14.9)	30 (26.3)	5 (12.2)	
Current smoker	15 (7.8)	9 (5.4)	8 (5.2)	8 (7)	6 (14.6)	
Not reported	33 (17.1)	36 (21.6)	37 (24%)	12 (10.5)	2 (4.9)	
Years of Service (years)						<0.001*
< 1, n (%)	23 (11.9)	21 (12.6)	28 (18.2)	14 (12.3)	4 (9.8)	
1 - 3, n (%)	17 (8.8)	27 (16.2)	20 (13)	10 (8.8)	6 (14.6)	
3 - 6, n (%)	30 (15.5)	24 (14.4)	14 (9.1)	9 (7.9)	5 (12.2)	
> 6, n (%)	117 (60.6)	94 (56.3)	92 (59.7)	81 (71.1)	26 (63.4)	
Not reported	6 (3.1)	1 (0.6)	0 (0)	0 (0)	0 (0)	
Respiratory Protection Use - Fire Task						0.002*
Low Use	52 (26.9)	32 (19.2)	39 (25.3)	31 (27.2)	12 (29.3)	
Medium Use	63 (32.6)	62 (37.1)	49 (31.8)	44 (38.6)	17 (41.5)	
High Use	49 (25.4)	61 (36.5)	62 (40.3)	32 (28.1)	9 (22.0)	
Not reported	29 (15)	12 (7.2)	4 (2.6)	7 (6.1)	3 (7.3)	
Respiratory Status						0.14
Asthma (diagnosis / symptoms)	0 (0)	4 (2.4)	3 (1.9)	3 (2.6)	0 (0)	
Chronic bronchitis/emphysema (diagnosis / symptoms)	18 (9.3)	13 (7.8)	14 (9.1)	14 (12.3)	3 (7.8)	
No reported diagnosis / symptoms	175 (90.7)	150 (89.8)	137 (89)	97 (85.1)	38 (92.7)	
Lung Function						
FEV1 z	0.36 (0.99)	0.32 (0.96)	0.57 (0.96)	0.42 (0.95)	0.90 (0.87)	<0.001*
FVC z	0.80 (0.99)	0.79 (0.85)	0.93 (0.90)	1.06 (0.84)	1.17 (0.69)	0.1
FEV1/FVC z	-0.69 (0.80)	-0.75 (0.83)	-0.56 (0.92)	-0.93 (0.98)	-0.74 (0.88)	0.02*

Data are n (%) or mean (SD). Denominators are shown where data are missing. * Significant difference $p < 0.05$.

GBMTM was performed incorporating those exposure variables demonstrating significance as co-variates. On addition of BMI, Smoking Status and Respiratory Protection Use the model outcome was unchanged. The participants were once again attributed to trajectory groups based on Posterior Probability of Assignment from the model with covariates. The group assignments were compared with the original model and showed almost perfect agreement (99.1%).

Table S8 Comparison of Trajectory Group Membership between Original Model and Model including Covariates

	Trajectory Group Membership (incl covariates)					
Trajectory Group Membership (original analysis)	1	2	3	4	5	Total
1	69	0	0	0	0	69
2	0	118	3	0	0	121
3	0	1	207	0	0	208
4	0	0	1	146	0	147
5	0	0	1	0	123	124
Total	69	119	212	146	123	669

REFERENCES:

1. Andruff H, Carraro N, Thompson A, Gaudreau P, Louvet B. Latent Class Growth Modelling: A Tutorial. Tutor Quant Methods Psychol. 2009;5(1):11–24.

2. Klijn SL, Weijenberg MP, Lemmens P, Van Den Brandt PA, Lima Passos V. Introducing the fit-criteria assessment plot-A visualisation tool to assist class enumeration in group-based trajectory modelling. Stat Methods Med Res. 2017;26(5):2424–36.

3. Nagin D. Group-Based Modeling of Development. Group-Based Modeling of Development. Harvard University Press; 2005.

Chapter 3 Urban Firefighter Experiences of and Attitudes towards Lung Function Surveillance

The third chapter is presented in manuscript form. It provides the results of a qualitative descriptive study investigating the experiences and perceived value of lung function surveillance in firefighters who participated in the RFMS-SAMFS study. This manuscript is currently under review by the peer reviewed journal, *Annals of Work Health and Exposures*. It is formatted to conform with this journal's guidelines, excepting references, that are formatted to the Vancouver style to maintain consistency throughout this thesis. A signed Statement of Authorship for this manuscript can be found in Appendix 3.1.

Publication under review:

Pendergrast, C, Boyle, T, Crockett, AJ, Eston R, Johnston KN. Perceptions of Lung Function Surveillance in Urban Firefighters submitted to *Annals of Work Health and Exposures*.

3.1 Abstract

Background and Objectives:

Workplace health and safety (WHS) is an important responsibility falling on both employers and employees and is most effective when the perspectives of all stakeholders are considered. This study aimed to explore the facilitators and barriers to a voluntary workplace lung function surveillance program from the perspective of urban firefighters and describe their perceptions of its value.

Methods:

Using a qualitative, descriptive methodology, firefighters who had participated in a longitudinal lung function surveillance study were invited to participate in semi-structured interviews. Purposeful, maximum variation sampling was used to achieve diversity in those firefighters invited to participate. We used inductive content analysis to identify themes.

Results:

Interviews with 15 firefighters identified three main themes: (1) practical experience of surveillance (administration, communication, workplace culture change, convenience, acceptability and appeal); (2) value of surveillance (lung health efficacy and control, social support, workplace management support/motivations, contribution to global firefighter health) and (3) contribution of surveillance to health (occupational risk, relevance in the context of total health, workability and fitness and future value).

Conclusion:

Practical and psychosocial facilitators and barriers to providing lung function surveillance in the fire service were identified. In addition to the personal benefits of detecting adverse lung health and allowing for medical intervention, factors known to positively influence firefighter workplace wellbeing, such as providing peace of mind, feedback on good work practices, motivation to utilise control measures, management commitment to health, and providing data to assist with global knowledge were valued aspects of longitudinal lung function surveillance.

Keywords:
firefighter, occupational exposure, spirometry, longitudinal studies, group-based multi-trajectory modelling

3.2 Introduction

Firefighting is a hazardous profession that places unique and extreme demands on its workforce. Risks to health and wellbeing are multifaceted, spanning physical (exertion, alarm response), environmental (heat, noxious fumes and fibres), and psychological domains (distress, injury and risk of fatality)(1–7). These workplace demands have the potential to negatively affect firefighter health and wellbeing.

Workplace health and safety (WHS) policy and programs are a long-standing mechanism to monitor and reduce hazards in the workplace(8). Health surveillance is a component of such programs and is a form of secondary prevention used to detect adverse health effects resulting from workplace exposures as early as possible. Detection of such effects allows preventive measures to be instituted. Findings from health surveillance may also indicate the absence of a significant hazard, the adequacy of control measures, individuals at increased risk, provide baseline medical data, benchmarks for preventive action and opportunities to provide health education(9). Another function is to quantify the incidence and prevalence of work-related diseases.

Workplace health and safety is the responsibility of both employers, who have a duty of care, and employees, who are required to take reasonable care of their health and safety in the workplace(10). Health in the workplace is impacted by personal health practices and resources, environmental and organisational factors (physical and psychosocial), and their interactions(11). Programs for WHS are most successful when there is consultation and engagement between employers and employees on the design, implementation and amendment of workplace health and safety policy and practice, resulting in greater awareness, commitment and understanding of workplace safety priorities and goals(10).

An essential part of effective engagement is understanding employee perspectives of workplace surveillance programs(12,13). Whilst quantitative research into the lung health of firefighters has been described(14–16), the views of firefighters participating in lung health surveillance have not been ascertained.

This study explored the experiences and attitudes of South Australian Metropolitan Fire Service firefighters who participated in a longitudinal respiratory function surveillance study. Specifically, we explored their perceptions of the value, benefits of, and barriers to participating in a lung health surveillance program.

3.3 Methods

Study Context and Design

This analysis is a part of the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study that collected occupational, health, lifestyle, and spirometry data in six waves between 2007 and 2019(14,15,17–19). It used a longitudinal, open cohort design to allow firefighters to participate in one, some or all waves of lung health surveillance. The study was a collaboration between SAMFS leadership and South Australian Universities under the supervision of Professor AJ Crockett (AJC).

After completing the quantitative data collection, we aimed to understand the participants' views on the value, benefits of, and barriers to their involvement in surveillance using a qualitative descriptive methodology(20). As a survey would not allow the in-depth understanding we wished to obtain, and focus groups are logistically problematic in the fire service due to the reactive nature of firefighter tasks, individual face-to-face semi-structured interviews were deemed the most appropriate data collection method.

The Consolidated Criteria for Reporting Qualitative research framework (COREQ) was used to guide our study design and reporting(21).

Recruitment and Sampling

The RFMS-SAMFS industry advisor (PF) distributed an email to all current SAMFS metropolitan and regional staff, inviting those who had previously contributed to the RFMS-SAMFS study to

express interest in participating in the study. Interested firefighters were asked to respond via a survey link within the email that forwarded their contact details to the lead investigator (LimeSurvey GmbH, 2006-2021). Those who responded were matched with their demographic, occupational and health data from their first wave of participation in the longitudinal study. Purposeful, maximum variation sampling was then used to sequentially invite firefighters for an interview to achieve diversity in the characteristics of age, years of service, respiratory protection use, number of waves participated in, self-reported respiratory disease, and lung function trajectory group classification(15). Invited firefighters were provided with a detailed study information sheet and the opportunity to self-select an interview time via email (Doodle Poll, Doodle AG, Switzerland). On selecting an interview time, online informed consent was collected before the interview (LimeSurvey GmbH, 2006-2021), and verbal consent was confirmed at the time of the interview after the participant had the opportunity to ask questions of the lead investigator.

A target sample size of 10-15 participants was planned. This study size was considered to have information power(22) to study the specific, well-defined phenomenon of interest and to gain perspectives across the spectrum of the longitudinal study population by including participants with targeted combinations of demographic, health and occupational characteristics.

Data Collection

Online semi-structured face-to-face interviews were conducted using an interview guide developed by the lead investigator (research student - CP) and research supervisor (KJ), who has prior experience in qualitative descriptive research. Interview questions were also reviewed by the wider research team and the SAMFS industry advisor (PF).

Interviews were conducted using the Zoom video conferencing platform by CP, a female clinical respiratory physiologist with more than 20 years of experience interacting with people in a healthcare setting. The interviewer had not been involved with lung function or questionnaire data collection during the RFMS-SAMFS study. Pilot interviews were conducted with KJ before study interviews commenced to allow for procedural and technical familiarisation and feedback.

At the commencement of the interview, study participants were informed that the meeting was being recorded. They were then provided with a standardised verbal overview of the study information, given an opportunity to ask questions, and asked to confirm they were happy to continue with the interview, understanding that they could withdraw from the interview or study at any time.

Data Analysis

Audio-visual recordings of the interviews were automatically transcribed by Zoom software (Zoom Video Communications Inc., 2016). Once the audio-visual and text transcript files were transferred to a secure local file location, those in Zoom cloud storage were deleted. The automatic transcriptions were corrected for accuracy against the audio-visual interview recording. Each transcript was emailed to the participant for validation.

Inductive content analysis was undertaken using the steps described by Erlingsson and Brysiewicz(11). In brief, transcriptions were read to develop familiarity with the content. They were then re-read, and quotes relevant to the study's aims were extracted and entered into an Excel spreadsheet. Each quote was condensed into a core meaning unit. Codes were formulated to summarise the meaning units, bringing quotes with similar meanings together. The first three interviews were independently coded by CP and KJ, after which discussion of the codes occurred until a consensus was reached that the codes were a good representation of the meaning units. Readjustments to codes were made as necessary by consensus, and were grouped into categories and finally brought together to form overarching themes.

3.4 Results

Participant Characteristics

An expression of interest email was sent to approximately 1200 SAMFS staff, of which about 1000 were operational firefighters, from which 104 expressions of interest were received. Of these, 17 firefighters were ineligible due to not previously participating in the RFMS-SAMFS study. Eighty-seven eligible firefighters were matched with their demographic, occupational and health data from their first wave of participation in the longitudinal study. Sequential invitation to participate was then based on creating a cohort with maximum variation in the categories of gender, age,

years of service, number of participations, respiratory protection use, respiratory disease and trajectory group membership (Table 1).

Table 1 Participant Characteristics

Participant ID	Location/ Gender	Current Role	Total number of waves participated	At first participation					GBMTM Group Membership (Pendergrast *et al.*, 2022)
				Age Category (years)	Years of Service Category	Respiratory Protection* (Pendergrast *et al.*, 2022)	Spirometry Pattern (Stanojevic *et al.*, 2021)	Respiratory Disease* (Pendergrast *et al.*, 2022)	
1	Metro/ Male	Commander (Day Work)	1	50 - 60	20 - 30	High	Abnormal	Asthma	na
2	Metro/ Male	Station Officer (Shift)	2	40 - 49	20 - 30	Low	Abnormal	Nil	Low stable lung function
3	Regional/ Male	Station Officer (Shift)	3	30 - 39	0 - 9	High	Normal	COPD	Average stable lung function
4	Metro/ Male	Firefighter	6	20 - 29	0 - 9	High	Normal	Nil	Average declining lung function
5	Metro/ Male	Station Officer (Shift)	6	40 - 49	20 - 30	Low	Normal	Nil	Very high stable lung function
6	Metro/ Male	Commander (Day Work)	3	30 - 39	10 - 19	Medium	Normal	Nil	Average declining lung function
7	Metro/ Male	Not reported	4	30 - 39	0 - 9	Medium	Normal	Nil	High declining lung function
8	Metro/ Male	Commander (Shift)	5	50 - 60	20 - 30	Low	Normal	Nil	Average declining lung function
9	Metro/ Male	Firefighter	5	40 - 49	10 - 19	High	Normal	COPD	Average declining lung function
10	Metro/ Male	Firefighter	6	40 - 49	10 - 19	Medium	Normal	Nil	Very high stable lung function
11	Metro/ Male	Firefighter	2	30 - 39	0 - 9	High	Normal	Nil	na
12	Metro/ Male	Firefighter	2	50 - 60	0 - 9	Medium	Normal	Nil	Very high stable lung function
13	Metro/ Male	Station Officer (Shift)	3	30 - 39	10 - 19	Medium	Normal	Nil	na
14	Metro/ Male	Station Officer (Shift)	2	40 - 49	20 - 30	Low	Normal	Nil	Average stable lung function
15	Metro/ Male	Not reported	5	30 - 39	0 - 9	High	Normal	Nil	Very high stable lung function

COPD, chronic obstructive pulmonary disease; GBMTM: Group Based Multi-Trajectory Modelling; [a] Self-reported data.

Fifteen interviews were conducted with durations of 16 - 42 minutes. All participants were male, and most self-reported no respiratory disease at the time of joining the study (12/15). The cohort included participants across a range of leadership categories, age groups, and potential markers

of exposure (self-reported degree of respiratory protection use and years of service). No participants requested changes to their transcript content.

Content Analysis

Three main themes (Figure 1) were identified: 1) Practical experience of surveillance, 2) Perceived value of surveillance, and 3) Contribution of surveillance to health. The analysis demonstrated that interactions existed between individual, organisational and whole-of-profession issues, encompassing benefits, barriers and values of each. Each theme and its corresponding categories are described, accompanied by exemplar quotes.

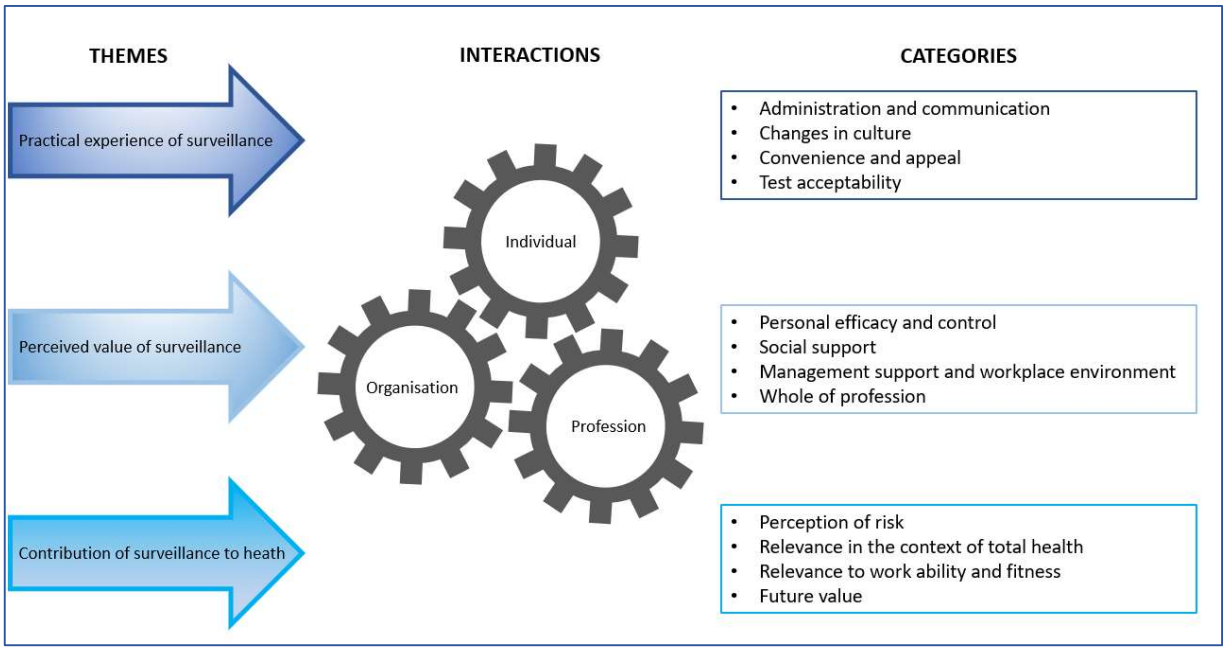


Figure 1 Identified themes, interactions and categories regarding the value, benefits of, and barriers to participating in a lung health surveillance program

Theme one: Practical Experience of Surveillance

Administration and communication

Provision of portable lung function testing to fire service sites whilst the crew was removed from duty to participate (i.e. covered by another crew) worked well. Firefighters reported that the people conducting the test were professional and friendly, putting them at ease, explaining the test well, and providing feedback on their test outcome. Motivation was high, and most

people were happy to participate. Overall, interviewees expressed gratitude toward those who implemented the program for being able to participate in the lung function surveillance study.

'The people conducting it were always positive, polite and friendly, always had time to explain things to you, you know, the graphs and the lines and the readings …. so no, for me there was no negative about it at all' (ID10)

Participants felt that communication about the study outcomes could have been improved.

'Maybe a bit more communication about outcomes or findings, but I guess that information goes to the management, right' (ID14)

Changes in culture

The firefighters reported that they had seen changes in practice from a time when using respiratory protection in the form of breathing apparatus (BA) was not the norm to today, where wearing breathing apparatus is mandatory and the accepted practice.

'In the olden days, you didn't use to wear your BA sets for jobs; you just walked into a house fire with a bloody cloth on your face or at car fires, you didn't wear it because it was seen as a bit of a hassle to put them on and wear them and now the practices, we adopt is very much the opposite of that' (ID4)

This was also evident in a generational difference in acceptance of lung function surveillance. Firefighters reported that the older demographic may have been distrustful of the motivation behind lung function surveillance and feared that it may have threatened their job security. The younger generation, particularly those who began their firefighter career whilst the surveillance program was collecting data, accepted the surveillance as standard practice.

'I was fairly new into the service, so it's (lung function) something that I think everyone from my group was doing' (ID11)

An alternate view expressed was that younger firefighters may not feel the need to monitor their lung function because they always use breathing apparatus.

Convenience and appeal

Participation in the surveillance study was perceived to be easy, and the SAMFS and University provided a setup that made it appealing for firefighters. It was often stated that it was 'done on work time' and that another firefighting team covered their duties.

'There was nothing really in my way holding me up from doing it, which again, made it appealing to do because it was done on work time, and we just sort of had to find where it was being done and go there. We were allocated time to do it, so it was good' (ID10)

Despite being covered, there were challenges to overcome; they could still get called away from lung function surveillance. Another challenge to overcome, particularly in the surveillance program's early years, was difficulty communicating with firefighters when they were not on-site at the fire station - e.g., on annual or sick leave. Many were unaware of the number of opportunities for lung function testing throughout the surveillance study.

'In hindsight, I'm thinking I can't believe I didn't sort of go to many as I could, if that's the case or whether I just wasn't aware of them' (ID2)

Participation was much more difficult for those located in regional centres. Firefighters in regional locations would not commute to the metropolitan testing sites and so only attended surveillance when the service was provided in their area.

'Probably thought, well, I'm not driving to Adelaide just to do a lung function test because it's a four-hour round trip for me' (ID3)

The challenges encountered with lung function surveillance were not thought to deter metropolitan firefighters from participating.

Test acceptability

Firefighters were unsure what to expect on their first surveillance test occasion. Some felt that the spirometry test was unusual and presented some minor difficulties and discomforts but not to such extremes as discouraging participation.

'But it's a confronting exercise, actually, doing it, that breathe and blowing out, you think you got nothing left, but you got to keep blowing' (ID2)

Some felt a little performance anxiety, and others expressed enjoyment and anticipation towards learning their results. Other participants felt that there was nothing stressful about the testing and that it was just a part of being a firefighter.

'Was it 13 - 14 years it's been going on, so, for me, it was pretty much just a part of being in the job, … it was fine, I think it's good' (ID15)

Theme two: The Perceived Value of Surveillance

Personal efficacy and control

Many firefighters felt it was important to monitor their health and welfare, particularly in a role that required good health and fitness. Participating in lung function surveillance provided them with a benchmark they could use if problems developed in the future. It also allowed them to monitor if their lung function changed over time.

'I like the idea of knowing how my lungs are going, the longer I'm in the job, just to see if there's any deterioration' (ID10)

Most were aware of how their lung function tracked and understood the expected decline in absolute lung function with age. Some felt that their lung function results reflected their fitness level and were motivated to improve their fitness based on a lower result. Participating in the lung function surveillance program provided firefighters with a method of monitoring their health, which promoted peace of mind and confidence in some. In others, it provided validation of good work health and safety practices.

'That was really good, especially once you get a couple of them, you can compare them over the years, and it gives you a bit of peace of mind, so no, that was really good' (ID7)

'If I hadn't had it, I wouldn't have had that validation that I was doing things right and wearing air sets not just when there was a lot of smoke around, but even a mild amount of smoke' (ID5)

A few reported that the surveillance allowed them to follow up on poor results with a health professional.

'I probably might not have even been diagnosed with the problem that I've got if it hadn't been for this regime' (ID2)

In some firefighters, lung function surveillance did not change their safety attitudes and practices, whilst others suggested that it provided a focus/reminder to protect their lungs when on the job.

'Probably on a basic level, I'm just maybe more mindful of what I breathe in, when I breathe it in, how long I breathe it in and wearing masks and air sets probably more regularly and for longer periods, rather than taking them off too quickly, like I used to probably' (ID10)

There was the opinion expressed that some firefighters, particularly smokers, may not have wanted to participate as they did not wish to know if they had poor lung health.

Social support

Participation in the lung function surveillance program was widely accepted, and firefighters felt free to participate or not participate without associated stigma. According to the firefighters interviewed, personal choice was respected, and if you wanted to attend, peers and the organisation made every effort to enable participation.

'There was no right or wrong; it's just if you want to do it, this is for you; if you don't want to do it, then that's, you know, perfectly fine' (ID4)

Most discussions regarding lung function results appeared related to friendly competition between crew members. Some also discussed the testing with their family members.

'There were a number of my peers participating in it at about the same time, so it was more of a competitive thing, to see who has the largest lung capacity' (ID8)

Management support and workplace environment

The firefighters appreciated the voluntary nature of lung function surveillance, and responses suggested that personal choice to participate was respected at both the peer and management level.

'I think it's the way it's being done, not in a heavy-handed way, is really, really good for the service, you know it's not like you have to do this, but giving people opportunities' (ID11)

There was a feeling that providing the program indicated that the organisation was serious about firefighter health. Those who held supervisory responsibility described that it was important to take an interest in surveillance and to encourage protection from the occupational hazards associated with firefighting.

I think (it) show(s) that the organisation is serious about the health of its people' (ID7)

Interviewees provided positive feedback about management support to enable participation. Still, they suggested that some may not have taken part due to distrust of how the fire service would use the surveillance data and the motivations behind providing the program.

'So there generally is an underlying stigma of any sort of data collection in the service, with people being a little bit paranoid or skeptical of how that could be potentially used against people in the future' (ID7)

Whole of profession

Participation in the surveillance study was motivated not only by personal health interests but also by a whole of profession perspective. Individuals reflected that by participating, they were contributing information that would benefit the firefighter profession and may be influential in improving fire services and their ability to monitor occupational hazards. They were interested to see if the data indicated deterioration in lung function potentially attributed to firefighting or if current safe work practices were appropriate.

'So, we need evidence that what we're doing is not working or what we're doing is working. So, I think that if at the end of your study, everyone's lungs are as they should be for our age and our

fitness level and everything else, then the system's working, and we should carry on with what we're doing, but if we're getting worse, we need to rethink how we how we do respiratory protection' (ID12)

Theme 3: Contribution of Surveillance to Health

Perception of risk

Interviewees acknowledged the inherent hazards of their day-to-day role as a firefighter, citing risks to lung health, including inhalation of fumes, fibres and the by-products of combustion. Breathing apparatus were routinely used, but there was a perception that this could not eliminate all exposure.

'One of the big things is that we are often exposed to smoke, and while we do have breathing apparatus, it's not always possible or practical to have breathing apparatus on' (ID9)

'We've got exhaust fans in the engine room, but you know you can still sort of taste the diesel in the air at times' (ID3)

The majority of those interviewed felt there was an increased risk to their lung health the longer they worked in the fire service. This led to the belief that lung function surveillance was important.

'So much more to be worried about as far as toxic vapours and fumes from combustibles, and you know we do more in the hazardous materials and substances area now as well…. always a concern about what cumulative effects you've had over a long period of time....' (ID14)

An alternative perspective was that lung function surveillance is unimportant *'because we have the control measures for managing our lungs' (ID1).*

Relevance in the context of total health

Whilst lung health surveillance was perceived as having significant value, firefighters stated that other aspects of health and wellbeing were also important to monitor. Aspects of health that were of concern and potential targets for monitoring included mental health, cancer, and sleep disturbance. Given the judgement required to keep colleagues, the general public and property safe, drug and alcohol monitoring was also suggested.

'It would be hard to sort of put one higher than the other because to me, at all things being equal' (ID8)

'If there was some sort of testing for cancers, that would be a number one on my hit parade' (ID5)

Relevance to workability and fitness

General health and fitness were valuable to the firefighters we interviewed and were perceived as essential for safely undertaking firefighter duties. The lack of ongoing health and fitness assessment surprised many firefighters, who compared the requirement for evaluation to the armed forces and when playing amateur sports.

'There is no fitness assessment or health assessment that's ongoing. I believe they are two things that should happen. Both for the public but also for our own safety that each person who is doing the job as an active firefighter is able to do so safely and is able to carry out the functions that would allow them to rescue a colleague, should they become injured or trapped' (ID9)

Many expressed that such assessments should be undertaken but also acknowledged there were difficulties associated with using fitness assessment in the fire service. Problems included how the service accommodated the broad age range of firefighters, those with experience that work smarter rather than harder, and remediation of those who were found to have significantly reduced fitness or health problems that were incompatible with their fire service role.

'What I've also found with the older guys in the job is, it's like any job once you build up experience, like in the younger days you really need all the strength and fitness to get through the job, the older guys, who have the knowledge and experience they work smarter' (ID7)

Firefighters felt that the fire service was progressing in encouraging health and fitness by providing good fitness facilities and implementing a voluntary Wellness Program that provided health checks and highlighted health issues.

Future value

Firefighters who participated in the interviews valued the continuation of the lung function surveillance program.

'But I think it should be a regular thing and particularly for me in my situation as I'm on the older end of the things, I think it's more important as we get older' (ID12)

'The firefighters coming into the job today, they probably won't have the benefit of what I've had through my career' (ID8)

'From a personal viewpoint to I would like to continue to monitor my own lung function and see how I'm tracking' (ID9)

It was suggested that the surveillance program could continue in its current form as a research program. However, this is only valuable if the outcomes are made available, and action on those outcomes is taken if indicated.

'Well, it's all good to keep doing this research, but if you're giving findings and they're not doing anything with it, well, you know what's the point' (ID3)

An alternative recommendation was to incorporate voluntary spirometry testing into the Wellness Program provided by the SAMFS. Firefighters felt strongly that spirometry testing should be done at the beginning of their careers and had differing views on how often it should be repeated.

3.5 Discussion

Voluntary lung function surveillance provided by the RFMS-SAMFS study was widely accepted and had value for firefighters in domains further reaching than the study's original main research aim of investigating longitudinal lung function decline. We identified through this analysis both practical and psychosocial facilitators and barriers to participation. We highlighted the difficulties of implementation in an organisation that provides an emergency response with an unpredictable workload across a wide geographic area and identified ways the study had successfully navigated these.

Health surveillance must be applied appropriately within the workplace based on contemporary evidence and ethically balanced against unwelcome intrusion into personal health(8,24). The current evidence for the long-term decline in urban firefighter lung function is unclear(14–16),

and mandatory lung function surveillance, such as is required in the mineral mines and quarry industries(25), may not be appropriate. Despite the equivocal evidence of lung function decline in firefighters and improvements in control measures, most of the firefighters interviewed in this study and in the New Jersey Firefighter Health Survey(26) believe there were unavoidable, chronic, low-level exposures to harmful substances that led to an underlying concern for their health. SAMFS firefighters welcomed the opportunity to have a voluntary, high-quality lung function testing service available to them, but without individual results being available to their employer, which met with some expressed concern about potential risks to individuals' ongoing employment.

In addition to monitoring personal lung health, this study revealed that the lung function surveillance program provided some antecedent factors related to improving firefighter wellbeing(27,28). Lung function surveillance allowed for personal control by its voluntary nature and the ability to act on poor results. It reduced anxiety caused by concern for health and validated good personal practices. There was social support and interaction, be that by the friendly competition between peers or the acceptance of everyone's right to decide if they would participate. Fire service management was seen as facilitating the program, showing commitment to their employee's health and safety. Finally, participation in the surveillance program provided a sense of belonging to a team that would increase the body of evidence on firefighter lung health. Given the low prevalence of mental wellbeing and high prevalence of psychological distress in fire and rescue services(29), these unforeseen benefits need to be considered alongside the actual and perceived risk to lung health when determining the utility of lung health surveillance within a fire service workplace health and safety program.

Strengths and Limitations

This study included South Australian urban firefighters who participated in an observational longitudinal research project to monitor lung function. Whilst we sought to enroll a diverse range of participants, recruitment may have favoured those with a positive view of the surveillance. In contrast, those with a negative or indifferent view would have reduced motivation for

participation. Expressions of interest from regional and female study participants were also low, limiting the generalisability of study findings in these groups.

Despite this, our sampling strategy successfully created maximum variation in the chosen characteristics providing a rich information source.

Conclusion

Understanding the broader value of lung function surveillance and its barriers and facilitators to those participating in the program is important when considering future workplace health and safety policies. Participation in the lung function surveillance program provided in the RFMS-SAMFS study was well received by firefighters of differing seniority, age, and length of service. Firefighters related that lung function surveillance added value to the fire service workplace health and safety program by providing baseline health data, detecting adverse health and allowing for medical intervention, providing peace of mind and feedback on good work practices, motivation to utilise control measures and, finally, providing data to assist with global knowledge. Overall, the firefighters in this study valued their opportunity to participate in the RFMS-SAMFS study and expressed the wish for the ongoing provision of voluntary lung function testing in the future.

3.6 Declarations

Conflicts of Interest

The authors have no conflicts of interest to declare.

Research Funding

Catherine Pendergrast's research is funded by the University of South Australia Firefighter Lung Function Scholarship provided by the SAMFS and the Australian Government Research Training Program.

Ethics Approval

Approval was obtained from the Human Research Ethics Committee of University of South Australia (Project no. 0000032662). The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to Participate

Informed consent was obtained from all individual participants included in the study.

Data Availability

The data that support the findings of this study are held by the corresponding author. Availability of the study data is at the discretion of the SAMFS upon application.

Author Contributions

Catherine Pendergrast: Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Project administration (lead); Visualisation (lead); Writing – original draft (lead); Writing – review & editing (lead). Terry Boyle: Conceptualisation (equal); Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Supervision (lead); Writing – review & editing (supporting); Alan J Crockett: Conceptualisation (equal); Data curation (supporting); Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting); Writing – review & editing (supporting). Roger Eston: Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting). Kylie N Johnston: Conceptualisation (equal); Investigation (supporting); Project administration (supporting); Supervision (lead); Writing – review & editing (supporting).

3.7 References

1. Wagner SL, White N, Buys N, Carey MG, Corneil W, Fyfe T, et al. Systematic Review of Mental Health Symptoms in Firefighters Exposed to Routine Duty-Related Critical Incidents. Traumatology. 2021;27(3):285–302.
2. Nazari G, MacDermid J, Cramm H. Prevalence of musculoskeletal disorders among Canadian firefighters: A systematic review and meta-analysis. Journal of Military, Veteran and Family Health. 2020(6):83–97.
3. Hunt AP, Stewart IB, Billing DC. Indices of physiological strain for firefighters of the Australian Defence Forces. J Occup Environ Hyg. 2019;16(11):727–34.
4. Walker A, Argus C, Driller M, Rattray B. Repeat work bouts increase thermal strain for Australian firefighters working in the heat. Int J Occup Environ Health. 2015;21(4):285–93.
5. Cheung SS, Petersen SR, McLellan TM. Physiological strain and countermeasures with firefighting. Scand J Med Sci Sport. 2010;20(SUPPL. 3):103–16.
6. Paterson JL, Aisbett B, Kovac K, Ferguson SA. Informal management of health and safety risks associated with alarm response by Australian firefighters. Ergonomics. 2022;65(2):233–41.
7. Paterson JL, Aisbett B, Ferguson SA. Sound the alarm: Health and safety risks associated with alarm response for salaried and retained metropolitan firefighters. Saf Sci. 2016;82:174–81.
8. Gochfeld M. Medical surveillance and screening in the workplace: Complementary preventive strategies. Environ Res. 1992;59(1):67–80.
9. Koh D, Aw TC. Surveillance in occupational health [Internet]. Occupational and Environmental Medicine. 2003;60:705–10.
10. Safe Work Australia. Work health and safety consultation, cooperation and coordination - Code of Practice. 2020.

11. Shain M, Kramer DM. Health promotion in the workplace: Framing the concept; reviewing the evidence. Occup Environ Med. 2004;61(7):643–8.

12. Grawitch MJ, Ledford GE, Ballard DW, Barber LK. Leading the Healthy Workforce: the Integral Role of Employee Involvement. Consult Psychol J. 2009;61(2):122–35.

13. NIOSH. Essential Elements of Effective Workplace Programs and Policies for Improving Worker Health and Wellbeing. 2008.

14. Slattery F, Johnston K, Paquet C, Bennett H, Crockett A. The long-term rate of change in lung function in urban professional firefighters: A systematic review. BMC Pulm Med. 2018;18(1):1–20.

15. Pendergrast C, Boyle T, Crockett AJ, Eston R, Johnston KN. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. Respirology. 2022;27.

16. Mathias KC, Graham E, Stewart D, Smith DL. Decreased Pulmonary Function Over 5 Years in US Firefighters. J Occup Environ Med. 2020;62(10):816–9.

17. Schermer T, Malbon W, Newbury W, Holton C, Smith M, Morgan M, et al. Spirometry and impulse oscillometry (IOS) for detection of respiratory abnormalities in metropolitan firefighters. Respirology. 2010;15(6):975–85.

18. Schermer TR, Malbon W, Adams R, Morgan M, Smith M, Crockett AJ. Change in lung function over time in male metropolitan firefighters and general population controls: A 3-year follow-up study. J Occup Health. 2013;55(4):267–75.

19. Schermer TR, Malbon W, Morgan M, Smith M, Crockett AJ. Chronic respiratory conditions in a cohort of metropolitan fire-fighters: associations with occupational exposure and quality of life. Int Arch Occup Environ Health. 2014;87(8):919–28.

20. Bradshaw C, Atkinson S, Doody O. Employing a Qualitative Description Approach in Health Care Research. Glob Qual Nurs Res. 2017;4:1–8.

21. Tong A, Sainsbury P, Craig J. Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups. Int J Qual Heal Care. 2007;19(6):349–57.

22. Malterud K, Siersma VD, Guassora AD. Sample Size in Qualitative Interview Studies: Guided by Information Power. Qual Health Res. 2016;26(13):1753–60.

23. Stanojevic S, Kaminsky DA, Miller M, Thompson B, Aliverti A, Barjaktarevic I, et al. ERS/ATS technical standard on interpretive strategies for routine lung function tests. Eur Respir J. 2021;2101499.

24. Roossien CC, de Jong M, Bonvanie AM, Maeckelberghe ELM. Ethics in Design and Implementation of Technologies for Workplace Health Promotion: A Call for Discussion. Front Digit Heal. 2021;3(August):1–14.

25. Resources Safety & Health Queensland. QGL04 - Guideline for respiratory health surveillance of workers in Queensland mineral mines and quarries Mining and Quarrying Safety and Health Act 1999. 2021.

26. Maloney SR, Udasin IG, Black TM, Shah NN, Steinberg MB, Pratt ME, et al. Perceived Health Risks Among Firefighters; The New Jersey Firefighter Health Survey. J Occup Environ Med. 2021;63(4):317–21.

27. Danna K, Griffin RW. Health and well-being in the workplace: A review and synthesis of the literature. J Manage. 1999;25(3):357–84.

28. Kling HE, Maldonado L, St George SM, Brannan D, Murphy LA, Schaefer Solle N, et al. Firefighter Well-Being Defined and Operationalized at the Organizational and Worker Level. J Occup Environ Med. 2022;64(11):e736–43.

29. Kyron MJ, Rikkers W, Bartlett J, Renehan E, Hafekost K, Baigent M, et al. Mental health and wellbeing of Australian police and emergency services employees. Arch Environ Occup Heal. 2022;77(4):282–92.

Chapter 4 Discussion

The fourth chapter of the thesis reviews the aims of my program of research and how they were achieved. It integrates the research program findings within the context of fire service workplace health and safety. Finally, it describes some of the important strengths and limitations, and provides suggestions for future research directions.

The program of research in this thesis aimed to investigate the lung function trajectories of urban firefighters and explore their perceptions of being involved in a longitudinal lung function surveillance program.

These aims were achieved by:

- Using data from the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study and applying group-based multi-trajectory modelling to simultaneously analyse the spirometry parameters of FEV_1, FVC and FEV_1/FVC ratio z scores (**Chapter 2**);
- Using semi-structured interviews to obtain the perspectives of firefighters on the facilitators, barriers and value of lung function surveillance using a qualitative descriptive methodology (**Chapter 3**).

4.1 Main Findings

The RFMS-SAMFS cohort exhibited spirometry parameters that were higher overall than the population mean, consistent with earlier work on this cohort by Schermer et al.(1) and Slattery et al. (2). Longitudinal analysis of spirometry data using group-based multi-trajectory modelling (GBMTM) was able to identify five distinct trajectories for the combined variables of FEV_1z, FVCz and FEV_1/FVCz. There were three stable trajectories described as *Stable Low Lung Function,* with parameters of FEV_1z & FVCz above the lower limit of normal and an FEV_1/FVCz below the LLN (physiologically described as a dysanaptic pattern of lung function - Chapter 2), *Stable Average Lung Function* (all parameters close to the population mean) and *Stable Very High Lung Function* (with FEV_1z and FVCz of 2.0 ± 0.05 and 1.8 ± 0.04 respectively). There were two declining trajectories described as *Declining Average Lung Function* and *Declining High Lung Function*. Fifty per cent of the cohort were members of declining lung function trajectory groups. Despite the declining trajectory, these groups showed a normal physiological pattern of lung function (FEV_1z, FVCz and FEV_1/FVCz all greater than the LLN). Declining trajectories were related to non-occupational factors of BMI and a history of lung disease or symptoms.

Firefighters from our cohort felt that some respiratory exposure to hazardous chemicals was unavoidable during day-to-day operations, and this is consistent with evidence from previous

research(3–14). Descriptive qualitative analysis of semi-structured interviews revealed that most of our interviewed firefighters participated in the surveillance study to determine their baseline level of lung function, act on abnormality if present and then monitor changes over time. We were able to delineate facilitators and barriers to participation and also reveal broader outcomes of participation that provided antecedents to workplace wellbeing such as peace of mind, feedback on good work practices, motivation to utilise control measures and, finally, providing data to assist with global knowledge.

4.2 Implications of the Research Program Findings

Urban firefighters are charged with protecting the public and our communities, particularly in emergency response situations. To be able to perform this role effectively, they need to be fit and healthy from both a physical and psychological perspective. Workplace health and safety (WHS) programs and policies in urban firefighting support this need by managing workplace risks and providing an optimal workplace environment.

The interviewed firefighters in the qualitative study (Chapter 3) overwhelmingly expressed that respiratory exposure to chemical substances was unavoidable while undertaking their firefighting duties, despite modern hazard control measures in place within the fire service. This is in keeping with evidence from cross-sectional lung function studies(3,4), biomarker studies (5–11,15,16) and other qualitative studies(12–14). These exposures led to expressed concerns for their personal health and wellbeing.

Lung function surveillance is one tool that can be used to monitor respiratory exposure effects as part of a WHS program, but research to date has not definitively determined if firefighting is associated with an increased risk of chronic lung disease, as represented by excessive lung function decline. As with many health outcomes, it is unlikely that all firefighters will suffer from lung health decline due to their occupational role. It is possible that a combination of factors, including genetic pre-disposition, timing, volume and composition of exposure, and other health and lifestyle factors, will combine to create a subgroup of firefighters that will suffer declines in lung health. Identification of these at-risk subgroups is important but challenging. Apart from the large variation in possible exposure characteristics, methodology that uses group means to

describe a cohort with higher-than-average lung function result in those with poorer lung function being unidentifiable.

The first study in this research program (Chapter 2) addressed this issue by investigating an alternative statistical modelling technique to analyse the lung function data. GBMTM is analytical methodology that is well suited to mapping the developmental course of outcome measures (in this case spirometry parameters) in a heterogeneous population(17). It allows the classification of individuals into subgroups that share greater similarities in their trajectory than individuals from the alternate subgroups(18). It is then possible to investigate the characteristics of those individuals. GBMTM has not previously been used to analyse combined lung function parameters and results from our investigation support its use as a promising analytical method to delineate groups of firefighters who would at higher risk of poor outcomes.

The GBMTM analysis provided evidence of firefighter sub-groups with declining but higher than average trajectories. This combination of lung function, together with unavoidable, repeated exposures that cause acute lung health effects, suggests that all firefighters should have good quality pre-exposure lung function results, that are accessible to either themselves or their healthcare provider, as a necessary reference in case of future lung health issues. Further to this, periodic lung function testing would be astute to monitor change given that there is possibility of declining lung function trajectories from high baseline values.

Results from the qualitative analysis (Chapter 3) also supported the provision of periodic lung function testing, as part of a fire service WHS program. The lung function surveillance program was widely accepted, particularly in the voluntary capacity provided. Facilitators and barriers to providing lung function surveillance in an urban fire service were identified that will allow refinement of future surveillance programs in an unpredictable workplace.

Further to being able to monitor their personal lung health, the perceived value of the lung health surveillance program was less tangible but can be explained within the context of a “Health Promotion in the Workplace” framework(19). This framework describes how physical and psychological health is influenced by the interaction of an individual’s behaviours, genetics, and

the environment. A large proportion of the environment throughout adulthood is spent in the workplace. The workplace impact on health is influenced by management decisions on not only physical safety but workplace culture. This environment may then feedback on the ability of the individual to care for their personal well-being.

Our outcomes suggested that the lung function surveillance program addressed key factors that contribute to health promotion and wellbeing in the workplace including personal control, social support, interactivity, broad appeal, convenience, employee participation and management enablement(19). The RFMS-SAMFS lung function surveillance program provided value in the WHS program by its ability to monitor lung function, and additionally positively influencing factors known to benefit firefighter psychological health in the workplace.

This program of research provided novel outcomes that contributes to the evidence base for fire service WHS programs. Without clear evidence, it is difficult to implement change from both a policy perspective and a cultural perspective. Understanding the priorities and opinions of those working on the front line is required to ensure appropriate policy(20,21). This evidence, taken together with the opinions of firefighters regarding the perceived risk to lung health and the value ascribed to monitoring lung health, suggest that periodic voluntary lung function testing would provide wide ranging benefits to fire service WHS programs.

4.3 Strengths of the Research Program

A thorough overview of the strengths of each study are discussed in their respective chapters (Chapters 2.5 and 3.5). A major strength of this program of study was the utilisation of quality spirometry data from one of the longest running prospective firefighter cohort studies to date, according to the published literature (22,23). All spirometry tests were performed to a high standard by trained operators, to ATS/ERS recommendations(24), and were further overread for quality by an eminent respiratory physiologist (AJC). An open cohort recruitment strategy maximised participant numbers, allowing eligible participants the ability to join the study at any wave (new recruits, those who were reticent to take part initially) and did not preclude those who were on leave or unavailable during a wave from participating in further waves. Further to this, our study was the first to analyse firefighter data using z-sores and GBMTM which permitted

normalisation of participant demographic characteristics and allowed clustering of firefighters into groups with similar trajectories. This methodology also avoided error associated with assigning explanatory exposure variables *a priori*(25). The firefighter trajectory subgroup membership from the quantitative study was able to be incorporated into the qualitative study contributing to the provision of maximum variation.

High study participation was also a strength when recruiting for the qualitative interview study. Due to the large number of participants, we were successful in recruiting firefighters with a wide range of occupational, lifestyle and demographic characteristics allowing expression of a wide range of perspectives on lung function surveillance.

This relatively unique combination of complex quantitative analysis with a qualitative study to incorporate stakeholder perspectives provides a valuable contribution to the current body of knowledge of lung function surveillance in urban firefighters in Australia.

4.4 Limitations of the Research Program

A thorough overview of the limitations of each study are reported in their respective chapters (Chapters 2.5 and 3.5). The primary limitations of this program of research arise from potential selection bias and information bias within the RFMS-SAMFS study. Whilst listed as a strength above, the recruitment of our cohort reflects a convenience sample of those firefighters who were willing to participate in spirometry testing, questionnaires, and interviews. This limits the generalisability of our results. Several reasons for non-participation in the lung function surveillance were suggested by our qualitative analysis. They included lack of awareness of wave occurrence, unavailability due to leave or other commitments, geographical location, distrust of data use or not wanting to know possibly poor results. A strong healthy worker effect may also have contributed to selection bias in the RFMS-SAMFS study(26). The selection criteria required for employment within the SAMFS requires good health and fitness ('healthy hired effect') while the requirement for firefighters to continue to pass mandatory competencies suggests that most who remain in the role of firefighter are also fit and healthy ('healthy worker survivor effect')(27). Those firefighters who discontinued their employment with the SAMFS, no longer participated in the study, despite the opportunity to do so, and it is possible that a number of those leaving the

fire service did so due to being unable to meet the physical and psychological requirements of their roles.

Finally, whilst the SAMFS cohort is large, the number of female participants was low, and we were unable to recruit any female participants into our qualitative study. Females may have been discouraged from participating as, due to their low numbers, they may have felt that they could be identified.

Exposure data collected in RFMS-SAMFS cohort was self-reported. Self-reported data may have been affected by recall error or concern for confidentiality of data that may affect continued employment. Objective and accurate cumulative exposure data is difficult to collect in firefighters due to the wide range of chemicals encountered and the complexity of quantifying the exposure strength and exposure time. Surrogate data for occupational exposure such as 'years of service'(28) and 'respiratory protection use'(23) are crude and have been shown to be a poor substitute for more direct exposure measurements. Despite relatively low individual chemical concentrations during exposure, the combination of hazardous chemicals may also elevate risk(10).

4.5 Future Opportunities

Future research should focus on reducing the bias seen in this and previous studies. Quality assurance of collected lung function data with pre-exposure baseline measurement is imperative. In combination with the use of contemporary longitudinal modelling methods such as GBMTM, valid, reliable and practical measures of exposure will need to be further developed and prospectively implemented to answer the question of if urban firefighting predisposes to excessive lung function decline, representing a disease process. Database technology that allows convenient cumulative tracking of the role, time on site and fire/emergency type will improve quantification of exposure over time(29).

4.6 Conclusion

This research program used quantitative and qualitative methods to investigate a 12-year biennial lung function surveillance program in South Australian Metropolitan Firefighters.

Whilst overall lung function in firefighters is within the expected range, groups of firefighters demonstrated a declining lung function trajectory. A single measurement taken when exposure or symptoms arise may not reveal a deficit or abnormality. There is a perceived risk of chronic exposure and value in voluntary lung function monitoring expressed by firefighters. Voluntary lung function surveillance adds value to work health and safety programs in the fire service.

4.7 References

1. Schermer T, Malbon T, Morgan M, Briggs N, Holton C, Appleton S, et al. Lung function and health status in metropolitan fire-fighters compared to general population controls. International Archives of Occupational and Environmental Health. 2010;83(7):715–23.

2. Slattery F, Schermer T, Esterman A, Johnston K, Crockett A. The Global Lung Function Initiative 2012 Equations Are as Well-Suited as Local Population Derived Equations to a Sample of Healthy Professional Firefighters. Canadian Respiratory Journal. 2017;5.

3. Burgess JL, Nanson CJ, Bolstad-Johnson DM, Gerkin R, Hysong TA, Lantz RC, et al. Adverse respiratory effects following overhaul in firefighters. J Occup Environ Med. 2001;43(5):467–73.

4. Miedinger D, Chhajed PN, Stolz D, Gysin C, Wanzenried AB, Schindler C, et al. Respiratory symptoms, atopy and bronchial hyperreactivity in professional firefighters. European Respiratory Journal [Internet]. 2007;30(3):538–44. Available from: www.erj.ersjournals.com/misc/

5. Burgess JL, Hoppe-Jones C, Griffin SC, Zhou JJ, Gulotta JJ, Wallentine DD, et al. Evaluation of Interventions to Reduce Firefighter Exposures. Journal of Occupational and Environmental Medicine. 2020;62(4):279–88.

6. Sparer EH, Prendergast DP, Apell JN, Bartzak MR, Wagner GR, Adamkiewicz G, et al. Assessment of Ambient Exposures Firefighters Encounter while at the Fire Station: An Exploratory Study. Journal of Occupational and Environmental Medicine. 2017;59(10):1017–23.

7. Gianniou N, Giannakopoulou C, Dima E, Kardara M, Katsaounou P, Tsakatikas A, et al. Acute effects of smoke exposure on airway and systemic inflammation in forest firefighters. Journal of Asthma and Allergy. 2018;11:81–8.

8. Greven FE, Krop EJ, Spithoven JJ, Burger N, Rooyackers JM, Kerstjens HA, et al. Acute respiratory effects in firefighters. American Journal of Industrial Medicine. 2012 Jan;55(1):54–62.

9. Allonneau A, Mercier S, Rieunier F, Menguy-Fleuriot A, Louyot C, Duvollet M, et al. Exposure to fire smoke in fire training structures: A prospective observational study. Archives of Environmental and Occupational Health. 2022;77(7):586–97.

10. Baxter CS, Hoffman JD, Knipp MJ, Reponen T, Haynes EN. Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. Journal of Occupational and Environmental Hygiene. 2014;11(7):85–91.

11. Evans DE, Fent KW. Ultrafine and respirable particle exposure during vehicle fire suppression. Environmental Science: Processes and Impacts. 2015;17(10):1749–59.

12. Maloney SR, Udasin IG, Black TM, Shah NN, Steinberg MB, Pratt ME, et al. Perceived Health Risks Among Firefighters; The New Jersey Firefighter Health Survey. J Occup Environ Med. 2021;63(4):317–21.

13. Mohamed Hanan MF. Perception of Firefighters on Risk of Exposure to Respiratory Health Hazard: A Qualitative Analysis in Malaysia. Medicine & Health. 2021;16(2):72–83.

14. Jahnke SA, Poston WSC, Jitnarin N, C. Keith Haddock. Health concerns of the U.S. fire service: Perspectives from the firehouse. American Journal of Health Promotion. 2012 Nov;27(2):111–8.

15. Bolstad-Johnson DM, Burgess JL, Crutchfield CD, Storment S, Gerkin R, Wilson JR. Characterization of firefighter exposures during fire overhaul. American Industrial Hygiene Association Journal. 2000;61(5):636–41.

16. Brandt-Rauf PW, Fallon LF, Tarantini T, Idema C, Andrews L. Health hazards of fire fighters: Exposure assessment. British Journal of Industrial Medicine. 1988;45(9):606–12.

17. Nagin DS, Odgers CL. Group-based trajectory modeling in clinical research. Annual Review of Clinical Psychology. 2010;6(May):109–38.

18. Nguena Nguefack HL, Pagé MG, Katz J, Choinière M, Vanasse A, Dorais M, et al. Trajectory modelling techniques useful to epidemiological research: A comparative narrative review of approaches. Clinical Epidemiology. 2020;12:1205–22.

19. Shain M, Kramer DM. Health promotion in the workplace: Framing the concept; reviewing the evidence. Occup Environ Med. 2004;61(7):643–8.

20. Safe Work Australia. Work health and safety consultation , cooperation and coordination Code of Practice. Code of Practice. 2018. 41 p.

21. NIOSH. Essential Elements of Effective Workplace Programs and Policies for Improving Worker Health and Wellbeing. 2008.

22. Slattery F. Longitudinal changes in South Australian metropolitan firefighter lung function. 2019;(July).

23. Pendergrast C, Boyle T, Crockett AJ, Eston R, Johnston KN, Boyle | Terry, et al. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. Respirology. 2022;27.

24. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates a., et al. Standardisation of spirometry. European Respiratory Journal. 2005;26(2):319–38.

25. Mergler D. Combining quantitative and qualitative approaches in occupational health for a better understanding of the impact of work-related disorders. Scandinavian Journal of Work, Environment and Health. 1999;25(SUPPL. 4):54–60.

26. Choi BCK. A technique to re-assess epidemiologic evidence in light of the healthy worker effect: The case of firefighting and heart disease. Journal of Occupational and Environmental Medicine. 2000;42(10):1021–34.

27. Choi CWJ, Stone RA, Kim KH, Ren D, Schulz R, Given CW, et al. Group-based trajectory modeling of caregiver psychological distress over time. Annals of Behavioral Medicine. 2012 Aug;44(1):73–84.

28. Austin CC, Dussault G, Ecobichon DJ. Municipal firefighter exposure groups, time spent at fires and use of self-contained-breathing-apparatus. American Journal of Industrial Medicine. 2001;40(6):683–92.

29. Glass D, Sim M, Pircher S, Del Monaco A, Dimitriadis C, Miosge J, et al. Final Report Australian Firefighters' Health Study. Melbourne; 2014.

Chapter 2 - Appendices

Appendix 2.1 Statement of Authorship

University of South Australia

Statement of Authorship

Title of Paper	Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach
Publication Status	X Published ☐ Accepted for Publication ☐ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details Relevant reference details	Pendergrast, C, Boyle, T, Crockett, AJ, Eston R, Johnston KN. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. Respirology. 2022. https://doi.org/10.1111/resp.1438

PRINCIPAL AUTHOR

Name of Principal Author (Candidate)	**Catherine Pendergrast**	
Contribution to the Paper Brief description of your work in this publication	CP, KJ, TB, AC and RE conceptualised the research question. CP and TB were responsible for methods, analysis and results. CP was responsible for drafting the manuscript. KJ, TB, AC and RE were responsible for review of the draft and approved the manuscript.	
Overall Percentage (%)	**80**	
Certification	I certify that all information provided on this form is correct, including contributions from myself and my co-authors.	
Signature	[redacted]	Date 15/12/22

CO-AUTHOR CONTRIBUTIONS

By signing the Statement of Authorship, each author certifies that:

I. the candidate's stated contribution to the publication is accurate (as detailed above);

II. permission is granted for the candidate in include the publication in the thesis; and

III. the sum of all co-author contribution is equal to 100% less the candidate's stated contribution.

Name of Co-Author 1	Terry Boyle	
% Contribution to the Paper	10	
Signature	[redacted]	Date 15/12/2022
Name of Co-Author 2	Alan Crockett	

CRICOS Provider No. 00121B

Last updated: 12 February 2019

University of South Australia

% Contribution to the Paper	2.5	
Signature	[redacted]	Date 8/1/2023
Name of Co-Author 3	Roger Eston	
% Contribution to the Paper	2.5	
Signature	[redacted]	Date 11/01/2023
Name of Co-Author 4	Kylie Johnston	
% Contribution to the Paper	5	
Signature	[redacted]	Date 12/01/2023

Appendix 2.2 Published Manuscript

Received: 7 June 2022 | Accepted: 14 September 2022

DOI: 10.1111/resp.14382

ORIGINAL ARTICLE

Respirology | WILEY

Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach

Catherine Pendergrast[1] | Terry Boyle[2] | Alan J. Crockett[3] | Roger Eston[4] | Kylie N. Johnston[1]

[1]Innovation, Implementation and Clinical Translation in Health (IIMPACT) Research Concentration, University of South Australia, Adelaide, South Australia, Australia

[2]Australian Centre for Precision Health, Allied Health and Human Performance, University of South Australia, Adelaide, South Australia, Australia

[3]Allied Health and Human Performance, University of South Australia, Adelaide, South Australia, Australia

[4]Alliance for Research in Exercise, Nutrition and Activity (ARENA), University of South Australia, Adelaide, South Australia, Australia

Correspondence
Catherine Pendergrast
Email: cathy.pendergrast@mymail.unisa.edu.au

Funding information
University of South Australia Firefighter Lung Function Scholarship; Australian Government Research Training Program

Associate Editor: Alexander Larcombe and **Senior Editor:** Lutz Beckert

Abstract

Background and Objective: Urban firefighters are routinely exposed to both physical and chemical hazards that can negatively impact lung health, but it is unclear if firefighters experience accelerated decline in spirometry parameters due to chronic exposure and acute insults. This study aimed to describe sub-groups of firefighters with differing spirometry trajectories and examine the relationship between the identified trajectories and demographic, lifestyle and occupational characteristics.

Methods: Data from six waves of the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service Study (2007–2019) were used to identify spirometry parameter z-score trajectories, using group-based multi-trajectory modelling (GBMTM). Analysis of variance and chi-square statistics were used to assess trajectory group differences in baseline self-reported demographic, lifestyle and occupational characteristics.

Results: In the 669 included firefighters, we identified five trajectories for the combination of Forced Expiratory Volume in the first second z-score (FEV_1z), Forced Vital Capacity z-score (FVCz) and the ratio of FEV_1 and FVC z-score (FEV_1/FVCz). There were three stable trajectories of low, average and very high lung function and two declining trajectories of average and high lung function. Analysis of subgroup characteristics revealed no significant differences between expected and actual group proportions for the occupational characteristics of years of service and respiratory protection use. Significant differences were seen in respiratory health and body mass index.

Conclusion: GBMTM defined distinct, plausible spirometry trajectory sub-groups. Firefighter longitudinal spirometry trajectory group membership was associated with BMI and respiratory disease or symptoms but not with self-reported smoking history or occupational factors.

KEYWORDS
firefighter, group-based multi-trajectory modelling, longitudinal studies, occupational exposure, spirometry

INTRODUCTION

Firefighters are routinely exposed to both physical and chemical hazards that are associated with health risks, including increased rates of cancer,[1,2] heart attack,[3] musculoskeletal injury[4] and respiratory dysfunction.[5] The acute responses of the respiratory system to inhalation of toxic gases and particulates are well documented.[6,7] Exposures can lead to acute airway hyper-responsiveness,[8] reductions in lung function[9–11] and lung inflammation,[11,12] and repeated insults could result in long-term sequelae.

Serial spirometry is used to investigate the long-term rate of change in firefighters' lung health and determine if it is consistent with the general healthy population.[5]

The study was previously presented at the TSANZSRS ASM 2022.

This is an open access article under the terms of the Creative Commons Attribution-NonCommercial-NoDerivs License, which permits use and distribution in any medium, provided the original work is properly cited, the use is non-commercial and no modifications or adaptations are made.
© 2022 The Authors. *Respirology* published by John Wiley & Sons Australia, Ltd on behalf of Asian Pacific Society of Respirology.

A systematic review synthesising 22 studies of longitudinal spirometry measurement in cohorts of professional firefighters found that non-smoking firefighters who wore respiratory protection were likely to have a normal rate of lung function decline with age.[5] Despite this review outcome, a more recent study of Virginian firefighters observed decreases in spirometry parameters two to four times greater than expected over five years.[13] Alternate methodological approaches may be necessary to delineate if there are long-term decrements in lung health related to repeated exposures and respiratory insults in this at-risk group.

Urban fire services have seen significant changes in technology, procedures and training over the last four decades since the first evidence of accelerated spirometry decline was reported.[14] Lower risk of accelerated decline in spirometry parameters has been demonstrated in those who frequently used respiratory protection,[5] whilst weight gain and smoking history are associated with an increased rate of spirometry decline.[5] Firefighters are a heterogeneous group whose work and lifestyle choices may cause a single averaged longitudinal trajectory to mask individual differences and lead to erroneous conclusions regarding lung health. Elucidation of sub-groups of firefighters following different spirometry trajectories and their characteristics may identify groups at risk of accelerated spirometry decline and those protective factors associated with the preservation of lung health.

Most longitudinal studies report changes in spirometry parameters in absolute terms (i.e., ml of volume change divided by the time between measurements).[5] Spirometry parameters and any associated changes are related to an individual's characteristics of age, height, gender and ethnicity.[15,16] Representation of spirometry parameters as a z-score (the number of SD from the mean) allows standardisation of the measurement and minimises the effect of these characteristics during any comparison.[17] Expressing firefighter spirometry as a z-score generated from Global Lung Initiative (GLI) reference values and examining z-score patterns over time is a contemporary approach to analysis that will build on existing knowledge in this field.[18]

This study aimed to identify distinct subgroups of spirometry trajectories in longitudinal firefighter data, and to assess if baseline lifestyle, health and occupational factors were associated with trajectory group membership.

SUMMARY AT A GLANCE

It is unclear if urban firefighters involved in routine firefighting suffer from accelerated decline in lung function. This analysis identified three stable and two declining spirometry parameter z-score trajectory groups within the cohort. The declining trajectories were not associated with self-reported occupational characteristics of Years of Service and Respiratory Protection Use.

METHODS

Study design and participants

Our study analysed data from the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study, conducted between 2007 and 2019 and included six waves of occupational, health, lifestyle and spirometry measurements.[19–24] The observational study collected data biennially and was open to all SAMFS active firefighters and administrative staff (approximately 5%). Firefighting tasks were of a routine urban nature (structural, waste, car fire attendance with limited exposure to bushfire) and no catastrophic events were experienced throughout the period of data collection. The study used an open cohort design, allowing firefighters to participate in one, some or all rounds of surveillance. Of the 976 firefighters who took part in the study, our analysis focused on those who performed technically acceptable spirometry measurements at two or more waves and provided questionnaire data on their first wave.[25]

We used the Guidelines for Reporting on Latent Trajectory Studies (GRoLTS) to inform our analysis and reporting.[26]

Outcome variables—Spirometry parameters

Pre-bronchodilator spirometry was measured using a Masterscreen PFT spirometer (Vyaire, Würzburg, Germany) at each study wave attended by the firefighters according to the American Thoracic Society and European Respiratory Society guidelines.[25] The FEV_1, FVC and FEV_1/FVC were converted to z-scores using the Global Lung Initiative (GLI) reference equations[17] that are validated for use in both the general Australian population[27,28] and the South Australian urban firefighter population.[23]

Exposure variables—Questionnaire data

Data about lifestyle, respiratory disease and symptoms, length of service and respiratory protection use were collected at each firefighter's first attended wave and used to define baseline exposure variables (Table S1 in the Supporting Information).

Lifestyle-related variables included BMI and smoking status. The height and weight measurements at the first spirometry test occasion were used to calculate BMI. Smoking status was based on self-report data, and firefighters were categorised as current smokers, ex-smokers and never-smokers.

For respiratory disease, firefighters were grouped into the categories 'Nil', 'Asthma' or 'Chronic Obstructive Pulmonary Disease (COPD)' according to self-reported doctor diagnosis and/or symptoms as previously described by Schermer.[19]

'Years of service' and 'Respiratory Protection Use' were calculated from self-report questionnaire baseline

data to provide surrogate measures of occupational exposure.

Statistical analysis

Baseline characteristics of participants were expressed as mean (SD) for continuous, normally distributed data and count (%) for categorical data.

We applied Group-Based Multi-Trajectory Modelling (GBMTM) to explore the presence of distinct subgroups of FEV_1z, FVCz and FEV_1/FVCz combinations within the cohort over the surveillance period. The spirometry parameters were considered to follow a censored normal distribution, and each participant's first wave attended was allocated as time equal to zero days.

Determination of the optimal number of trajectory groups was based on Growth Based Trajectory Modelling (GBTM) of individual spirometry parameters with the assistance of the Fit-Criteria Assessment Plot[29] (Appendix S1, Figure S1 in the Supporting Information). A five-trajectory model was deemed most appropriate, yielding the Bayesian Information Criteria (BIC) and Akaike Information Criteria (AIC) closest to zero, Average Posterior Probability of Assignment (APPA) greater than 0.7 and adequate sample sizes for each group (Table S2 in the Supporting Information).[29,30] Subsequent application of GBMTM with stepwise analysis of polynomial significance led to the determination of a linear model shape. Model fit statistics (BIC, AIC and APPA), expert knowledge and parsimony contributed to the final model determination (Table S3 in the Supporting Information).

TABLE 1 Baseline demographic, lifestyle and occupational characteristics by spirometry trajectory group

	Overall ($n = 669$)	Group 1 Stable low lung function ($n = 69$)	Group 2 Stable average lung function ($n = 121$)	Group 3 Declining average lung function ($n = 208$)	Group 4 Declining high lung function ($n = 147$)	Group 5 Stable very high lung function ($n = 124$)
Characteristics at baseline						
Male (%)	656 (98%)	69 (100%)	119 (98%)	203 (98%)	144 (98%)	121 (98%)
Age (years)	41.7 (8.6)	39.7 (8.2)	42.3 (9.9)	41.5 (8.7)	41.6 (7.5)	42.6 (8.5)
BMI (kg/m^2)	27.3 (3.2)	27.8 (3.3)	28.2 (4.0)	26.9 (2.8)	26.9 (3.1)	27.0 (2.6)
<25 kg/m^2	153 (23%)	14 (20%)	23 (19%)	54 (26%)	40 (27%)	22 (18%)
25–30 kg/m^2	406 (61%)	41 (60%)	66 (55%)	128 (62%)	80 (54%)	91 (73%)
>30 kg/m^2	110 (16%)	14 (20%)	32 (26%)	26 (13%)	27 (18%)	11 (9%)
Smoking status[a]						
Non-smoker	386 (70%)	42 (61%)	65 (54%)	116 (56%)	90 (61%)	73 (59%)
Ex-smoker	117 (21%)	8 (12%)	28 (23%)	35 (17%)	20 (14%)	26 (21%)
Current smoker	46 (9%)	8 (12%)	7 (6%)	16 (8%)	8 (5%)	7 (6%)
Not reported	120 (19%)	11 (16%)	21 (17%)	41 (20%)	29 (20%)	18 (15%)
Occupational factors[a]						
Years of service	13.4 (10.5)	12.16 (9.9)	14.8 (11.5)	13.0(10.4)	13.1 (9.6)	13.7 (10.7)
Respiratory protection use—fire task	0.49 (0.26)	0.45 ± 0.27	0.48 ± 0.25	0.50 ± 0.27	0.50 ± 0.28	0.49 ± 0.25
Respiratory status[a]						
No reported diagnosis or symptoms	597 (89%)	57 (82%)	106 (88%)	192 (92%)	125 (85%)	117 (94%)
Asthma (diagnosis or symptoms)	10 (2%)	4 (6%)	0 (0%)	2 (1%)	4 (3%)	0 (0%)
Chronic bronchitis/emphysema (diagnosis or symptoms)	62 (9%)	8 (12%)	15 (12%)	14 (7%)	18 (12%)	7 (6%)
Spirometry						
FEV_1z	0.44 (0.97)	−0.89 (0.58)	−0.54 (0.47)	0.66 (0.50)	0.46 (0.52)	1.73 (0.54)
FVCz	0.89 (0.90)	0.57 (0.60)	−0.21 (0.48)	0.68 (0.49)	1.36 (0.56)	1.97 (0.65)
FEV_1/FVCz	−0.70 (0.88)	−2.07 (0.63)	−0.59 (0.63)	−0.08 (0.57)	−1.26 (0.61)	−0.43 (0.69)

Note: Baseline characteristics of participants according to lung function trajectories. Data are *n* (%) or mean (SD). Denominators are shown where data are missing. All spirometry parameter z-scores are based on the Global Lung Initiative reference values.[44]

Abbreviations: BMI, body mass index; COPD, chronic obstructive pulmonary disease; FEV_1z, forced expiratory volume in 1 s expressed as a z-score; FVCz, forced vital capacity expressed as a z-score; FEV_1/FVCz, ratio of FEV_1 and FVC expressed as a z-score.

[a]Self-reported data.

Assignment of an individual participant to a specific trajectory group was based on their highest posterior probability of group membership. Between-group differences for the lifestyle factors, respiratory status and occupational factors were tested using chi-square tests for categorical factors and analysis of variance for continuous factors.

As GBMTM analysis assumes that missing data are missing at random (MAR),[30] we performed a sensitivity analysis where we first investigated which baseline factors were associated with the number of waves participated in (i.e., those factors that help to predict missingness in the trajectory analysis). We then repeated the GBMTM analysis with those factors included as covariates and compared trajectory group allocation between the two models.

Data cleaning and regression analysis were performed using SPSS (version 26, IBM SPSS 26, Armonk, NY), and Stata (version 16, StataCorp LLC, College Station, TX) was used to perform the trajectory analysis.[31]

RESULTS

Firefighter characteristics

Of the 976 firefighters that took part in the study, 669 performed spirometry testing in at least two waves and supplied baseline questionnaire responses allowing them to be included in this analysis. The included cohort was 98% male, had a mean age at baseline of 41.7 (SD = 8.6) years, and had spent an average of 13.6 (6.6) years as a firefighter (Table 1).

At baseline measurement, mean firefighter lung function was within the normal range (FEV_1z: 0.44[0.97]; FVCz: 0.90 [0.89]; $FEV_1/FVCz$: −0.70[0.88]). More than half of the group were non-smokers (57.7%), and 89% reported no respiratory disease diagnosis or symptoms. Characteristics of included firefighters were not significantly different from those who were excluded, except FEV_1z, which was, on average, higher in those included (0.44[0.97] vs. 0.24[0.95], $p_{difference} = 0.003$) and excluded firefighters were more likely to have missing data for smoking status, years of service and respiratory protection use (Table S4 in the Supporting Information). Participants provided an average of 4(1) spirometry results for the analysis. Wave data points were an average of 670(57) days apart.

Trajectory analysis

The selected model identified five spirometry trajectories (Figure 1) and performed well on all indexes of model fit (Table S5 in the Supporting Information). Trajectory groups were labelled based on their relative differences from Group 2 ($n = 121$, 18.7% of the included sample), which demonstrated stability over time in all spirometry parameters around the population mean. Group 1 displayed stable relatively low function ($n = 69$, 10.3%), Group 3 displayed declining lung function around the population mean ($n = 208$, 30.5%), Group 4 displayed relatively high but declining lung function ($n = 147$, 22.3%) and Group 5 displayed very high stable lung function ($n = 124$, 18.3%; Table 1, Table S6 in the Supporting Information).

Analysis of the characteristics of each trajectory group revealed no significant differences between the groups for the occupational characteristics of Years of Service and Respiratory Protection Use. However, significant differences were seen for Respiratory Status ($p = 0.006$) and BMI ($p = 0.002$). The stable, very high lung function group had a lower proportion (9%) of firefighters with a high BMI, whilst the stable, low lung function group had the highest proportion (18%) of firefighters with self-reported respiratory disease or symptoms (Table 1).

The sensitivity analysis found that BMI, Smoking Status, Years of Service and Respiratory Protection Use were associated with the number of waves participated in. Adding these variables to the trajectory analysis resulted in almost identical (99.1% agreement) trajectory group allocation to the original trajectory analysis (Table S7).

DISCUSSION

This novel approach using GBMTM identified five distinct trajectories of spirometry parameter z-scores in an urban firefighter cohort. All trajectories for FVCz, FEV_1z and $FEV_1/FVCz$ were above the lower limit of normal (z-score > −1.64) except the $FEV_1/FVCz$ in Group 1 (Stable Low Lung Function trajectory). The analysis revealed that firefighters had average to very high FVCz that remained stable over the time of surveillance. The stable FVCz trajectories combined with either

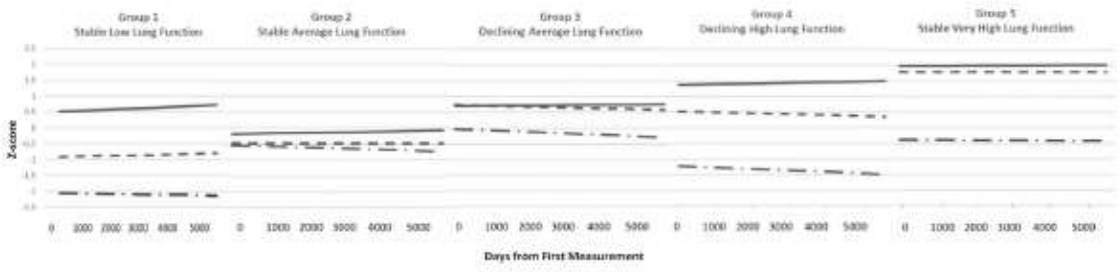


FIGURE 1 Graphical representation of the five trajectory groups of spirometry parameter z-scores in the urban firefighter cohort from 2007 to 2019. In each group FVCz is represented by a solid line, FEV_1z by a dashes and $FEV_1/FVCz$ by a dash, dot line.

stable or declining FEV_1z trajectories resulted in stable or declining $FEV_1/FVCz$ trajectories. This outcome contrasts with an earlier analysis of our dataset performed before the final wave of data collection (2019), which demonstrated that mean spirometry parameters in the whole study population remained stable over 10 years.[24]

The Stable Low Lung Function group displayed FEV_1z and FVCz within the normal range but a reduced $FEV_1/FVCz$, consistent with a dysanaptic pattern of spirometry parameters.[32] It is unclear if dysanapsis (a reduced airway calibre relative to lung size) is a normal physiological phenomenon or a precursor to worsening obstructive lung disease.[32] This firefighter cohort had characteristics comparable with those observed in a group of healthy people with a dysanaptic spirometry pattern (i.e., male sex, age < 55 years and FVC > 105% predicted), in contrast to people with dysanaptic spirometry and clinically confirmed obstructive lung disease.[33] Recent studies of USA and Canadian population cohorts suggest that those with dysanapsis have a predisposition for developing obstructive lung disease[34] and may be particularly susceptible to the long-term effects of air pollution.[35] Levels of air pollution regularly encountered by firefighters are significantly greater than ambient air pollution so it is conceivable that risk of developing obstructive lung disease in later life is heightened further in firefighters with lower airway to lung size ratios.[36,37]

As previously described,[19,21–23] this firefighter cohort has higher than average spirometry, possibly due to selection into an active occupation and the healthy worker effect.[38] Analysis techniques that average change in volume over time or use simple linear regression in the cohort, may result in those with above-average spirometry masking those firefighters whose spirometry is low, contributing to inconsistent study outcomes. Seventy-two percent of our cohort had FEV_1z and FVCz higher than the population average, and almost one fifth (19.5%) had z-scores above the 95th percentile. Group membership of declining trajectories was 50% and occurred in groups where lung function was at or greater than the population mean. Irrespective of the normality of baseline lung function results, accelerated lung function decline is associated with poor clinical outcomes.[32] GBMTM allowed us to identify those groups within the cohort who may be susceptible to poor outcomes and define their associated characteristics.

Firefighter occupational characteristics of Years of Service and Respiratory Protection Use were not related to the prevalence of declining or low lung function in this analysis, with similar proportions observed in each of the trajectory groups. This result is consistent with previous studies that have failed to find a robust relationship between these occupational characteristics and lung function decline in routine urban firefighters.[5] However, addressing whether occupational firefighting predisposes those on the frontline to accelerated spirometry decline has, and continues to be, a challenging problem. The long latency of possible lung disease from cumulative exposures, lack of pre-exposure baseline measurement, lifestyle confounders such as smoking history and weight gain, evolving improvements in work health safety and the healthy worker effect pose difficulties for researchers.

The Stable Very High Lung Function group had the lowest proportion of firefighters with a BMI greater than 30 kg/m^2. An increased BMI changes chest wall mechanics, lowering operating lung volumes, vital capacity and promoting airway narrowing and closure.[39] Preserved spirometry in those with lower BMI is consistent with the evidence provided by previous longitudinal studies of firefighters[40,41] and non-firefighters.[42] Unsurprisingly, the highest prevalence of self-reported respiratory disease or symptoms at baseline was seen in the Stable Low Lung Function (18%) and Declining High Lung Function (15%) groups. Whilst the relationship between respiratory disease and lung function has not been investigated explicitly in firefighters, it is plausible that those with symptoms or diagnosed disease will demonstrate low or reducing lung function consistent with progression of disease-associated mechanical lung changes.

The study exclusion criteria and open cohort nature of the study may have contributed to selection bias in our analysis. Although excluded participants were similar to the included participants in terms of their reported questionnaire data (exposures), they were more likely to have missing questionnaire data (i.e., 'Not Reported' exposures). In addition, firefighters who were located at regional stations or those who suspected their health and fitness were compromised may have been less likely to participate and may be under-represented. This may limit the generalizability of our results.

The self-report nature of the data also introduced the risk of measurement error. Recall bias, breach of workplace policy and concern about data use in an occupational setting, reliant on health and fitness, may have negatively impacted exposure reporting. Ideally, objective measures of firefighter exposures and respiratory protection use, along with physician confirmed respiratory status at baseline would strengthen the methodology of studies in this occupational group.

The major strength of this study was the use of the contemporary methods of normalising and interpreting the spirometry data, consistent with the ATS/ERS recommendations.[32,43] The use of absolute change over time and percentage of predicted in the analysis of spirometry and other lung function testing data are no longer recommended.[32,43] Another strength of our study was the ability to explore undefined trajectories that were not based on an *a priori* hypothesis. By applying GBMTM, we were able to simultaneously analyse the combination of spirometry parameters that are clinically reflective of lung health. Despite the benefits of this type of analysis, there is currently no validated approach to determining the normal variation of z-scores over time[32] and hence if our declining trajectories are likely to represent clinical significance. We are currently limited to a purely descriptive outcome.

In conclusion, this study demonstrates that GBMTM was able to identify five distinct, biologically plausible firefighter spirometry trajectories. It failed to find evidence of an association between self-reported occupational factors and declining spirometry trajectories. Despite this reassuring outcome, group membership of declining trajectories was

>50% and these were characterised by spirometry parameters that were at or greater than the population mean. This highlights the need for pre-exposure baseline screening of lung health in all firefighters, to ensure that decline in lung health can be identified, given the high risk of acute and chronic exposure.

AUTHOR CONTRIBUTION

Catherine Pendergrast: Data curation (lead); formal analysis (lead); investigation (lead); methodology (lead); project administration (lead); visualization (lead); writing – original draft (lead); writing – review and editing (lead). **Terry Boyle:** Conceptualization (equal); data curation (supporting); formal analysis (supporting); investigation (supporting); methodology (supporting); project administration (supporting); supervision (lead); writing – review and editing (supporting). **Alan J. Crockett:** Conceptualization (equal); data curation (supporting); funding acquisition (equal); project administration (supporting); resources (equal); supervision (supporting); writing – review and editing (supporting). **Roger Eston:** Funding acquisition (equal); project administration (supporting); resources (equal); supervision (supporting); writing – review and editing (supporting). **Kylie Johnston:** Conceptualization (equal); investigation (supporting); project administration (supporting); supervision (lead); writing – review and editing (supporting).

ACKNOWLEDGEMENTS

We wish to thank and acknowledge the generosity of the South Australian Metropolitan Fire Service (SAMFS) firefighters in contributing their time and effort to this study. The authors would also like to thank Deputy Chief Officer Paul Fletcher, SAMFS, for his communication, planning and logistical assistance.

Research funding: Catherine Pendergrast's research is funded by the University of South Australia Firefighter Lung Function Scholarship provided by the SAMFS and the Australian Government Research Training Program. Open access funding facilitated by University of South Australia, as part of the Wiley - University of South Australia agreement via the Council of Australian University Librarians.

CONFLICT OF INTEREST

None declared.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are held by the corresponding author. Availability of the study data is at the discretion of the SAMFS upon application.

HUMAN ETHICS APPROVAL DECLARATION

This study was performed in accordance with the Declaration of Helsinki. This human study was approved by the University of South Australia Human Research Ethics Committee (Protocol no. 0000032662). All participant provided written informed consent to participate in this study.

ORCID

Catherine Pendergrast https://orcid.org/0000-0002-1989-0934
Terry Boyle https://orcid.org/0000-0001-6741-330X
Alan J. Crockett https://orcid.org/0000-0002-0335-2031
Roger Eston https://orcid.org/0000-0002-2680-7473
Kylie N. Johnston https://orcid.org/0000-0002-4436-3108

REFERENCES

1. Jalilian H, Ziaei M, Weiderpass E, Rueegg CS, Khosravi Y, Kjaerheim K. Cancer incidence and mortality among firefighters. Int J Cancer. 2019 Nov 15;145(10):2639–46.
2. Laroche E, L'espérance S. Cancer incidence and mortality among firefighters: an overview of epidemiologic systematic reviews. Int J Environ Res Public Health. 2021;18:1–32. https://doi.org/10.3390/ijerph18052519
3. Soteriades ES, Smith DL, Tsismenakis AJ, Baur DM, Kales SN. Cardiovascular disease in US firefighters: a systematic review. Cardiol Rev. 2011;19(4):202–15.
4. Nazari G, MacDermid J, Cramm H. Prevalence of musculoskeletal disorders among Canadian firefighters: a systematic review and meta-analysis. J Mil Veteran Fam Health. 2020;6:83–97.
5. Slattery F, Johnston K, Paquet C, Bennett H, Crockett A. The long-term rate of change in lung function in urban professional firefighters: a systematic review. BMC Pulm Med. 2018;18(1):1–20.
6. Fent KW, Evans DE. Assessing the risk to firefighters from chemical vapors and gases during vehicle fire suppression. J Environ Monit. 2011;13(3):536–43. Available from: www.cdc.gov/niosh/hhe
7. Guidotti TL, Clough VM. Occupational health concerns of firefighting. Annu Rev Public Health. 1992;13:151–71.
8. Chia KS, Jeyaratnam J, Chan TB, Lim TK. Airway responsiveness of firefighters after smoke exposure. Br J Ind Med. 1990;47(8):524–7.
9. Burgess JL, Nanson CJ, Bolstad-Johnson DM, Gerkin R, Hysong TA, Lantz RC, et al. Adverse respiratory effects following overhaul in firefighters. J Occup Environ Med. 2001;43(5):467–73.
10. Gaughan DM, Piacitelli CA, Chen BT, Law BF, Virji MA, Edwards NT, et al. Exposures and cross-shift lung function declines in wildland firefighters. J Occup Environ Hyg. 2014;11(9):591–603.
11. Gianniou N, Katsaounou P, Dima E, Giannakopoulou CE, Kardara M, Saltagianni V, et al. Prolonged occupational exposure leads to allergic airway sensitization and chronic airway and systemic inflammation in professional firefighters. Respir Med. 2016;118:7–14. https://doi.org/10.1016/j.rmed.2016.07.006
12. Swiston JR, Davidson W, Attridge S, Li GT, Brauer M, Van Eeden SF. Wood smoke exposure induces a pulmonary and systemic inflammatory response in firefighters. Eur Respir J. 2008;32(1):129–38.
13. Mathias KC, Graham E, Stewart D, Smith DL. Decreased pulmonary function over 5 years in US firefighters. J Occup Environ Med. 2020;62(10):816–9.
14. Peters JM, Theriault GP, Fine LJ, Wegman DH. Chronic effect of fire fighting on pulmonary function. N Engl J Med. 1974;291(25):1320–2. https://doi.org/10.1056/NEJM197412192912502
15. Quanjer PH, Hall GL, Stanojevic S, Cole TJ, Stocks J. Age- and height-based prediction bias in spirometry reference equations. Eur Respir J. 2012;40(1):190–7.
16. Stanojevic S, Quanjer P, Miller MR, Stocks J. The Global Lung Function Initiative: dispelling some myths of lung function test interpretation. Breathe. 2013;9(6):462–74.
17. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3-95 year age range: the Global Lung Function 2012 equations. Report of the Global Lung Function Initiative (GLI), ERS Task Force to establish improved lung function reference values. Eur Respir J. 2012;40(6):1324–43. Available from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3786581/pdf/nihms513963.pdf

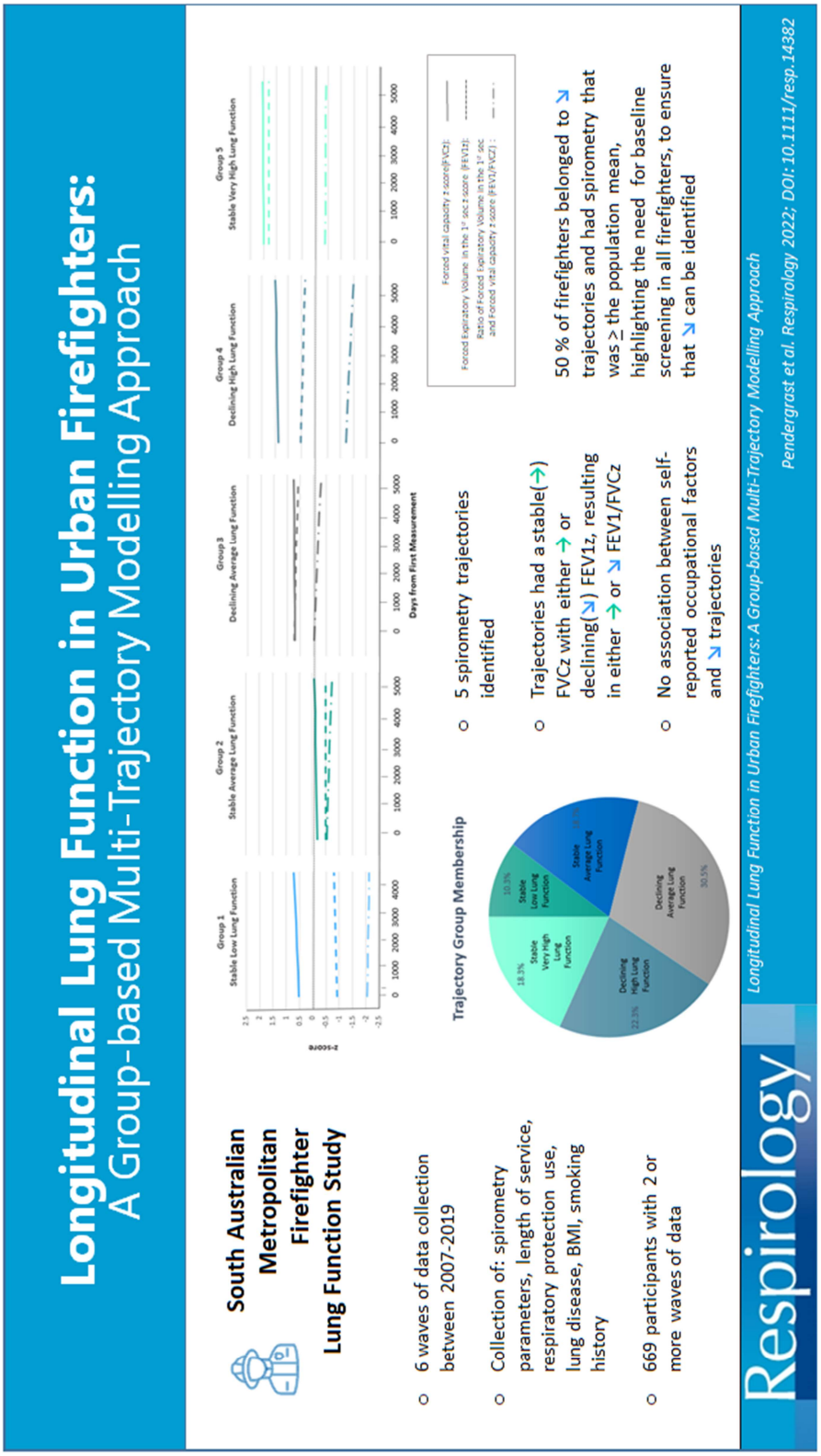
18. Bui DS, Lodge CJ, Burgess JA, Lowe AJ, Perret J, Bui MQ, et al. Childhood predictors of lung function trajectories and future COPD risk: a prospective cohort study from the first to the sixth decade of life. Lancet Respir Med. 2018;6(7):535–44.
19. Schermer T, Malbon T, Morgan M, Briggs N, Holton C, Appleton S, et al. Lung function and health status in metropolitan fire-fighters compared to general population controls. Int Arch Occup Environ Health. 2010;83(7):715–23.
20. Schermer T, Malbon W, Newbury W, Holton C, Smith M, Morgan M, et al. Spirometry and impulse oscillometry (IOS) for detection of respiratory abnormalities in metropolitan firefighters. Respirology. 2010;15(6):975–85.
21. Schermer TR, Malbon W, Adams R, Morgan M, Smith M, Crockett AJ. Change in lung function over time in male metropolitan firefighters and general population controls: a 3-year follow-up study. J Occup Health. 2013;55(4):267–75.
22. Schermer TR, Malbon W, Morgan M, Smith M, Crockett AJ. Chronic respiratory conditions in a cohort of metropolitan fire-fighters: associations with occupational exposure and quality of life. Int Arch Occup Environ Health. 2014;87(8):919–28.
23. Slattery F, Schermer T, Esterman A, Johnston K, Crockett A, The Global Lung Function Initiative. Equations are as well-suited as local population derived equations to a sample of healthy professional fire-fighters. Can Respir J. 2012;2017:5.
24. Slattery F. Longitudinal changes in South Australian metropolitan firefighter lung function [dissertation]. Adelaide: University of South Australia; 2019.
25. Miller MR, Hankinson J, Brusasco V, Burgos F, Casaburi R, Coates A, et al. Standardisation of spirometry. Eur Respir J. 2005;26(2):319–38.
26. van de Schoot R, Sijbrandij M, Winter SD, Depaoli S, Vermunt JK. The GRoLTS-checklist: guidelines for reporting on latent trajectory studies. Struct Equ Model. 2017;24(3):451–67.
27. Thompson BR, Stanojevic S, Abramson MJ, Beasley R, Coates A, Dent A, et al. The all-age spirometry reference ranges reflect contemporary Australasian spirometry. Respirology. 2011;16(6):912–7.
28. Hall GL, Thompson BR, Stanojevic S, Abramson MJ, Beasley R, Coates A, et al. The Global Lung Initiative 2012 reference values reflect contemporary Australasian spirometry. Respirology. 2012 Oct; 17(7):1150–1.
29. Klijn SL, Weijenberg MP, Lemmens P, Van Den Brandt PA, Lima PV. Introducing the fit-criteria assessment plot-A visualisation tool to assist class enumeration in group-based trajectory modelling. Stat Methods Med Res. 2017;26(5):2424–36. Available from: http://www.andrew.cmu.edu/user/bjones/
30. Nagin DS, Odgers CL. Group-based trajectory modeling in clinical research. Annu Rev Clin Psychol. 2010;6(May):109–38.
31. Jones B, Nagin DS. A note on a stata plugin for estimating group-based trajectory models. Sociological Methods & Research. 2013;42(4):608–613.
32. Stanojevic S, Kaminsky DA, Miller M, Thompson B, Aliverti A, Barjaktarevic I, et al. ERS/ATS technical standard on interpretive strategies for routine lung function tests. Eur Respir J. 2021;60(1): 2101499.
33. Andreata LDS, Soares MR, Pereira CAC. Reduced FEV1/FVC and FEV1in the normal range as a physiological variant. Respir Care. 2019;64(5):570–5.
34. Smith BM, Kirby M, Hoffman EA, Kronmal RA, Aaron SD, Allen NB, et al. Association of dysanapsis with chronic obstructive pulmonary disease among older adults. J Am Med Assoc. 2020;323(22):2268–80.
35. Bourbeau J, Doiron D, Biswas S, Smith BM, Benedetti A, Brook JR, et al. Ambient air pollution and dysanapsis: associations with lung function and COPD in the CanCOLD study. Am J Respir Crit Care Med. 2022;206(1):44–55.
36. Evans DE, Fent KW. Ultrafine and respirable particle exposure during vehicle fire suppression. Environ Sci Process Impacts. 2015;17(10): 1749–59.
37. Baxter CS, Hoffman JD, Knipp MJ, Reponen T, Haynes EN. Exposure of firefighters to particulates and polycyclic aromatic hydrocarbons. J Occup Environ Hyg. 2014;11(7):85–91.
38. Li CY, Sung FC. A review of the healthy worker effect in occupational epidemiology. Occup Med. 1999;49(4):225–9.
39. Jones RL, Nzekwu MMU. The effects of body mass index on lung volumes. Chest. 2006;130(3):827–33.
40. Aldrich TK, Ye F, Hall CB, Webber MP, Cohen HW, Dinkels M, et al. Longitudinal pulmonary function in newly hired, non-world trade center-exposed fire department city of New York firefighters: the first 5 years. Chest. 2013;143(3):791–7.
41. Kim S, Jeon YE, Ryu H, Lee MY, Chung I. Related factors for preserving firefighter's pulmonary function. Ann Occup Environ Med. 2020;32(1):e40.
42. Wang ML, Avashia BH, Petsonk EL. Interpreting longitudinal spirometry: weight gain and other factors affecting the recognition of excessive FEV 1 decline. Am J Ind Med. 2009;52(10):782–9.
43. Graham BL, Steenbruggen I, Barjaktarevic IZ, Cooper BG, Hall GL, Hallstrand TS, et al. Standardization of spirometry 2019 update an official American Thoracic Society and European Respiratory Society technical statement. Am J Respir Crit Care Med. 2019;200(8):E70–88.
44. Quanjer PH, Stanojevic S, Cole TJ, Baur X, Hall GL, Culver BH, et al. Multi-ethnic reference values for spirometry for the 3-95-yr age range: the global lung function 2012 equations. Eur Respir J. 2012;40(6): 1324–43.

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

How to cite this article: Pendergrast C, Boyle T, Crockett AJ, Eston R, Johnston KN. Longitudinal lung function in urban firefighters: A group-based multi-trajectory modelling approach. Respirology. 2022. https://doi.org/10.1111/resp.14382

2.3 Manuscript Visual Abstract



Chapter 3 Appendices

Appendix 3.1 Statement of Authorship

University of South Australia

Statement of Authorship

Title of Paper	Perceptions of Lung Function Surveillance in Urban Firefighters.
Publication Status	☐ Published ☐ Accepted for Publication ☒ Submitted for Publication ☐ Unpublished and Unsubmitted work written in manuscript style
Publication Details Relevant reference details	Submitted to Annals of Work Exposures and Health

PRINCIPAL AUTHOR

Name of Principal Author (Candidate)	**Catherine Pendergrast**	
Contribution to the Paper Brief description of your work in this publication	CP, KJ, TB, AC and RE conceptualised the research question. CP and KJ were responsible for methods, analysis and results. CP was responsible for drafting the manuscript. KJ, TB, AC and RE were responsible for review of the draft and approved the manuscript.	
Overall Percentage (%)	**80**	
Certification	I certify that all information provided on this form is correct, including contributions from myself and my co-authors.	
Signature	[redacted]	Date 15/12/22

CO-AUTHOR CONTRIBUTIONS

By signing the Statement of Authorship, each author certifies that:

I. the candidate's stated contribution to the publication is accurate (as detailed above);
II. permission is granted for the candidate in include the publication in the thesis; and
III. the sum of all co-author contribution is equal to 100% less the candidate's stated contribution.

Name of Co-Author 1	Terry Boyle	
% Contribution to the Paper	5	
Signature	[redacted]	Date 15/12/2022
Name of Co-Author 2	Alan Crockett	
% Contribution to the Paper	2.5	

The University of South Australia
www.unisa.edu.au
CRICOS Provider No. 00121B

Last updated: 12 February 2019

University of South Australia

Signature	[redacted]	Date 8/1/2023
Name of Co-Author 3	Roger Eston	
% Contribution to the Paper	2.5	
Signature	[redacted]	Date 11/01/2023
Name of Co-Author 4	Kylie Johnston	
% Contribution to the Paper	10	
Signature	[redacted]	Date 12/1/2023

Appendix 3.2 Manuscript Under Review

Annals of Work Exposures and Health

BOHS
The Chartered Society for Worker Health Protection

Perceptions of Lung Function Surveillance in Urban Firefighters

Journal:	*Annals of Work Exposures and Health*
Manuscript ID	Draft
Manuscript Type:	Original Article
Date Submitted by the Author:	n/a
Complete List of Authors:	Pendergrast, Catherine; University of South Australia, Innovation, Implementation and Clinical Translation in Health (IIMPACT) Research Concentration Boyle, Terry; University of South Australia, Australian Centre for Precision Health, Allied Health and Human Performance Crockett, Alan; University of South Australia, Allied Health and Human Performance Eston, Roger; University of South Australia, Alliance for Research in Exercise, Nutrition and Performance (ARENA) Johnston, Kylie; University of South Australia, Allied Health and Human Performance
Keywords:	firefighter, lung function surveillance, workplace health and safety, qualitative, wellbeing

SCHOLARONE™
Manuscripts

ORIGINAL ARTICLE:

TITLE: Perceptions of Lung Function Surveillance in Urban Firefighters

Authors' full names:

Catherine Pendergrast[1]

Terry Boyle[2]

Alan J Crockett[3]

Roger Eston[4]

Kylie N Johnston[1]

Author's affiliation(s):

[1]Innovation, Implementation and Clinical Translation in Health (IIMPACT) Research Concentration, University of South Australia, Adelaide, Australia

[2]Australian Centre for Precision Health, Allied Health and Human Performance, University of South Australia, Adelaide, Australia

[3]Allied Health and Human Performance, University of South Australia, Adelaide, Australia

[4]Alliance for Research in Exercise, Nutrition and Performance (ARENA), University of South Australia, Adelaide, Australia

Corresponding author's full contact details:

Name: Catherine Pendergrast

Address: Corner of North Terrace & Frome Road

Postcode: 5001

City: Adelaide

Country: Australia

Email: cathy.pendergrast@mymail.unisa.edu.au

Twitter account name: @PendergrastC17

ORCID:

Catherine Pendergrast https://orcid.org/0000-0002-1989-0934

Terry Boyle https://orcid.org/0000-0001-6741-330X

Alan J Crockett https://orcid.org/0000-0002-0335-2031

Roger Eston https://orcid.org/0000-0002-2680-7473

Kylie N Johnston https://orcid.org/0000-0002-4436-3108

ACKNOWLEDGEMENTS:

We wish to thank and acknowledge the generosity of the South Australian Metropolitan Fire Service (SAMFS) firefighters in contributing their time and effort to this study. The authors would also like to thank Deputy Chief Officer Paul Fletcher (PF), SAMFS, for his communication, planning, and logistical assistance.

For Review Only

ABSTRACT:

Background and objective:

Workplace health and safety (WHS) is an important responsibility falling on both employers and employees and is most effective when the perspectives of all stakeholders are considered. This study aimed to explore the facilitators and barriers to a voluntary workplace lung function surveillance program from the perspective of urban firefighters and describe their perceptions of its value.

Methods:

Using a qualitative, descriptive methodology, firefighters who had participated in a longitudinal lung function surveillance study were invited to participate in semi-structured interviews. Purposeful, maximum variation sampling was used to achieve diversity in those firefighters invited to participate. We used inductive content analysis to identify themes.

Results:

Interviews with 15 firefighters identified three main themes: (1) practical experience of surveillance (administration, communication, workplace culture change, convenience, acceptability and appeal); (2) value of surveillance (lung health efficacy and control, social support, workplace management support/motivations, contribution to global firefighter health) and (3) contribution of surveillance to health (occupational risk, relevance in the context of total health, workability and fitness and future value).

Conclusion:

Practical and psychosocial facilitators and barriers to providing lung function surveillance in the fire service were identified. In addition to the personal benefits of detecting adverse lung health and allowing for medical intervention, factors known to positively influence firefighter workplace wellbeing, such as providing peace of mind, feedback on good work practices, motivation to utilise control measures, management commitment to health, and providing data to assist with global knowledge were valued aspects of longitudinal lung function surveillance.

Keywords:

Firefighter, Lung function surveillance, Workplace health and safety, Qualitative, Wellbeing

For Review Only

INTRODUCTION:

Firefighting is a hazardous profession that places unique and extreme demands on its workforce. Risks to health and wellbeing are multifaceted, spanning physical (exertion, alarm response), environmental (heat, noxious fumes and fibres), and psychological domains (distress, injury and risk of fatality)(Cheung, Petersen and McLellan, 2010; Walker *et al.*, 2015; Paterson, Aisbett and Ferguson, 2016; Hunt, Stewart and Billing, 2019; Nazari, MacDermid and Cramm, 2020; Wagner *et al.*, 2021; Paterson *et al.*, 2022). These workplace demands have the potential to negatively affect firefighter health and wellbeing.

Workplace health and safety (WHS) policy and programs are a long-standing mechanism to monitor and reduce hazards in the workplace(Gochfeld, 1992). Health surveillance is a component of such programs and is a form of secondary prevention used to detect adverse health effects resulting from workplace exposures as early as possible. Detection of such effects allows preventive measures to be instituted. Findings from health surveillance may also indicate the absence of a significant hazard, the adequacy of control measures, individuals at increased risk, provide baseline medical data, benchmarks for preventive action and opportunities to provide health education(Koh and Aw, 2003). Another function is to quantify the incidence and prevalence of work-related diseases.

Workplace health and safety is the responsibility of both employers, who have a duty of care, and employees, who are required to take reasonable care of their health and safety in the workplace(Safe Work Australia, 2018). Health in the workplace is impacted by personal health practices and resources, environmental and organisational factors (physical and psychosocial), and their interactions(Shain and Kramer, 2004). Programs for WHS are most successful when there is consultation and engagement between employers and employees on the design, implementation and amendment of workplace health and safety policy and practice, resulting in greater awareness, commitment and understanding of workplace safety priorities and goals(Safe Work Australia, 2018).

An essential part of effective engagement is understanding employee perspectives of workplace surveillance programs(NIOSH, 2008; Grawitch *et al.*, 2009). Whilst quantitative research into the lung health of firefighters has been described(Slattery *et al.*, 2018; Mathias *et al.*, 2020; Pendergrast *et al.*, 2022), the views of firefighters participating in lung health surveillance have not been ascertained.

This study explored the experiences and attitudes of South Australian Metropolitan Fire Service firefighters who participated in a longitudinal respiratory function surveillance study.

Specifically, we explored their perceptions of the value, benefits of, and barriers to participating in a lung health surveillance program.

METHODS:

Study context and design

This analysis is a part of the Respiratory Function Measurement and Surveillance for South Australian Metropolitan Fire Service (RFMS-SAMFS) study that collected occupational, health, lifestyle, and spirometry data in six waves between 2007 and 2019(Schermer *et al.*, 2010, 2013, 2014; Slattery *et al.*, 2018; Pendergrast *et al.*, 2022). It used a longitudinal, open cohort design to allow firefighters to participate in one, some or all waves of lung health surveillance. The study was a collaboration between SAMFS leadership and South Australian Universities under the supervision of Professor AJ Crockett.

After completing the quantitative data collection, we aimed to understand the participants' views on the value, benefits of, and barriers to their involvement in surveillance using a qualitative descriptive methodology(Bradshaw, Atkinson and Doody, 2017). As a survey would not allow the in-depth understanding we wished to obtain, and focus groups are logistically problematic in the fire service due to the reactive nature of firefighter tasks, individual face-to-face semi-structured interviews were deemed the most appropriate data collection method.

The Consolidated Criteria for Reporting Qualitative research framework (COREQ) was used to guide our study design and reporting(Tong, Sainsbury and Craig, 2007).

Recruitment and Sampling

The RFMS-SAMFS industry advisor (PF) distributed an email to all current SAMFS metropolitan and regional staff, inviting those who had previously contributed to the RFMS-SAMFS study to express interest in participating in the study. Interested firefighters were asked to respond via a survey link within the email that forwarded their contact details to the lead investigator (LimeSurvey GmbH, 2006-2021). Those who responded were matched with their demographic, occupational and health data from their first wave of participation in the longitudinal study. Purposeful, maximum variation sampling was then used to sequentially invite firefighters for an interview to achieve diversity in the characteristics of age, years of service, respiratory protection use, number of waves participated in, self-reported respiratory disease, and lung function trajectory group classification(Pendergrast *et al.*, 2022). Invited firefighters were provided with a detailed study information sheet and the opportunity to self-

select an interview time via email (Doodle Poll, Doodle AG, Switzerland). On selecting an interview time, online informed consent was collected before the interview (LimeSurvey GmbH, 2006-2021), and verbal consent was confirmed at the time of the interview after the participant had the opportunity to ask questions of the lead investigator.

A target sample size of 10-15 participants was planned. This study size was considered to have information power(Malterud, Siersma and Guassora, 2016) to study the specific, well-defined phenomenon of interest and to gain perspectives across the spectrum of the longitudinal study population by including participants with targeted combinations of demographic, health and occupational characteristics.

Data Collection

Online semi-structured face-to-face interviews were conducted using an interview guide developed by the lead investigator (research student - CP) and research supervisor (KJ), who has prior experience in qualitative descriptive research. Interview questions were also reviewed by the wider research team and the SAMFS industry advisor (PF).

Interviews were conducted using the Zoom video conferencing platform by CP, a female clinical respiratory physiologist with more than 20 years of experience interacting with people in a healthcare setting. The interviewer had not been involved with lung function or questionnaire data collection during the RFMS-SAMFS study. Pilot interviews were conducted with KJ before study interviews commenced to allow for procedural and technical familiarisation and feedback.

At the commencement of the interview, study participants were informed that the meeting was being recorded. They were then provided with a standardised verbal overview of the study information, given an opportunity to ask questions, and asked to confirm they were happy to continue with the interview, understanding that they could withdraw from the interview or study at any time.

Data Analysis

Audio-visual recordings of the interviews were automatically transcribed by Zoom software (Zoom Video Communications Inc., 2016). Once the audio-visual and text transcript files were transferred to a secure local file location, those in Zoom cloud storage were deleted. The automatic transcriptions were corrected for accuracy against the audio-visual interview recording. Each transcript was emailed to the participant for validation.

Inductive content analysis was undertaken using the steps described by Erlingsson and Brysiewicz(Shain and Kramer, 2004). In brief, transcriptions were read to develop familiarity

with the content. They were then re-read, and quotes relevant to the study's aims were extracted and entered into an Excel spreadsheet. Each quote was condensed into a core meaning unit. Codes were formulated to summarise the meaning units, bringing quotes with similar meanings together. The first three interviews were independently coded by CP and KJ, after which discussion of the codes occurred until a consensus was reached that the codes were a good representation of the meaning units. Readjustments to codes were made as necessary by consensus, and were grouped into categories and finally brought together to form overarching themes.

RESULTS:

Participant Characteristics

An expression of interest email was sent to approximately 1200 SAMFS staff, of which about 1000 were operational firefighters, from which 104 expressions of interest were received. Of these, 17 firefighters were ineligible due to not previously participating in the RFMS-SAMFS study. Eighty-seven eligible firefighters were matched with their demographic, occupational and health data from their first wave of participation in the longitudinal study. Sequential invitation to participate was then based on creating a cohort with maximum variation in the categories of gender, age, years of service, number of participations, respiratory protection use, respiratory disease and trajectory group membership (Table 1).

For Review Only

Table 1 Participant Characteristics

Participant ID	Location/ Gender	Current Role	Total number of waves participated	At first participation					GBMTM Group Membership (Pendergrast *et al.*, 2022)
				Age Category (years)	Years of Service Category	Respiratory Protection* (Pendergrast *et al.*, 2022)	Spirometry Pattern (Stanojevic *et al.*, 2021)	Respiratory Disease* (Pendergrast *et al.*, 2022)	
1	Metro/ Male	Commander (Day Work)	1	50 - 60	20 - 30	High	Abnormal	Asthma	na
2	Metro/ Male	Station Officer (Shift)	2	40 - 49	20 - 30	Low	Abnormal	Nil	Low stable lung function
3	Regional/ Male	Station Officer (Shift)	3	30 - 39	0 - 9	High	Normal	COPD	Average stable lung function
4	Metro/ Male	Firefighter	6	20 - 29	0 - 9	High	Normal	Nil	Average declining lung function
5	Metro/ Male	Station Officer (Shift)	6	40 - 49	20 - 30	Low	Normal	Nil	Very high stable lung function
6	Metro/ Male	Commander (Day Work)	3	30 - 39	10 - 19	Medium	Normal	Nil	Average declining lung function
7	Metro/ Male	Not reported	4	30 - 39	0 - 9	Medium	Normal	Nil	High declining lung function
8	Metro/ Male	Commander (Shift)	5	50 - 60	20 - 30	Low	Normal	Nil	Average declining lung function
9	Metro/ Male	Firefighter	5	40 - 49	10 - 19	High	Normal	COPD	Average declining lung function
10	Metro/ Male	Firefighter	6	40 - 49	10 - 19	Medium	Normal	Nil	Very high stable lung function
11	Metro/ Male	Firefighter	2	30 - 39	0 - 9	High	Normal	Nil	na
12	Metro/ Male	Firefighter	2	50 - 60	0 - 9	Medium	Normal	Nil	Very high stable lung function
13	Metro/ Male	Station Officer (Shift)	3	30 - 39	10 - 19	Medium	Normal	Nil	na
14	Metro/ Male	Station Officer (Shift)	2	40 - 49	20 - 30	Low	Normal	Nil	Average stable lung function
15	Metro/ Male	Not reported	5	30 - 39	0 - 9	High	Normal	Nil	Very high stable lung function

COPD, chronic obstructive pulmonary disease; GBMTM: Group Based Multi-Trajectory Modelling; * Self-reported data.

Fifteen interviews were conducted with durations of 16 - 42 minutes. All participants were male, and most self-reported no respiratory disease at the time of joining the study (12/15). The cohort included participants across a range of leadership categories, age groups, and potential markers of exposure (self-reported degree of respiratory protection use and years of service). No participants requested changes to their transcript content.

Content Analysis

Three main themes (Figure 1) were identified: 1) *Practical experience of surveillance*, 2) *Perceived value of surveillance,* and 3) *Contribution of surveillance to health*. The analysis demonstrated that interactions existed between individual, organisational and whole-of-

profession issues, encompassing benefits, barriers and values of each. Each theme and its corresponding categories are described, accompanied by exemplar quotes.

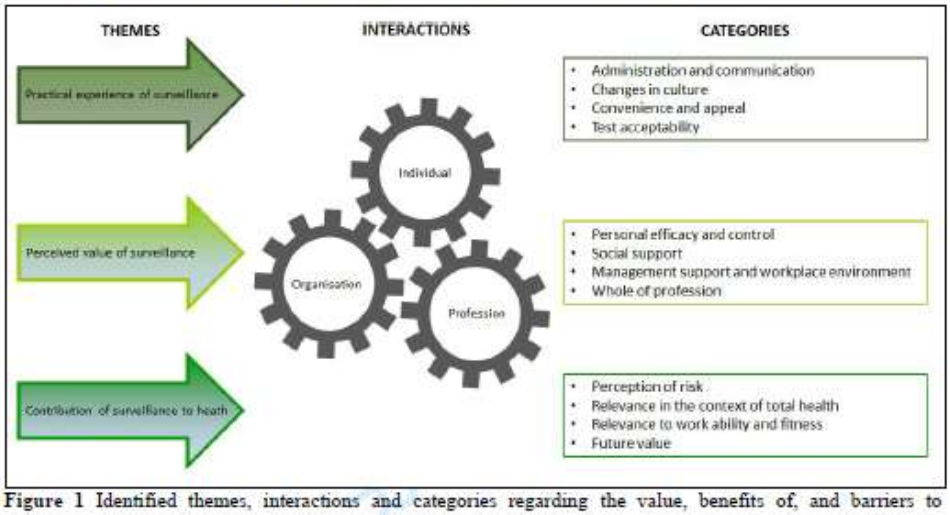


Figure 1 Identified themes, interactions and categories regarding the value, benefits of, and barriers to participating in a lung health surveillance program

Theme one: Practical Experience of Surveillance

Administration and communication

Provision of portable lung function testing to fire service sites whilst the crew was removed from duty to participate (i.e. covered by another crew) worked well. Firefighters reported that the people conducting the test were professional and friendly, putting them at ease, explaining the test well, and providing feedback on their test outcome. Motivation was high, and most people were happy to participate. Overall, interviewees expressed gratitude toward those who implemented the program for being able to participate in the lung function surveillance study.

'The people conducting it were always positive, polite and friendly, always had time to explain things to you, you know, the graphs and the lines and the readings .... so no, for me there was no negative about it at all' (ID10)

Participants felt that communication about the study outcomes could have been improved.

'Maybe a bit more communication about outcomes or findings, but I guess that information goes to the management, right' (ID14)

Changes in culture

The firefighters reported that they had seen changes in practice from a time when using respiratory protection in the form of breathing apparatus (BA) was not the norm to today, where wearing breathing apparatus is mandatory and the accepted practice.

'In the olden days, you didn't use to wear your BA sets for jobs; you just walked into a house fire with a bloody cloth on your face or at car fires, you didn't wear it because it was seen as a bit of a hassle to put them on and wear them and now the practices we adopt is very much the opposite of that' (ID4)

This was also evident in a generational difference in acceptance of lung function surveillance. Firefighters reported that the older demographic may have been distrustful of the motivation behind lung function surveillance and feared that it may have threatened their job security. The younger generation, particularly those who began their firefighter career whilst the surveillance program was collecting data, accepted the surveillance as standard practice.

'I was fairly new into the service, so it's (lung function) something that I think everyone from my group was doing' (ID11)

An alternate view expressed was that younger firefighters may not feel the need to monitor their lung function because they always use breathing apparatus.

Convenience and appeal

Participation in the surveillance study was perceived to be easy, and the SAMFS and University provided a setup that made it appealing for firefighters. It was often stated that it was 'done on work time' and that another firefighting team covered their duties.

'There was nothing really in my way holding me up from doing it, which again, made it appealing to do because it was done on work time, and we just sort of had to find where it was being done and go there. We were allocated time to do it, so it was good' (ID10)

Despite being covered, there were challenges to overcome; they could still get called away from lung function surveillance. Another challenge to overcome, particularly in the surveillance program's early years, was difficulty communicating with firefighters when they were not on-site at the fire station - e.g., on annual or sick leave. Many were unaware of the number of opportunities for lung function testing throughout the surveillance study.

'In hindsight, I'm thinking I can't believe I didn't sort of go to many as I could, if that's the case or whether I just wasn't aware of them' (ID2)

Participation was much more difficult for those located in regional centres. Firefighters in regional locations would not commute to the metropolitan testing sites and so only attended surveillance when the service was provided in their area.

'Probably thought, well, I'm not driving to Adelaide just to do a lung function test because it's a four-hour round trip for me' (ID3)

The challenges encountered with lung function surveillance were not thought to deter metropolitan firefighters from participating.

Test acceptability

Firefighters were unsure what to expect on their first surveillance test occasion. Some felt that the spirometry test was unusual and presented some minor difficulties and discomforts but not to such extremes as discouraging participation.

'But it's a confronting exercise, actually, doing it, that breathe and blowing out, you think you got nothing left, but you got to keep blowing' (ID2)

Some felt a little performance anxiety, and others expressed enjoyment and anticipation towards learning their results. Other participants felt that there was nothing stressful about the testing and that it was just a part of being a firefighter.

'Was it 13 - 14 years it's been going on, so, for me, it was pretty much just a part of being in the job, ... it was fine, I think it's good' (ID15)

Theme two: The Perceived Value of Surveillance

Personal efficacy and control

Many firefighters felt it was important to monitor their health and welfare, particularly in a role that required good health and fitness. Participating in lung function surveillance provided them with a benchmark they could use if problems developed in the future. It also allowed them to monitor if their lung function changed over time.

'I like the idea of knowing how my lungs are going, the longer I'm in the job, just to see if there's any deterioration' (ID10)

Most were aware of how their lung function tracked and understood the expected decline in absolute lung function with age. Some felt that their lung function results reflected their fitness level and were motivated to improve their fitness based on a lower result. Participating in the lung function surveillance program provided firefighters with a method of monitoring their health, which promoted peace of mind and confidence in some. In others, it provided validation of good work health and safety practices.

'That was really good, especially once you get a couple of them, you can compare them over the years, and it gives you a bit of peace of mind, so no, that was really good' (ID7)

'If I hadn't had it, I wouldn't have had that validation that I was doing things right and wearing air sets not just when there was a lot of smoke around, but even a mild amount of smoke' (ID5)

A few reported that the surveillance allowed them to follow up on poor results with a health professional.

'I probably might not have even been diagnosed with the problem that I've got if it hadn't been for this regime' (ID2)

For Review Only

In some firefighters, lung function surveillance did not change their safety attitudes and practices, whilst others suggested that it provided a focus/reminder to protect their lungs when on the job.

'Probably on a basic level, I'm just maybe more mindful of what I breathe in, when I breathe it in, how long I breathe it in and wearing masks and air sets probably more regularly and for longer periods, rather than taking them off too quickly, like I used to probably' (ID10)

There was the opinion expressed that some firefighters, particularly smokers, may not have wanted to participate as they did not wish to know if they had poor lung health.

Social support

Participation in the lung function surveillance program was widely accepted, and firefighters felt free to participate or not participate without associated stigma. According to the firefighters interviewed, personal choice was respected, and if you wanted to attend, peers and the organisation made every effort to enable participation.

'There was no right or wrong; it's just if you want to do it, this is for you; if you don't want to do it, then that's, you know, perfectly fine' (ID4)

Most discussions regarding lung function results appeared related to friendly competition between crew members. Some also discussed the testing with their family members.

'There were a number of my peers participating in it at about the same time, so it was more of a competitive thing, to see who has the largest lung capacity' (ID8)

Management support and workplace environment

The firefighters appreciated the voluntary nature of lung function surveillance, and responses suggested that personal choice to participate was respected at both the peer and management level.

'I think it's the way it's being done, not in a heavy-handed way, is really, really good for the service, you know it's not like you have to do this, but giving people opportunities' (ID11)

There was a feeling that providing the program indicated that the organisation was serious about firefighter health. Those who held supervisory responsibility described that it was important to take an interest in surveillance and to encourage protection from the occupational hazards associated with firefighting.

I think (it) show(s) that the organisation is serious about the health of its people' (ID7)

Interviewees provided positive feedback about management support to enable participation. Still, they suggested that some may not have taken part due to distrust of how the fire service would use the surveillance data and the motivations behind providing the program.

'So there generally is an underlying stigma of any sort of data collection in the service, with people being a little bit paranoid or sceptical of how that could be potentially used against people in the future' (ID7)

Whole of Profession

Participation in the surveillance study was motivated not only by personal health interests but also by a whole of profession perspective. Individuals reflected that by participating, they were contributing information that would benefit the firefighter profession and may be influential in improving fire services and their ability to monitor occupational hazards. They were interested to see if the data indicated deterioration in lung function potentially attributed to firefighting or if current safe work practices were appropriate.

'So, we need evidence that what we're doing is not working or what we're doing is working. So, I think that if at the end of your study, everyone's lungs are as they should be for our age and our fitness level and everything else, then the system's working, and we should carry on with what we're doing, but if we're getting worse, we need to rethink how we how we do respiratory protection' (ID12)

Theme 3: Contribution of Surveillance to Health

Perception of risk

Interviewees acknowledged the inherent hazards of their day-to-day role as a firefighter, citing risks to lung health, including inhalation of fumes, fibres and the by-products of combustion. Breathing apparatus were routinely used, but there was a perception that this could not eliminate all exposure.

'One of the big things is that we are often exposed to smoke, and while we do have breathing apparatus, it's not always possible or practical to have breathing apparatus on' (ID9)

'We've got exhaust fans in the engine room, but you know you can still sort of taste the diesel in the air at times' (ID3)

The majority of those interviewed felt there was an increased risk to their lung health the longer they worked in the fire service. This led to the belief that lung function surveillance was important.

'So much more to be worried about as far as toxic vapours and fumes from combustibles, and you know we do more in the hazardous materials and substances area now as well.... always a concern about what cumulative effects you've had over a long period of time....' (ID14)

An alternative perspective was that lung function surveillance is unimportant *'because we have the control measures for managing our lungs' (ID1).*

Relevance in the context of total health

Whilst lung health surveillance was perceived as having significant value, firefighters stated that other aspects of health and wellbeing were also important to monitor. Aspects of health that were of concern and potential targets for monitoring included mental health, cancer, and sleep disturbance. Given the judgement required to keep colleagues, the general public and property safe, drug and alcohol monitoring was also suggested.

'It would be hard to sort of put one higher than the other because to me, at all things being equal' (ID8)

'If there was some sort of testing for cancers, that would be a number one on my hit parade' (ID5)

Relevance to workability and fitness

General health and fitness were valuable to the firefighters we interviewed and were perceived as essential for safely undertaking firefighter duties. The lack of ongoing health and fitness assessment surprised many firefighters, who compared the requirement for evaluation to the armed forces and when playing amateur sports.

'There is no fitness assessment or health assessment that's ongoing. I believe they are two things that should happen. Both for the public but also for our own safety that each person who is doing the job as an active firefighter is able to do so safely and is able to carry out the functions that would allow them to rescue a colleague, should they become injured or trapped' (ID9)

Many expressed that such assessments should be undertaken but also acknowledged there were difficulties associated with using fitness assessment in the fire service. Problems included how the service accommodated the broad age range of firefighters, those with experience that work smarter rather than harder, and remediation of those who were found to have significantly reduced fitness or health problems that were incompatible with their fire service role.

'What I've also found with the older guys in the job is, it's like any job once you build up experience, like in the younger days you really need all the strength and fitness to get through the job, the older guys, who have the knowledge and experience they work smarter' (ID7)

Firefighters felt that the fire service was progressing in encouraging health and fitness by providing good fitness facilities and implementing a voluntary Wellness Program that provided health checks and highlighted health issues.

Future value

Firefighters who participated in the interviews valued the continuation of the lung function surveillance program.

'But I think it should be a regular thing and particularly for me in my situation as I'm on the older end of the things, I think it's more important as we get older' (ID12)

'The firefighters coming into the job today, they probably won't have the benefit of what I've had through my career' (ID8)

'From a personal viewpoint to I would like to continue to monitor my own lung function and see how I'm tracking' (ID9)

It was suggested that the surveillance program could continue in its current form as a research program. However, this is only valuable if the outcomes are made available, and action on those outcomes is taken if indicated.

'Well, it's all good to keep doing this research, but if you're giving findings and they're not doing anything with it, well, you know what's the point' (ID3)

An alternative recommendation was to incorporate voluntary spirometry testing into the Wellness Program provided by the SAMFS. Firefighters felt strongly that spirometry testing should be done at the beginning of their careers and had differing views on how often it should be repeated.

DISCUSSION:

Voluntary lung function surveillance provided by the RFMS-SAMFS study was widely accepted and had value for firefighters in domains further reaching than the study's original main research aim of investigating longitudinal lung function decline. We identified through this analysis both practical and psychosocial facilitators and barriers to participation. We highlighted the difficulties of implementation in an organisation that provides an emergency response with an unpredictable workload across a wide geographic area and identified ways the study had successfully navigated these.

Health surveillance must be applied appropriately within the workplace based on contemporary evidence and ethically balanced against unwelcome intrusion into personal health(Gochfeld, 1992; Roossien *et al.*, 2021). The current evidence for the long-term decline in urban firefighter lung function is unclear(Slattery *et al.*, 2018; Mathias *et al.*, 2020; Pendergrast *et al.*, 2022), and mandatory lung function surveillance, such as is required in the mineral mines and quarry industries(Resources Safety & Health Queensland, 2021), may not be appropriate. Despite the equivocal evidence of lung function decline in firefighters and improvements in control measures, most of the firefighters interviewed in this study and in the New Jersey Firefighter Health Survey(Maloney *et al.*, 2021) believe there were unavoidable, chronic, low-level exposures to harmful substances that led to an underlying concern for their health. SAMFS firefighters welcomed the opportunity to have a voluntary, high-quality lung function testing

service available to them, but without individual results being available to their employer, which met with some expressed concern about potential risks to individuals' ongoing employment.

In addition to monitoring personal lung health, this study revealed that the lung function surveillance program provided some antecedent factors related to improving firefighter wellbeing(Danna and Griffin, 1999; Kling *et al.*, 2022). Lung function surveillance allowed for personal control by its voluntary nature and the ability to act on poor results. It reduced anxiety caused by concern for health and validated good personal practices. There was social support and interaction, be that by the friendly competition between peers or the acceptance of everyone's right to decide if they would participate. Fire service management was seen as facilitating the program, showing commitment to their employee's health and safety. Finally, participation in the surveillance program provided a sense of belonging to a team that would increase the body of evidence on firefighter lung health. Given the low prevalence of mental wellbeing and high prevalence of psychological distress in fire and rescue services(Kyron *et al.*, 2022), these unforeseen benefits need to be considered alongside the actual and perceived risk to lung health when determining the utility of lung health surveillance within a fire service workplace health and safety program.

Strengths and limitations

This study included South Australian urban firefighters who participated in an observational longitudinal research project to monitor lung function. Whilst we sought to enrol a diverse range of participants, recruitment may have favoured those with a positive view of the surveillance. In contrast, those with a negative or indifferent view would have reduced motivation for participation. Expressions of interest from regional and female study participants were also low, limiting the generalisability of study findings in these groups.

Despite this, our sampling strategy successfully created maximum variation in the chosen characteristics providing a rich information source.

Conclusion

Understanding the broader value of lung function surveillance and its barriers and facilitators to those participating in the program is important when considering future workplace health and safety policies. Participation in the lung function surveillance program provided in the RFMS-SAMFS study was well received by firefighters of differing seniority, age, and length of service. Firefighters related that lung function surveillance added value to the fire service workplace health and safety program by providing baseline health data, detecting adverse health and allowing for medical intervention, providing peace of mind and feedback on good

work practices, motivation to utilise control measures and, finally, providing data to assist with global knowledge. Overall, the firefighters in this study valued their opportunity to participate in the RFMS-SAMFS study and expressed the wish for the ongoing provision of voluntary lung function testing in the future.

DECLARATIONS:

Conflict of interest:

The authors have no conflicts of interest to declare.

Funding:

Cathy Pendergrast's research is funded by a scholarship from the South Australian Metropolitan Fire service and the Australian Government Research Training Program

Ethics approval:

Approval was obtained from the Human Research Ethics Committee of University of South Australia (Project no. 0000032662). The procedures used in this study adhere to the tenets of the Declaration of Helsinki.

Consent to participate:

Informed consent was obtained from all individual participants included in the study.

Data availability:

The data that support the findings of this study are held by the corresponding author. Availability of the study data is at the discretion of the SAMFS upon application.

Author contribution:

Catherine Pendergrast: Data curation (lead); Formal analysis (lead); Investigation (lead); Methodology (lead); Project administration (lead); Visualisation (lead); Writing – original draft (lead); Writing – review & editing (lead). **Terry Boyle:** Conceptualisation (equal); Data curation (supporting); Formal analysis (supporting); Investigation (supporting); Methodology (supporting); Project administration (supporting); Supervision (supporting); Writing – review & editing (supporting); **Alan J Crockett:** Conceptualisation (equal); Data curation (supporting); Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting); Writing – review & editing (supporting). **Roger Eston:** Funding acquisition (equal); Project administration (supporting); Resources (equal); Supervision (supporting); Writing – review & editing (supporting). **Kylie N Johnston:**

For Review Only

Conceptualisation (equal); Investigation (supporting); Project administration (supporting); Supervision (lead); Writing – review & editing (supporting).

For Review Only

REFERENCES:

Bradshaw, C., Atkinson, S. and Doody, O. (2017) 'Employing a Qualitative Description Approach in Health Care Research', *Global Qualitative Nursing Research*, 4, pp. 1–8. Available at: https://doi.org/10.1177/2333393617742282.

Cheung, S.S., Petersen, S.R. and McLellan, T.M. (2010) 'Physiological strain and countermeasures with firefighting', *Scandinavian Journal of Medicine and Science in Sports*, 20(SUPPL. 3), pp. 103–116. Available at: https://doi.org/10.1111/j.1600-0838.2010.01215.x.

Danna, K. and Griffin, R.W. (1999) 'Health and well-being in the workplace: A review and synthesis of the literature', *Journal of Management*, 25(3), pp. 357–384. Available at: https://doi.org/10.1177/014920639902500305.

Gochfeld, M. (1992) 'Medical surveillance and screening in the workplace: Complementary preventive strategies', *Environmental Research*, 59(1), pp. 67–80. Available at: https://doi.org/10.1016/S0013-9351(05)80226-9.

Grawitch, M.J., Ledford, G.E., Ballard, D.W. and Barber, L.K. (2009) 'Leading the Healthy Workforce: the Integral Role of Employee Involvement', *Consulting Psychology Journal*, 61(2), pp. 122–135. Available at: https://doi.org/10.1037/a0015288.

Hunt, A.P., Stewart, I.B. and Billing, D.C. (2019) 'Indices of physiological strain for firefighters of the Australian Defence Forces', *Journal of Occupational and Environmental Hygiene*, 16(11), pp. 727–734. Available at: https://doi.org/10.1080/15459624.2019.1666211.

Kling, H.E., Maldonado, L., St George, S.M., Brannan, D., Murphy, L.A., Schaefer Solle, N., Kobetz, E.N. and Caban-Martinez, A.J. (2022) 'Firefighter Well-Being Defined and Operationalized at the Organizational and Worker Level', *Journal of Occupational & Environmental Medicine*, 64(11), pp. e736–e743. Available at: https://doi.org/10.1097/jom.0000000000002685.

Koh, D. and Aw, T.C. (2003) 'Surveillance in occupational health', *Occupational and Environmental Medicine*, pp. 705–710. Available at: https://doi.org/10.1136/oem.60.9.705.

Kyron, M.J., Rikkers, W., Bartlett, J., Renehan, E., Hafekost, K., Baigent, M., Cunneen, R.

and Lawrence, D. (2022) 'Mental health and wellbeing of Australian police and emergency services employees', *Archives of Environmental and Occupational Health*, 77(4), pp. 282–292. Available at: https://doi.org/10.1080/19338244.2021.1893631.

Maloney, S.R., Udasin, I.G., Black, T.M., Shah, N.N., Steinberg, M.B., Pratt, M.E. and Graber, J.M. (2021) 'Perceived Health Risks Among Firefighters; The New Jersey Firefighter Health Survey', *Journal of occupational and environmental medicine*, 63(4), pp. 317–321. Available at: https://doi.org/10.1097/JOM.0000000000002125.

Malterud, K., Siersma, V.D. and Guassora, A.D. (2016) 'Sample Size in Qualitative Interview Studies: Guided by Information Power', *Qualitative Health Research*, 26(13), pp. 1753–1760. Available at: https://doi.org/10.1177/1049732315617444.

Mathias, K.C., Graham, E., Stewart, D. and Smith, D.L. (2020) 'Decreased Pulmonary Function Over 5 Years in US Firefighters', *Journal of occupational and environmental medicine*, 62(10), pp. 816–819. Available at: https://doi.org/10.1097/JOM.0000000000001944.

Nazari, G., MacDermid, J. and Cramm, H. (2020) 'Prevalence of musculoskeletal disorders among Canadian firefighters: A systematic review and meta-analysis', *Journal of Military, Veteran and Family Health*. University of Toronto Press, pp. 83–97. Available at: https://doi.org/10.3138/jmvfh-2019-0024.

NIOSH (2008) *Essential Elements of Effective Workplace Programs and Policies for Improving Worker Health and Wellbeing*. Available at: https://www.cdc.gov/niosh/twh/essentials.html.

Paterson, J.L., Aisbett, B. and Ferguson, S.A. (2016) 'Sound the alarm: Health and safety risks associated with alarm response for salaried and retained metropolitan firefighters', *Safety Science*, 82, pp. 174–181. Available at: https://doi.org/10.1016/j.ssci.2015.09.024.

Paterson, J.L., Aisbett, B., Kovac, K. and Ferguson, S.A. (2022) 'Informal management of health and safety risks associated with alarm response by Australian firefighters', *Ergonomics*, 65(2), pp. 233–241. Available at: https://doi.org/10.1080/00140139.2021.1967460.

Pendergrast, C., Boyle, T., Crockett, A.J., Eston, R. and Johnston, K.N. (2022) 'Longitudinal

lung function in urban firefighters: A group-based multi-trajectory modelling approach', *Respirology*, 27. Available at: https://doi.org/10.1111/resp.14382.

Resources Safety & Health Queensland (2021) *QGL04 - Guideline for respiratory health surveillance of workers in Queensland mineral mines and quarries Mining and Quarrying Safety and Health Act 1999*. Available at: https://www.business.qld.gov.au/industries/mining-energy-water/resources/safety-health/mining/legislation-standards/recognised-standards.

Roossien, C.C., de Jong, M., Bonvanie, A.M. and Maeckelberghe, E.L.M. (2021) 'Ethics in Design and Implementation of Technologies for Workplace Health Promotion: A Call for Discussion', *Frontiers in Digital Health*, 3(August), pp. 1–14. Available at: https://doi.org/10.3389/fdgth.2021.644539.

Safe Work Australia (2018) *Work health and safety consultation , cooperation and coordination Code of Practice, Code of Practice*. Available at: www.swa.gov.au (Accessed: 11 September 2022).

Schermer, T., Malbon, W., Newbury, W., Holton, C., Smith, M., Morgan, M. and Crockett, A. (2010) 'Spirometry and impulse oscillometry (IOS) for detection of respiratory abnormalities in metropolitan firefighters', *Respirology*, 15(6), pp. 975–985. Available at: https://doi.org/10.1111/j.1440-1843.2010.01809.x.

Schermer, T.R., Malbon, W., Adams, R., Morgan, M., Smith, M. and Crockett, A.J. (2013) 'Change in lung function over time in male metropolitan firefighters and general population controls: A 3-year follow-up study', *Journal of Occupational Health*, 55(4), pp. 267–275. Available at: https://doi.org/10.1539/joh.12-0189-OA.

Schermer, T.R., Malbon, W., Morgan, M., Smith, M. and Crockett, A.J. (2014) 'Chronic respiratory conditions in a cohort of metropolitan fire-fighters: associations with occupational exposure and quality of life', *International Archives of Occupational and Environmental Health*, 87(8), pp. 919–928. Available at: https://doi.org/10.1007/s00420-014-0935-8.

Shain, M. and Kramer, D.M. (2004) 'Health promotion in the workplace: Framing the concept; reviewing the evidence', *Occupational and Environmental Medicine*, 61(7), pp. 643–648. Available at: https://doi.org/10.1136/oem.2004.013193.

Slattery, F., Johnston, K., Paquet, C., Bennett, H. and Crockett, A. (2018) 'The long-term rate

of change in lung function in urban professional firefighters: A systematic review', *BMC Pulmonary Medicine*, 18(1), pp. 1–20. Available at: https://doi.org/10.1186/s12890-018-0711-8.

Stanojevic, S., Kaminsky, D.A., Miller, M., Thompson, B., Aliverti, A., Barjaktarevic, I., Cooper, B.G., Culver, B., Derom, E., Hall, G.L., Hallstrand, T.S., Leuppi, J.D., MacIntyre, N., McCormack, M., Rosenfeld, M. and Swenson, E.R. (2021) 'ERS/ATS technical standard on interpretive strategies for routine lung function tests', *European Respiratory Journal*, p. 2101499. Available at: https://doi.org/10.1183/13993003.01499-2021.

Tong, A., Sainsbury, P. and Craig, J. (2007) 'Consolidated criteria for reporting qualitative research (COREQ): A 32-item checklist for interviews and focus groups', *International Journal for Quality in Health Care*, 19(6), pp. 349–357. Available at: https://doi.org/10.1093/intqhc/mzm042.

Wagner, S.L., White, N., Buys, N., Carey, M.G., Corneil, W., Fyfe, T., Matthews, L.R., Randall, C., Regehr, C., White, M., Alden, L.E., Krutop, E., Fraess-phillips, A. and Fleischmann, M.H. (2021) 'Systematic Review of Mental Health Symptoms in Firefighters Exposed to Routine Duty-Related Critical Incidents', *Traumatology*, 27(3), pp. 285–302. Available at: https://doi.org/10.1037/trm0000275.supp.

Walker, A., Argus, C., Driller, M. and Rattray, B. (2015) 'Repeat work bouts increase thermal strain for Australian firefighters working in the heat', *International Journal of Occupational and Environmental Health*, 21(4), pp. 285–293. Available at: https://doi.org/10.1179/2049396715Y.0000000006.

For Review Only

Appendix 3.3 Interview Guide

Participant Name:	
1st Wave:	
No of Waves:	
Location:	
YOS:	

Prior to Meeting

1. Send meeting request email	
2. Check consent form on Lime Survey	
3. Check settings on Zoom Meeting – Waiting room, record to cloud at onset	
4. Join meeting	

Beginning of Meeting

1. Introductions	
2. Reminder that meeting is being recorded	
3. Confirm your name and date of birth so that we can link your interview to the surveillance study data	
4. Thank you for signing the consent form – do you have any questions for me before we begin the interview?	
5. I'm just going to read out a standard introduction to the interview before I ask you some questions	

Aim: This study aims to **explore** your **experience** and **attitudes** to the **value**, **benefits** of, and **barriers to participating** in a longitudinal lung health surveillance program.

Standard Introduction

We are interested in your experience of being in the lung function study and your views about the value, and any possible positive or negative aspects of monitoring firefighter lung health. There are no right or wrong answers, we are interested in your thoughts and opinions. Your responses are confidential and will not be reported using any features that will identify you personally. During the interview I may take some notes and we will be video recording to make sure I don't miss anything. Remember that you do not need to answer anything that makes you uncomfortable and can end the interview at any time.

Interview Questions

1. Did you participate in the Lung Function Surveillance study? If not, why not?	
2. Can you tell me about what interested you in first participating in the Lung Function Surveillance study when you heard about it?	
3. Did you continue to participate after your first time? Why / Why not?	

4. What kind of things made it difficult to participate? Was there a stigma associated with participating?	
5. What kind of things made participation easier? (or convenient)	
6. Is there anything that could have been done differently, in your opinion?	
7. How did you feel about having your lung function tested the first time (and after that)?	
8. There are many aspects of firefighting that can affect health and wellbeing. Do you feel that monitoring your lung function is important? Why / Why not?	
9. Are there other things that are monitored that are less important to you?	
10. Are there other things that are not monitored that are more important?	
11. How did participating in the study change/influence your understanding of and attitude to respiratory health? Both individually and in general	
12. Are you aware if your lung function changed over the time you were having it measured? What factors (at work, in life) do you think might have contributed to it changing/improving/decreasing over time?	
13. Did you discuss your lung function results with anyone (colleagues, family, health professional)?	
14. What would you like to see happen into the future with the lung function surveillance program?	
15. Do you have an extra comments you would like to add regarding your participation in the study?	

End of Meeting

1. Next you will receive an email that will have a written transcript of this interview and I would be grateful if you could read it and adjust anything that you feel does not represent you correctly	
2. Once we have analysed the data we will send you a summary report of our findings. This report will also be sent to the SAMFS	
3. Finally, I would really like to thank you for taking the time to be a part of this study.	

General Comments – general mood, openness, agenda
