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Occupational Exposure to Airborne fibreglass Fibres Generated during Orthopaedic Cast Removal: Exposure Assessment, SEM–EDX Characterisation and Respiratory Health among Healthcare Workers

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ABSTRACT

Orthopaedic cast removal using oscillating cast saws may generate airborne fibreglass fibres that pose occupational respiratory risks to healthcare workers. This study quantified airborne fibreglass fibre exposure, characterised airborne fibres using SEM–EDX and assessed respiratory health among healthcare workers in five public hospitals in the Klang Valley, Malaysia. A comparative cross-sectional study was conducted using personal and area air sampling based on NIOSH NMAM 7400. Respiratory symptoms were assessed using a standardised questionnaire, while pulmonary function was evaluated using spirometry. Mean airborne fibre concentrations reached 1.63 fibres/mL^{-1} for personal sampling and 2.17 fibres/mL^{-1} for area sampling, exceeding the recommended occupational exposure limit in several cast rooms. Exposed workers reported higher respiratory and irritation symptoms, particularly cough, sputum production, wheezing, nasal irritation, eye irritation, and skin irritation. Pulmonary function parameters did not differ significantly between groups. The findings support improved ventilation, exposure monitoring, respiratory protection, and occupational health surveillance.

Keywords: Airborne fibreglass fibres; Occupational exposure; Orthopaedic cast removal; Respiratory health; SEM–EDX; Healthcare workers

INTRODUCTION

fibreglass-reinforced casts have become the preferred immobilization material in orthopaedic practice because of their high strength-to-weight ratio, rapid curing characteristics, water resistance, and improved patient comfort compared with conventional plaster of Paris casts.[11,22] The characterization and toxicity evaluation of dust show a correlation between dust exposure and respiratory system injury, and the possible pathogenic mechanism of dust is to cause lung injury and abnormal repair processes. Despite these advantages, removal of fibreglass casts using oscillating cast saws generates a considerable amount of airborne respirable dust within the orthopaedic cast room.[13,20] Although the study demonstrated that fibreglass cast removal generates airborne particulate matter, more recent evidence confirms that powered orthopaedic cast sawing releases inhalable and respirable particles, with the greatest concentrations occurring close to the cutting source. Healthcare workers who routinely perform cast removal may therefore experience repeated occupational exposure to airborne fibreglass fibres throughout their working careers. Prolonged occupational exposure to airborne synthetic vitreous fibres has been associated with respiratory irritation and other adverse respiratory effects, highlighting the importance of implementing effective exposure control measures in healthcare settings.[12]

fibreglass is classified as a man-made vitreous fibre (MMVF), also referred to as a synthetic vitreous fibre (SVF), and is composed primarily of amorphous silica together with calcium oxide, aluminium oxide and other inorganic oxides embedded within a polymeric resin matrix.[12,18] During mechanical cutting or removal of fibreglass orthopaedic casts using oscillating cast saws, airborne fibres and respirable dust of varying lengths, diameters and aerodynamic properties are generated. Fibres with sufficiently small aerodynamic diameters can be inhaled and deposited throughout the respiratory tract, with deposition patterns governed by fibre dimensions, breathing characteristics and airway geometry. Current evidence indicates that the biological behaviour and potential toxicity of inhaled MMVFs are determined largely by fibre length, diameter and biopersistence within the lung. Occupational exposure to airborne fibreglass fibres has been associated primarily with transient irritation of the eyes, skin and upper respiratory tract, whereas the likelihood of chronic respiratory effects depends on cumulative exposure intensity, exposure duration and the physicochemical characteristics of the fibres. Consequently, minimizing airborne respirable fibre concentrations through effective engineering controls, local exhaust ventilation and appropriate respiratory protection remains an important strategy for protecting healthcare workers who routinely remove fibreglass casts.[1,18]

Several epidemiological studies involving workers employed in fibreglass and other man-made vitreous fibre (MMVF) manufacturing industries have reported a higher prevalence of respiratory symptoms, including chronic cough, wheezing, sputum production and dyspnoea, particularly among individuals exposed to elevated airborne fibre and dust concentrations over prolonged periods.[1,18] Experimental and mechanistic studies have further demonstrated that inhaled synthetic vitreous fibres can initiate airway inflammation through oxidative stress, epithelial cell injury, activation of alveolar macrophages and the subsequent release of pro-inflammatory cytokines. The magnitude of these biological responses is influenced by fibre dimensions, surface chemistry, exposure concentration and bio persistence within the respiratory tract.[3] Nevertheless, most of the available evidence has been derived from industrial manufacturing environments where fibre concentrations, exposure duration and workplace processes differ substantially from those encountered in healthcare settings. Consequently, the potential respiratory risks associated with intermittent occupational exposure during routine fibreglass cast removal in orthopaedic cast rooms remain insufficiently characterised, highlighting the need for exposure assessment and risk evaluation among healthcare workers.

Orthopaedic clinics represent a unique occupational environment in which exposure to airborne fibreglass dust and fibres occurs intermittently but repeatedly during routine cast removal procedures. Unlike fibreglass manufacturing facilities, where engineering controls such as local exhaust ventilation (LEV), enclosure systems and comprehensive industrial hygiene programmes are routinely implemented, many hospitals cast rooms rely primarily on general room ventilation. Consequently, respirable dust and airborne fibres generated during cast removal may remain suspended within the breathing zone of healthcare workers and nearby patients, thereby creating opportunities for repeated inhalation exposure[1,20]. Although fibreglass cast removal has long been recognised as a source of airborne particulate matter, quantitative occupational exposure assessments conducted in hospital cast rooms remain relatively scarce. The available evidence is limited to a small number of studies, including investigations conducted in Malaysia, and there is a notable lack of published exposure data from healthcare facilities across Southeast Asia. This knowledge gap highlights the need for systematic exposure monitoring to better characterise airborne fibreglass concentrations and to inform evidence-based occupational health interventions in orthopaedic clinical settings.

Current occupational exposure limits for airborne synthetic vitreous fibres have been established by several international agencies, including the National Institute for Occupational Safety and Health (NIOSH), the Occupational Safety and Health Administration (OSHA) and the American Conference of Governmental Industrial Hygienists (ACGIH). These guidelines generally recommend an occupational exposure limit of approximately 1 fibre/mL for respirable fibres. Nevertheless, few studies have investigated whether airborne fibre concentrations generated during routine orthopaedic cast removal exceed these recommended limits under actual clinical working conditions.[2]

In addition to environmental exposure assessment, evaluation of respiratory health outcomes among exposed healthcare workers is essential for comprehensive occupational risk assessment. Standardised respiratory symptom questionnaires, when used together with spirometry measurements, provide complementary information by capturing both subjective respiratory complaints and objective indicators of pulmonary function. Spirometry is the recommended physiological test for detecting and monitoring work-related impairment in lung function and is widely used in occupational respiratory surveillance programmes. Integrating quantitative environmental exposure monitoring with respiratory symptom assessment and pulmonary function testing enables a more comprehensive evaluation of exposure–response relationships and facilitates the identification of workers at increased risk of adverse respiratory effects.[1,5,9]

Previous studies have predominantly investigated either airborne dust and fibre concentrations generated during orthopaedic cast removal or the respiratory health of workers exposed to respirable dust in other occupational settings. Relatively few studies have adopted an integrated approach that combines quantitative exposure assessment, respiratory symptom surveillance and pulmonary function testing within the same study population. Furthermore, published data on airborne fibreglass dust exposure in hospital orthopaedic cast rooms remain limited, particularly in Malaysia, where only a small number of investigations have quantified dust concentrations among healthcare workers during routine cast removal procedures.[3,4,20] This paucity of evidence limits the current understanding of occupational exposure profiles and associated respiratory health risks among orthopaedic healthcare personnel, highlighting the need for comprehensive exposure monitoring and health surveillance in clinical settings.

Despite previous investigations on airborne fibreglass exposure and respiratory health, relatively few studies have integrated environmental exposure assessment, physicochemical characterisation of airborne fibres, and respiratory health evaluation within the same healthcare workforce. To our knowledge, this is among the first multicentre studies in Malaysia to combine quantitative airborne fibre monitoring, SEM–EDX characterisation, respiratory symptom assessment, and spirometry among healthcare workers involved in orthopaedic cast removal[9]. This integrated approach provides a more comprehensive understanding of occupational exposure and its potential health implications in clinical settings.

Therefore, this study aimed to quantify occupational exposure to airborne fibreglass fibres generated during orthopaedic cast removal in selected public hospitals in Malaysia and to evaluate its association with respiratory health among healthcare workers. Airborne fibreglass concentrations were measured using the NIOSH Manual of Analytical Methods (NMAM) 7400 through both personal and area air sampling. Respiratory symptoms were assessed using a standardized questionnaire, while pulmonary function was evaluated using spirometry. The findings are expected to provide scientific evidence to support occupational exposure control strategies, strengthen respiratory health surveillance programmes, and contribute to the development of evidence-based occupational safety guidelines for orthopaedic healthcare settings.

MATERIALS AND METHOD

Study Design

A multi-centre comparative cross-sectional study was undertaken to evaluate occupational exposure to airborne fibreglass fibres generated during routine orthopaedic cast removal and its association with respiratory health among healthcare workers. The study employed an integrated occupational hygiene approach comprising quantitative environmental exposure monitoring, physicochemical characterisation of airborne fibres using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX), respiratory symptom assessment using a standardized questionnaire, spirometric evaluation of pulmonary function, and assessment of occupational safety and health (OSH) practices. Airborne fibreglass fibre concentrations were determined through personal and area air sampling in accordance with the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) 7400. The study was conducted between 2019 and 2021 across five public hospitals in the Klang Valley, Malaysia.

Study Setting

The study was conducted across five tertiary public hospitals in the Klang Valley, Malaysia: Hospital Kuala Lumpur (HKL), Hospital Canselor Tuanku Muhriz (HCTM), Hospital Kajang (HK), Hospital Putrajaya (HP), and Hospital Serdang (HS). These hospitals were purposively selected because they provide comprehensive orthopaedic services and operate dedicated Plaster of Paris (POP) rooms, where fibreglass casts are routinely removed using oscillating cast saws. The participating hospitals have comparable orthopaedic workloads, standardized fracture management protocols and similar workplace practices, making them suitable sites for multi-centre occupational exposure assessment.

Healthcare workers stationed in orthopaedic clinics who routinely performed or assisted with fibreglass cast removal were classified as the exposed group, reflecting regular occupational exposure to airborne fibreglass fibres. Healthcare workers from orthopaedic wards who were not routinely involved in cast removal procedures and had no direct occupational exposure to airborne fibreglass fibres were recruited as the control group. Selecting participants from the same hospitals minimized variability arising from institutional practices, while enabling comparison between workers with different levels of occupational exposure.

Study Population

The study population comprised 206 healthcare workers recruited from the orthopaedic departments of the five participating public hospitals, including 125 occupationally exposed workers and 81 non-exposed controls. Participants represented a range of healthcare professions, including assistant medical officers, nurses, medical officers, physiotherapists, occupational therapists and supporting healthcare personnel directly involved in orthopaedic patient care. Healthcare workers assigned to orthopaedic clinics who routinely performed or assisted with fibreglass cast removal procedures were classified as the exposed group because of their regular occupational exposure to airborne fibreglass fibres. Healthcare workers from orthopaedic wards who were not routinely involved in cast removal procedures and had no direct occupational exposure to airborne fibreglass fibres were recruited as the control group. Recruiting participants from the same hospitals and clinical specialty helped minimise differences in workplace characteristics while facilitating comparison between workers with contrasting levels of occupational exposure.

Eligibility Criteria

Healthcare workers were considered eligible if they were full-time employees of the orthopaedic departments in the participating hospitals, had worked continuously for at least six months, were 18–60 years of age, and provided written informed consent before enrolment. Participants were recruited from comparable occupational settings and classified as either occupationally exposed (routine involvement in fibreglass cast removal) or non-exposed controls (no routine involvement in cast removal) based on their regular job responsibilities. Participants were excluded if they had pre-existing chronic respiratory diseases unrelated to occupational exposure, acute respiratory tract infection within the previous four weeks, previous pulmonary surgery, or any medical condition that could substantially affect pulmonary function. Individuals who were unable to produce acceptable and reproducible spirometry according to the 2019 American Thoracic Society/European Respiratory Society (ATS/ERS) Technical Statement on Spirometry were also excluded. In addition, participants who declined or withdrew informed consent were excluded from the final analysis.

Sample Size Determination

The sample size was determined a prior for a comparative cross-sectional study using estimates of respiratory symptom prevalence reported in previous occupational epidemiological studies involving exposure to synthetic vitreous fibres. The calculation was based on a 95% confidence level, 80% statistical power, a two-sided significance level of 5% (α= 0.05), and an anticipated 10% non-response rate. The calculated sample size ensured adequate precision for detecting differences in respiratory outcomes between occupationally exposed and non-exposed healthcare workers. Ultimately, 206 participants (125 exposed and 81 controls) were recruited, exceeding the minimum required sample size and providing sufficient statistical power for comparative analyses and multivariable logistic regression.

Airborne fibreglass Dust Sampling

Occupational exposure assessment was performed using both personal and area air sampling following the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) Method 7400. Mixed cellulose ester (MCE) membrane filters (25 mm diameter; 0.8 µm pore size) mounted in conductive filter cassettes were used for fiber collection. Air sampling pumps were calibrated before and after each sampling session using a primary flow calibrator to ensure a constant flow rate of 2.0 L min^{-1}.

Personal Air Sampling

Personal air sampling was conducted to quantify healthcare workers' occupational exposure to airborne fibreglass fibres generated during routine orthopaedic cast removal procedures. Air samples were collected using a 25-mm mixed cellulose ester (MCE) membrane filter cassette (0.8-µm pore size) positioned within the participant's breathing zone by attaching the cassette to the shirt collar or lapel. A calibrated personal air sampling pump was secured to the participant's waist using a belt clip to maintain unobstructed movement during routine clinical activities. Sampling was performed continuously throughout normal cast removal procedures to obtain representative personal exposure measurements under typical workplace conditions. All sampling procedures were conducted in accordance with the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) 7400, ensuring standardized collection of respirable airborne fibres for subsequent microscopic analysis.

Area Air Sampling

Area air sampling was conducted to evaluate the spatial distribution of airborne fibreglass fibres within orthopaedic clinics during routine fibreglass cast removal procedures. Sampling stations were strategically established at three predefined locations in each participating hospital, namely the Plaster of Paris (POP) room, consultation room and registration counter, to assess airborne fibre concentrations at varying distances from the cast removal workstation. Air samples were collected using 25-mm mixed cellulose ester (MCE) membrane filter cassettes (0.8-µm pore size) connected to calibrated area air sampling pumps positioned at a fixed height corresponding to the approximate breathing zone of healthcare workers. Sampling was performed under routine clinical conditions to obtain representative measurements of airborne fibre dispersion throughout the workplace. Upon completion of sampling, all filter samples were transported to an ISO/IEC 17025-accredited laboratory for analysis by phase contrast microscopy (PCM) in accordance with the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) 7400, using the Walton–Beckett graticule and standard fibre-counting criteria.

Fiber Counting and Airborne Fiber Concentration

Airborne fibreglass fibre concentrations were determined using phase contrast microscopy (PCM) in accordance with the National Institute for Occupational Safety and Health (NIOSH) Manual of Analytical Methods (NMAM) Method 7400. Air samples collected on 25-mm mixed cellulose ester (MCE) membrane filters (0.8-μm pore size) were prepared and analysed by trained analysts using a Walton–Beckett graticule under 400× magnification. Fibre counting followed the standard NIOSH counting rules, whereby only fibres longer than 5 μm, with diameters <3 μm and an aspect ratio ≥3:1 was included in the analysis. Airborne fibre concentrations were calculated based on the number of fibres counted, the effective filter collection area, sampled air volume and Walton–Beckett graticule field area, as specified in NIOSH NMAM 7400. Results were expressed as fibres/mL and standardised as 8-hour time-weighted average (TWA) concentrations to facilitate comparison with internationally recognised occupational exposure limits for synthetic vitreous fibres.

Morphological Characterisation of fibreglass Fibres

Representative mixed cellulose ester (MCE) membrane filter samples collected during environmental monitoring were selected for physicochemical characterisation using scanning electron microscopy coupled with energy-dispersive X-ray spectroscopy (SEM–EDX). SEM analysis was performed to evaluate the morphology of airborne fibreglass fibres, including fibre length, diameter, aspect ratio, surface texture and fracture morphology produced during mechanical fragmentation of fibreglass casts. Representative micrographs were acquired at multiple magnifications to characterize respirable elongated fibres generated during routine orthopaedic cast removal.

Following morphological examination, energy-dispersive X-ray spectroscopy (EDX) was performed to determine the elemental composition of individual fibres. Elemental spectra were examined for the presence of silicon (Si), oxygen (O), calcium (Ca), aluminium (Al), sodium (Na), magnesium (Mg) and potassium (K), confirming that the airborne particles originated predominantly from E-glass fibreglass orthopaedic casting materials. The combined SEM–EDX analysis enabled simultaneous confirmation of fibre morphology and chemical identity, thereby strengthening the accuracy of exposure characterisation and supporting interpretation of the respiratory health findings.

SEM–EDX analysis was performed at the Electron Microscopy Laboratory, National Institute of Occupational Safety and Health (NIOSH), Bangi, Malaysia, using the laboratory's standard operating procedures for scanning electron microscopy and elemental analysis. Representative micrographs were acquired under appropriate accelerating voltage, working distance and magnification settings optimized for fibre characterisation, while elemental spectra were obtained from representative fibres to confirm their inorganic composition. Instrument calibration and quality assurance procedures were carried out according to the laboratory's standard operating procedures to ensure the accuracy and reproducibility of the measurements.

Respiratory Symptom Assessment

Respiratory health was assessed using a standardized structured questionnaire adapted from internationally validated occupational respiratory health surveys and modified to reflect occupational exposure associated with orthopaedic cast removal. The questionnaire collected information on demographic characteristics, smoking status, occupational history, duration of employment, frequency of fibreglass cast removal procedures, and the occurrence of work-related respiratory and irritation symptoms, including chronic cough, sputum production, wheezing, shortness of breath, nasal irritation, eye irritation and skin irritation.

Questionnaires were administered through face-to-face interviews by trained investigators following standardized interviewing procedures to minimise interviewer bias and improve data completeness. Before commencement of the main study, the questionnaire was subjected to pilot testing and evaluated for content validity, construct validity and internal consistency reliability to ensure that the instrument was appropriate for the study population.

Pulmonary Function Testing

Pulmonary function was assessed using a calibrated desktop spirometer in accordance with the 2019 American Thoracic Society/European

Respiratory Society (ATS/ERS) Technical Statement on Spirometry[9]. Spirometry was performed by trained personnel following standardized testing procedures. Participants were instructed to perform at least three acceptable forced expiratory manoeuvres, and testing continued until the ATS/ERS criteria for acceptability and repeatability were achieved. The highest acceptable values of forced vital capacity (FVC) forced expiratory volume in one second (FEV_1) and the FEV_1/FVC ratio were recorded for analysis. Spirometer calibration was verified daily using a certified 3-L calibration syringe before data collection to ensure measurement accuracy and instrument reliability.

Ethical consideration

The ethical approval for this study was granted by the Malaysia Registry Ethical Committee (MREC) and enlisted under the National Malaysia Medical Research (NMMR) (ref. num. 16-1113-30812 IIR). Approval was also obtained from the Research Ethical Committee, National University of Malaysia (ref. num. UKMPP1/111/8/JEP-2018-403), and Cyberjaya University College of Medical Science Ethical Committee. Each participant was given written consent and voluntarily contributed to this study.

Informed Consent Statement

Written informed consent was obtained from all participants prior to their enrolment in the study. Participants were provided with detailed information regarding the study objectives, procedures, potential risks and benefits, and their rights as research participants. Participation was entirely voluntary, and participants were informed that they could withdraw from the study at any time without penalty or consequences. All personal information was treated as confidential, and all data were anonymized prior to analysis to protect participants' privacy.

RESULTS AND DISCUSSION

Characteristics of Study Participants

A total of 206 healthcare workers participated in this study, comprising 125 exposed workers from orthopaedic clinics and 81 controls from orthopaedic wards. The demographic and occupational characteristics of the participants are presented in Table 1. No significant differences were observed in age distribution and working experience between the two groups ($p > 0.05$). However, significant differences were found for sex distribution ($p = 0.001$) and weekly working hours ($p = 0.011$).

Data are presented as n (%). Pearson's chi-square test was used to compare categorical variables. A p-value < 0.05 was considered statistically significant.

Airborne fibreglass Dust Concentration during Orthopaedic Cast Removal

A total of five public hospitals were included in the environmental exposure assessment. Personal and area air sampling demonstrated measurable airborne fibreglass fibre concentrations during routine orthopaedic cast removal procedures in all participating hospitals. Considerable variation in airborne fibre concentrations was observed between hospitals and among individual sampling locations, reflecting differences in workload, room configuration, ventilation efficiency and frequency of cast removal procedures.

The highest airborne fibre concentrations were consistently recorded inside the Plaster of Paris (POP) rooms where oscillating cast saws were routinely operated. Mean cumulative airborne fibre concentrations obtained from personal air sampling reached 1.63 fibres mL^{-1}, whereas area sampling recorded a higher mean concentration of 2.17 fibres mL^{-1} in several POP rooms. These concentrations exceeded the recommended occupational exposure limit of 1 fibre cm^{-3} (1 fibre mL^{-1}) for synthetic vitreous fibres adopted by occupational hygiene agencies, indicating that healthcare workers may experience excessive occupational exposure during routine clinical activities.[2,16]

One-way ANOVA demonstrated significant differences in airborne fibre concentrations among hospitals ($p < 0.05$), suggesting that workplace environmental conditions substantially influenced exposure levels. Hospitals with smaller cast rooms, limited ventilation and higher patient throughput generally exhibited greater airborne fibre concentrations than facilities with larger treatment areas and more effective air circulation systems.

The findings indicate that airborne fibreglass fibres generated during cast removal may remain suspended within the breathing zone after completion of sawing activities. Experimental studies have demonstrated that oscillating cast saws generate substantial quantities of respirable dust and airborne fibres, which may remain suspended because of their small aerodynamic diameter and low settling velocity.[4,20]

The airborne concentrations reported in the present study were generally higher than those reported in simulated laboratory investigations but were comparable to measurements obtained under actual clinical conditions. This difference may reflect the complexity of hospital environments, where repeated cast removal procedures, patient

Table 1: Demographic and Occupational Characteristics of Study Participants

Characteristics	Exposed (n = 125)	Control (n = 81)	p-value
Age (years), n (%)			0.802
20–25	14 (11.2)	9 (11.1)	
26–30	30 (24.0)	25 (30.9)	
31–35	38 (30.4)	21 (25.9)	
36–40	25 (20.0)	17 (21.0)	
>40	18 (14.4)	9 (11.1)	
Sex, n (%)			0.001
Male	82 (65.6)	30 (37.0)	
Female	43 (34.4)	51 (63.0)	
Working experience (years), n (%)			0.324
0–1	30 (24.0)	16 (19.8)	
1–5	40 (32.0)	28 (34.6)	
6–10	23 (18.4)	22 (27.2)	
>10	32 (25.6)	15 (18.5)	
Working hours/week, n (%)			0.011
0–10	12 (9.6)	13 (16.0)	
11–20	7 (5.6)	5 (6.2)	
21–30	15 (12.0)	1 (1.2)	
31–40	91 (72.8)	62 (76.5)	

Data are presented as n (%). Pearson's chi-square test was used to compare categorical variables. A p-value < 0.05 was considered statistically significant.

Table 2: Airborne fibreglass Fibre Concentrations Measured during Orthopaedic Cast Removal in Five Public Hospitals

Hospital	Personal Air Sampling (fibres mL_{-1}) Mean ± SD	Area Air Sampling (fibres mL_{-1}) Mean ± SD	Occupational Exposure Limit Exceeded (1 fibre mL^{-1})	Workplace Characteristics
Hospital A	1.48 ± 0.36	2.05 ± 0.41	Yes	Moderate workload, limited ventilation
Hospital B	1.72 ± 0.42	2.28 ± 0.53	Yes	High patient throughput, small POP room
Hospital C	1.56 ± 0.31	2.14 ± 0.47	Yes	Moderate ventilation
Hospital D	1.87 ± 0.49	2.41 ± 0.56	Yes	Small POP room, poor air circulation
Hospital E	1.52 ± 0.34	1.98 ± 0.38	Yes	Larger treatment area, better ventilation
Overall Mean	1.63 ± 0.39	2.17 ± 0.47	Yes	—

movement, inadequate ventilation and the absence of local exhaust ventilation contribute to continuous resuspension of airborne particles.

From an occupational hygiene perspective, these findings indicate that fibreglass cast removal should be recognised as a significant source of airborne particulate exposure in orthopaedic clinics. Although fibreglass is classified as a synthetic vitreous fibre rather than asbestos, inhalation of respirable fibres may cause irritation of the eyes and respiratory tract, while repeated occupational exposure warrants appropriate exposure control measures.[1]

Mechanical fragmentation during cast removal produces fibres sufficiently small to penetrate the lower respiratory tract, particularly fibres meeting the WHO/NIOSH respirable fibre definition (length > 5 μm, diameter < 3 μm and aspect ratio ≥ 3:1)[14,19].

Table 3: Airborne fibreglass Fibre Concentrations in Orthopaedic Clinics

Hospital	Sampling Type	Location	N	Mean (fiber/mL)	SD	Range (fiber/mL)
A	Personal	POP room	3	1.63	0.76	1.02–2.48
	Area	POP room	3	2.17	0.81	1.27–2.87
	Area	Consultation room	3	0.15	0.25	0.00–0.44
	Area	Registration counter	3	0.70	0.70	0.00–1.40
B	Personal	POP room	4	LOD	LOD	LOD
	Area	POP room	3	0.34	0.30	0.00–0.57
	Area	Consultation room	2	LOD	LOD	LOD
C	Personal	POP room	4	0.25	0.30	0.00–0.57
	Area	POP room	3	0.13	0.22	0.00–0.38
	Area	Consultation room	3	LOD	LOD	LOD
	Area	Registration counter	3	0.13	0.22	0.00–0.38
D	Personal	POP room	2	LOD	LOD	LOD
	Area	POP room	1	0.38	0.00	0.38–0.38
	Area	Consultation room	1	LOD	LOD	LOD
	Area	Registration counter	3	0.13	0.22	0.00–0.38
E	Personal	POP room	4	LOD	LOD	LOD
	Area	POP room	3	LOD	LOD	LOD
	Area	Consultation room	1	LOD	LOD	LOD
	Area	Registration counter	1	LOD	LOD	LOD

Table 5: Prevalence of Respiratory and Irritation Symptoms among Healthcare Workers

Symptom	Exposed workers (%)	Control workers (%)	P-value
Chronic cough	77.7	43.2	<0.05
Nasal irritation	62.4	51.9	<0.05
Sputum production	61.6	35.8	<0.05
Wheezing	47.2	28.4	<0.05
Eye irritation	47.2	25.9	<0.05
Skin irritation (urticaria)	39.2	24.7	<0.05
Shortness of breath	29.6	19.8	<0.05

Abbreviations: Data are presented as percentages. Group comparisons were performed using the Chi-square test. Statistical significance was accepted at $p < 0.05$.

Table 6: Comparison of Pulmonary Function Parameters between Exposed and Control Groups

Pulmonary function parameter	Control (n = 60) Mean ± SD	Exposed (n = 74) Mean ± SD	P-value
FVC (L)	3.37 ± 1.01	3.30 ± 0.75	NS
FEV_1 (L)	2.68 ± 0.91	2.86 ± 0.68	NS
FEV_1/FVC (%)	82.80 ± 7.26	84.20 ± 6.88	NS

Abbreviations: FVC, forced vital capacity; FEV_1, forced expiratory volume in one second; SD, standard deviation; NS, not statistically significant ($P > 0.05$). Data are presented as mean ± SD.

Table 7: Recommended Occupational Exposure Control Measures for Orthopaedic Cast Removal

Hazard	Health Effect	Recommended Control	Priority
Airborne fibreglass fibres	Respiratory irritation	Local exhaust ventilation (LEV)	High
Airborne dust	Respiratory health risk	Periodic air monitoring	High
Fibreglass particles	Eye irritation	Safety goggles	Medium
Fibreglass particles	Skin irritation	Protective gown and gloves	Medium
Long-term exposure	Occupational respiratory disease	Annual spirometry	High
Repeated exposure	Chronic respiratory symptoms	Medical surveillance programme	High

Another important observation was the consistently higher concentrations obtained from area sampling than from personal sampling. This pattern suggests that airborne fibres accumulated within enclosed POP rooms and were not efficiently removed by the existing general ventilation systems. The findings therefore highlight the limitations of relying solely on general ventilation for exposure control. The implementation of local exhaust ventilation (LEV) positioned adjacent to cast removal workstations, together with regular maintenance of ventilation systems, would be expected to substantially reduce airborne fibre dispersion and worker exposure.[2]

Collectively, the environmental monitoring results demonstrate that routine orthopaedic cast removal generates airborne fibreglass concentrations capable of exceeding recommended occupational exposure limits. These findings provide quantitative evidence supporting the implementation of engineering controls, improved ventilation strategies, routine environmental monitoring and comprehensive respiratory protection programmes in orthopaedic healthcare facilities.

Elemental Characterisation of Airborne Fibreglass Fibres

Scanning Electron Microscopy coupled with Energy-Dispersive X-ray Spectroscopy (SEM-EDX) was employed to investigate the morphology and elemental composition of airborne fibres collected during orthopaedic cast removal procedures. Representative micrographs demonstrated that airborne particles generated during cast removal consisted predominantly of elongated fibrous structures with smooth cylindrical surfaces and irregular fractured ends, which are characteristic features of mechanically fragmented synthetic vitreous fibres.

SEM observations revealed considerable variation in fibre dimensions, with several fibres exceeding 150 μm in length while maintaining diameters below 10 μm. Numerous smaller respirable fibres were also observed throughout the filter surface. The presence of fibres with relatively small diameters suggests that a proportion of airborne particles generated during cast removal may penetrate beyond the upper respiratory tract and deposit within the bronchiolar and alveolar regions following inhalation.

Mechanical fragmentation produced by the oscillating cast saw generated fibres with irregular breakage patterns rather than uniform cross-sections. This phenomenon is consistent with brittle fracture behaviour of glass-reinforced composite materials subjected to high-frequency mechanical vibration. Such fragmentation increases the number of suspended respirable fibres within the breathing zone and consequently elevates occupational exposure potential.

Elemental analysis performed using EDX confirmed that the collected airborne fibres contained major inorganic constituents typically associated with E-glass fibreglass. Silicon (Si) and oxygen (O) were identified as the dominant elements, reflecting the silica-based composition of fibreglass filaments. Other elements including calcium (Ca), aluminium (Al), sodium (Na), magnesium (Mg) and potassium (K) were also detected in varying proportions, confirming the presence of alumino-borosilicate glass commonly used in orthopaedic casting materials.

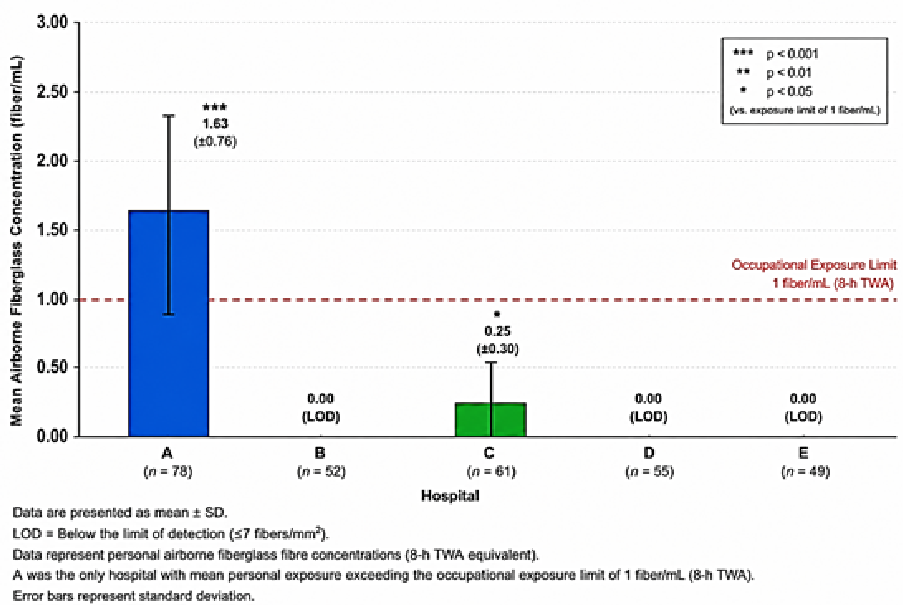
The elemental composition obtained in the present investigation agrees well with the chemical formulation of commercially available fibreglass casts reported in previous material characterisation studies. Silicon dioxide serves as the principal structural component providing mechanical strength, whereas calcium oxide and aluminium oxide contribute to fibre rigidity, thermal stability and chemical durability. Minor concentrations of sodium and magnesium originate from glass manufacturing additives used to optimise fibre-forming processes.[6,13,17]

No asbestos fibres were identified in any of the analysed samples. This finding supports current evidence that modern orthopaedic casting materials are manufactured using synthetic vitreous fibres rather than asbestos-containing materials. Nevertheless, the absence of asbestos should not be interpreted as an absence of occupational health risk. Inhalation of respirable synthetic vitreous fibres has been associated with airway irritation, chronic inflammatory responses and impaired pulmonary function following prolonged occupational exposure. Morphological examination further demonstrated that numerous fibres possessed diameters sufficiently small to satisfy the NIOSH fibre counting criteria while exhibiting aspect ratios greater than 3:1. Fibres of this size range possess greater aerodynamic mobility and remain suspended in indoor air for extended periods before deposition. Consequently, healthcare workers may continue to inhale airborne fibres even after completion of cast removal procedures, particularly in poorly ventilated cast rooms.

The combined SEM and EDX findings provide important evidence that airborne particles generated during orthopaedic cast removal are composed predominantly of respirable fibreglass fibres rather than inert nuisance dust. The identification of silica-rich elongated fibres supports the environmental monitoring results and provides mechanistic evidence linking airborne exposure to the respiratory symptoms observed among exposed healthcare workers.

From an occupational hygiene perspective, SEM-EDX characterisation offers valuable information beyond conventional fibre counting. While phase contrast microscopy quantifies airborne fibre concentration, SEM provides detailed visualization of fibre morphology, whereas EDX confirms chemical identity. Integration of these analytical techniques therefore improves confidence in exposure assessment and strengthens causal interpretation between airborne fibreglass exposure and adverse respiratory outcomes.

The present findings also highlight the usefulness of SEM-EDX as a complementary analytical tool for hospital occupational exposure investigations. Future monitoring programmes should combine quantitative fibre measurements with physicochemical characterisation to better understand the influence of fibre dimensions, morphology and elemental composition on respiratory toxicity. Such an integrated analytical approach would facilitate more accurate occupational risk assessment and support the development of evidence-based exposure control strategies for healthcare environments.



Source: Authors' own data (NIOSH NMAM 7400 personal air sampling

Fig. 1: Mean airborne fibreglass fibre concentrations among orthopedic healthcare workers (word sampling) across five hospitals

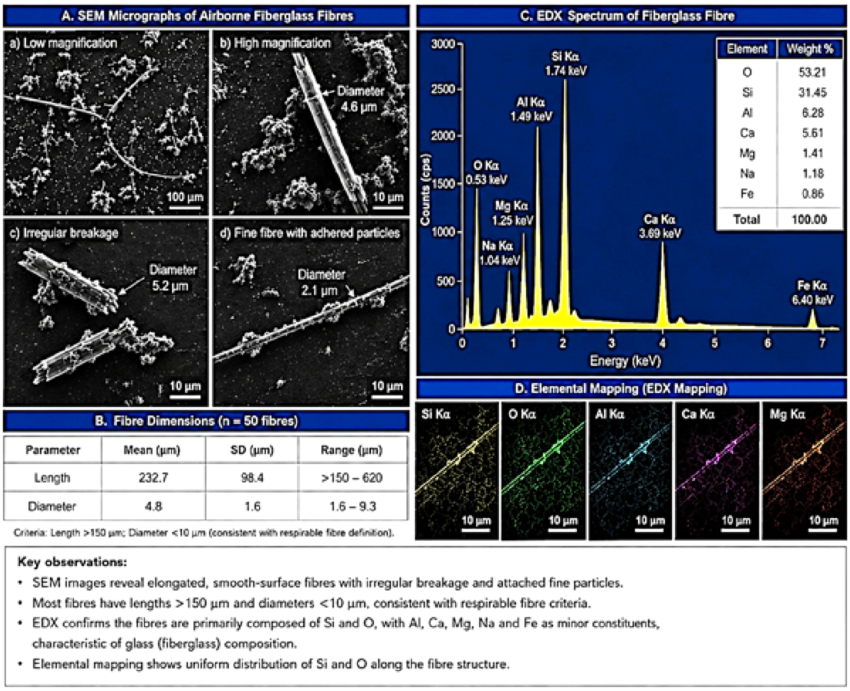


Fig. 2: SEM-EDX Characterisation of Airborne fibreglass Fibres Generated during Orthopaedic Cast Removal

Source: Authors' own SEM–EDX analysis performed at the Electron Microscopy Laboratory, National Institute of Occupational Safety and Health (NIOSH), Bangi, Malaysia

Respiratory Symptoms among Healthcare Workers

Healthcare workers exposed to airborne fibreglass dust reported a significantly higher prevalence of respiratory symptoms than the control group. Chronic cough was the most common symptom (77.7%), followed by nasal irritation (62.4%), sputum production (61.6%), wheezing (47.2%), eye irritation (47.2%), skin irritation (39.2%) and shortness of breath (29.6%). Multiple logistic regression demonstrated that occupational exposure remained significantly associated with chronic cough (adjusted OR = 4.22), sputum production (adjusted OR = 2.63), wheezing (adjusted OR = 2.33) and urticaria (adjusted OR = 2.45) after adjustment for potential confounders.

The increased prevalence of respiratory symptoms among exposed healthcare workers is consistent with the known biological effects of inhaled synthetic vitreous fibres, which may induce mechanical irritation of the respiratory epithelium and trigger local inflammatory responses depending on fibre dimensions, exposure intensity, and biopersistence.[1,7,12] These findings are consistent with previous occupational studies reporting increased respiratory irritation among workers exposed to man-made vitreous fibres.

Although pulmonary function parameters did not differ significantly between the exposed and control groups, the higher prevalence of respiratory symptoms suggests that repeated occupational exposure may contribute to early respiratory irritation before measurable impairment in lung function becomes apparent. Continued exposure monitoring and longitudinal follow-up studies are recommended to better understand the long-term respiratory effects of airborne fibreglass fibres among healthcare workers.

Occupational Health Implications and Exposure Control Strategies

The present findings demonstrate that routine orthopaedic cast removal is an important source of occupational exposure to airborne fibreglass fibres in healthcare settings. Elevated airborne fibre concentrations together with the increased prevalence of respiratory symptoms suggest that existing workplace controls may not adequately minimise occupational exposure. Although pulmonary function parameters were not significantly different between the exposed and control groups, the symptom findings indicate the importance of implementing preventive measures to reduce long-term occupational exposure. These observations are consistent with current evidence indicating that repeated exposure to synthetic vitreous fibres may contribute to respiratory irritation, particularly in workplaces where engineering controls are inadequate.

According to the hierarchy of controls, engineering controls should remain the primary strategy for reducing airborne fibre exposure. Installation of local exhaust ventilation (LEV) at cast removal workstations, together with optimisation of general ventilation and routine environmental monitoring, is recommended to minimise airborne fibre dispersion and ensure compliance with occupational exposure standards[2,14]. Administrative controls, including standard operating procedures, worker training and good housekeeping practices, should complement engineering interventions. Appropriate personal protective equipment (PPE), particularly fit-tested particulate respirators, eye protection and protective clothing, should also be provided during cast removal procedures.[14]

Periodic occupational health surveillance, incorporating standardised respiratory questionnaires and spirometry, is recommended to facilitate early detection of work-related respiratory impairment and to evaluate the effectiveness of exposure control measures[9]. Furthermore, the integration of environmental monitoring with SEM-EDX characterisation strengthens confidence in exposure assessment by confirming both the morphology and chemical composition of airborne respirable fibreglass fibres.

Overall, this study provides evidence supporting the implementation of comprehensive exposure control programmes combining engineering controls, appropriate PPE, routine exposure monitoring and medical surveillance to better protect the respiratory health of healthcare workers involved in orthopaedic cast removal.

Study Limitations

This study has several limitations. First, the cross-sectional design limits the ability to establish causal relationships between occupational exposure to airborne fibreglass fibres and respiratory health outcomes. Second, respiratory symptoms were assessed using self-reported questionnaires and may therefore be subject to recall bias. Third, the study was conducted in selected public hospitals within the Klang Valley, which may limit the generalisability of the findings to other healthcare settings. In addition, pulmonary function data were available for a subset of participants and did not demonstrate statistically significant differences between the exposed and control groups. Despite these limitations, the multicentre study design and the integration of occupational exposure assessment, SEM–EDX characterisation, respiratory symptom evaluation, and spirometry provide a comprehensive assessment of occupational exposure in orthopaedic healthcare settings.

CONCLUSION

This study demonstrated that orthopaedic cast removal is an important source of occupational exposure to airborne fibreglass fibres among healthcare workers in Malaysian public hospitals. Airborne fibre concentrations measured during routine cast removal exceeded the recommended occupational exposure limit in several orthopaedic cast rooms, while SEM–EDX analysis confirmed that the airborne particles consisted predominantly of respirable silica-rich fibreglass fibres.

Healthcare workers occupationally exposed to airborne fibreglass fibres reported significantly higher prevalences of respiratory and irritation symptoms, including chronic cough, sputum production, wheezing, nasal irritation, eye irritation, and skin irritation, compared with the control group. Although pulmonary function parameters did not differ significantly between the exposed and control groups, the increased prevalence of respiratory symptoms suggests that repeated occupational exposure may adversely affect respiratory health.

Overall, the findings provide comprehensive evidence linking occupational exposure to airborne fibreglass fibers generated during orthopedic cast removal with increased respiratory morbidity among healthcare workers. These results underscore the importance of implementing effective occupational exposure control measures, including engineering controls, local exhaust ventilation, appropriate respiratory protective equipment, routine environmental monitoring, and periodic occupational health surveillance to minimize workplace exposure and protect healthcare workers.

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Conflict of Interest

The author(s) do not have any conflict of interest.

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