

EVALUATING FACE MASK EFFICIENCY ON CHILDREN AND ADULTS

by

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A thesis
presented to the University of Waterloo
in fulfillment of the
thesis requirement for the degree of
Master of Applied Science
in
Mechanical Engineering

Waterloo, Ontario, Canada, 2025

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Author's Declarations

This thesis consists of material all of which I authored or co-authored: see Statement of Contributions included in the thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Statement of Contributions

I, Hicham El Khayri, was the sole author of all chapters with the exception of Chapters 1–3 and 7 as well as Appendices A–C, which were written under the supervision of Dr. Sean Peterson and Dr. Serhiy Yarusevych. Chapters 4–6 were adapted from manuscripts that are published, under review, or are being prepared for publication as follows.

- 1) Chapter 4: El Khayri, H. *et al.* 2025 Study of the inward protection efficiency of various facial masks. *Aerosol Science and Technology* 1–12. [DOI](#).
- 2) Chapter 5: El Khayri, H., Peterson, S. D., & Yarusevych, S. Source control efficiency of child masking. Manuscript under preparation
- 3) Chapter 6: El Khayri, H., Peterson, S. D., & Yarusevych, S. Protective efficiency of child masking. Manuscript under preparation

Funding was provided by the Natural Sciences and Engineering Research Council of Canada.

Abstract

Small infectious aerosols have been a major vector for the spread of diseases such as COVID-19 and influenza. During the recent global pandemic, masking played a key role in reducing airborne transmission, although significant variability has been noted in the ability of different mask types to limit pathogen-laden aerosol dispersion and inhalation. Moreover, there remain significant gaps in the literature regarding mask performance for children. The aim of this thesis is to characterize mask inward protection efficiency for both children and adults, and source control efficiency for children in the 0.2 μm to 1 μm particle size range.

An approach based on the conservation of mass guided the experimental methodology used to estimate mask filtration characteristics. For all tested masks, the material filtration efficiency was measured to be at or near 100%, whereas fitted filtration efficiencies for both source control and personal protection were significantly lower. This disparity underscores the highly degrading effects of leakage from gaps at the mask-face interface.

Inward protection efficiency of N95, KN95, and surgical masks donned regularly and using the tie and tuck method were estimated on a medium NIOSH adult head form. The tested N95 barrier provided the greatest protection, followed by the KN95 respirator, while the surgical masks offered the least protection. Use of the tie and tuck for surgical masks method yielded only a small, statistically insignificant improvement in inward protection compared to regularly worn variants. Incorporating results from broader literature, mean inward protection efficiency ranges of [67.9%, 100%] and [12.5%, 79.6%] were determined for the N95 and regularly worn surgical masks, respectively.

Both inward protection and apparent filtration efficiencies of adult, modified adult, and child variants of the KN95, CA-N95, and surgical mask as well as the N95 respirator, were estimated on a child manikin. Results further underscore the critical importance of proper fit to mask performance. Child-sized respirators provided higher source control and personal protection compared to other barriers tested. In contrast, the adult-sized surgical mask, which exhibited a loose fit on the child manikin, demonstrated poor performance in both metrics due to the highly degrading effects of leakage. Overall, whenever both variants are available, adult-sized masks demonstrate markedly reduced fitted efficiencies on the child manikin relative to child-sized variants, attributed to larger gaps at the mask-face interface. Flow visualization of air exhaled through the tested barriers qualitatively corroborated these findings, revealing substantially reduced leakage for child-sized variants compared to adult-sized equivalents.

Given the increased sensitivity of children to mask breathing resistance, pressure differentials measured across masks donned on the child head form provided relative indicators of breathability. Results demonstrated that masks with similar filtration efficiency can exhibit significant differences in breathability. For example, the child-sized CA-N95 achieved equal or greater fitted filtration efficiency while consistently maintaining lower pressure drops compared to the child KN95. In fact, KN95 respirators showed differential pressures greater than or equal to those of all other tested masks. For a given mask type,

better fit was associated with higher differential pressures. However, across different mask designs, higher filtration efficiency did not necessarily compromise breathability.

Acknowledgements

I would like to begin by thanking my supervisors, Dr. Sean D. Peterson and Dr. Serhiy Yarusevych, for their guidance and encouragement throughout this project. The growth I have experienced during this program would not have been possible without your dedication to high-quality work.

Thank you, Supun, for laying the groundwork for this project. I am truly grateful for your support and patience during my first months as a graduate student. I would also like to acknowledge my colleagues at FMRL, Nianhua, Connor, Deep, Johan, and Nikhilesh, for your friendship and constant willingness to help over the past two years.

To Antonio, Jordan, Julia, Shalini, the roommates, and all the friends who have made my university experience a blast, thank you for the countless memorable moments that made this journey so enjoyable.

Finally, thank you to my mother, sister, and all my family for motivating me to keep striving toward my goals and for pushing me to persevere through every challenge.

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List of Abbreviations

AFE	Apparent Filtration Efficiency
ASTM	American Society for Testing and Materials
BFE	Bacterial Filtration Efficiency
COVID-19	Coronavirus Disease 2019
CSA	Canadian Standards Association
CV	Control Volume
FFR	Filtering Facepiece Respirator
IPE	Inward Protection Efficiency
MFE	Material Filtration Efficiency
NIOSH	National Institute for Occupational Safety and Health
OSHA	Occupational Safety and Health Administration
PPE	Personal Protective Equipment
WHO	World Health Organization

List of Symbols

Accents and Subscripts

Example Description

$\bar{a}$	averaged quantity
a_M	quantity under masked condition
a_{NM}	quantity under unmasked condition
a_{ss}	quantity in steady state particle conditions
a_1	quantity relating to control volume ‘1’
a_2	quantity relating to control volume ‘2’

Dimensionless Quantities

Symbol	Description	Definition
Stk	Stokes Number	$d_p^2 \rho_p u_b C_c / 18 \nu_a \rho_a d_b$
C_c	Slip Correction Factor	$1 + (2.52 \Lambda / d_p^2)$

Roman Symbols

Symbol	Description	Units
A_{test}	mask test surface area	m^2
c	particle number concentration	particles m^{-3}
dc	differential particle number concentration	particles m^{-3}
d_b	breathing tube diameter	m
d_p	particle diameter	m
h_{exh}	exhalation rate	exhalation s^{-1}
h_{inh}	inhalation rate	inhalation s^{-1}
n_{leak}	number of particles leaking through mask gaps	particles
n_{mask}	number of particles going through mask material	particles
ΔP	pressure drop	Pa
Q_{in}	flow passing inwards the mask during inhalation	$L s^{-1}$

Q_{leak}	flow leaking through mask gaps	$L s^{-1}$
Q_{mask}	flow leaking going through mask material	$L s^{-1}$
Q_{out}	flow passing outwards the mask during exhalation	$L s^{-1}$
Q_{test}	flow rate used in material filtration efficiency testing	$L s^{-1}$
u_b	breath velocity out of or into breathing tube	$m s^{-1}$
u_f	mask face velocity in material filtration efficiency testing	$m s^{-1}$
V	volume	m^3
V_{exh}	exhalation volume	$m^3 \text{ exhalation}^{-1}$
V_{inh}	inhalation volume	$m^3 \text{ inhalation}^{-1}$

Greek Symbols

Symbol	Description	Units
ζ	particle leakage proportion through mask gaps	%
η_{AFE}	source control fitted mask filtration efficiency	%
$\eta_{diffusion}$	efficiency due to diffusion in material	%
$\eta_{electrostatic}$	efficiency due to electrostatic attraction in material	%
$\eta_{interception}$	efficiency due to interception in material	%
$\eta_{impaction}$	efficiency due impaction in material	%
η_{IPE}	personal protective fitted mask filtration efficiency	%
η_{MFE}	mask material filtration efficiency	%
ν_a	kinematic viscosity of air	$m^2 s^{-1}$
ρ_a	air density	$kg m^{-3}$
ρ_p	particle density	$kg m^{-3}$
Λ	mean free path of air	m

Chapter 1

Introduction

Aerosols are liquid or solid particles suspended in a gas, typically ranging in diameter from approximately $0.002\text{ }\mu\text{m}$ to $100\text{ }\mu\text{m}$ [1]. These particles can originate from numerous sources, including combustion byproducts and metered-dose inhalers. Those stemming from exhalatory activities, such as breathing, sneezing, coughing, and talking, represent a primary vector for the spread of pathogen-laden particles capable of transmitting diseases such as COVID-19 and influenza [2–6]. These particles are exhaled into the air where they can be inhaled by susceptible individuals, potentially causing infection. The hierarchy of hazard controls (Fig. 1.1) provides a framework to prioritize and implement strategies to manage airborne transmission of diseases [7–9].

The inverted pyramid outlines mitigation strategies from most effective at the top to the least effective at the bottom. Sehgal & Milton [9] applied this framework to the context of reducing the airborne transmission of diseases, including of COVID-19. The most effective strategy is hazard elimination, which involves removing exposure to airborne pathogen-laden aerosols through measures such as stay at home orders and quarantines [10–12]. Substitution entails encouraging behavioral changes to limit exposure to infectious particles, such as working from home or moving indoor activities outdoors [13, 14]. Engineering controls reduce exposure to pathogen-laden particles by increasing building ventilation and air filter installation [15–19]. Administrative controls involve measures such as mask and vaccination mandates and occupancy limits [20–22]. Finally, personal protective equipment (PPE) is the donning of protective gear to limit the inhalation of disease-carrying airborne aerosols [23].

Masking as a means to limit disease transmission has been practiced for more than a century, including during the influenza pandemic of the early 20th century [24]. Face masks function as wearable filtration devices that reduce both the inhalation and exhalation of potentially pathogen-carrying aerosols. These devices consist of a fibrous medium that captures particles as airflow passes through them. The fluid mechanics of mask performance

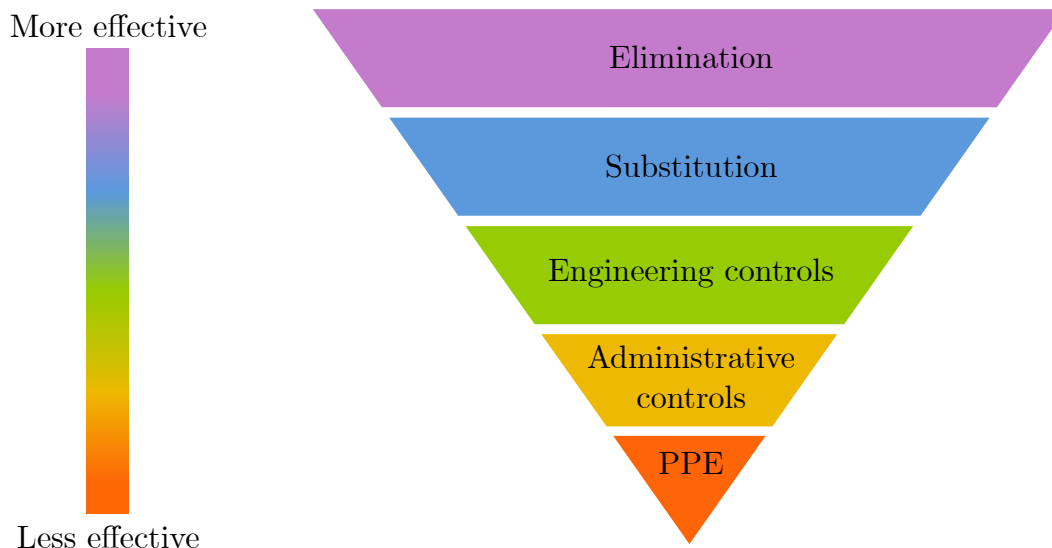


Figure 1.1: Hierarchy of hazard controls. Image adapted from NIOSH [8].

are inherently complex, encompassing scales from nanometers to meters [25]. The filtration efficiency of a mask against airborne particles depends on several factors, including particle size and velocity, the topology of the filter medium, and the quality of fit on the wearer [1, 25, 26].

Masking can be both an administrative control in the form of mask mandates, potentially helping to reduce the prevalence of aerosols in the ambient, and a form of personal protective equipment against inhalation of infectious particles. While in an ideal scenario the hazard would be eliminated, during times of pervasive disease spread, such as in the recent COVID-19 pandemic, masking becomes a critical tool for mitigating virus transmission [21, 23]. Lessons learned about masking during the pandemic remain valuable as outbreaks of illnesses like the flu, the common cold, and COVID-19, continue. Despite falling under the two categories which are the least effective for hazard control, widespread adoption of face masks was highly recommended by public health authorities both within Canada and abroad to reduce COVID-19 transmission [27, 28].

A study by An *et al.* [29] of measures taken by governments to combat the first wave of the COVID-19 pandemic suggests early adoption of mask mandates corresponded with the most immediate reduction in infection rates compared to other actions, such as domestic lockdowns and international travel bans. In the United States, where masking policies varied by state, studies from Huang *et al.* [30] and Lyu & Wehby [31] suggest lower transmission rates in jurisdictions with mask mandates. Similarly, in Ontario, mask mandates were associated in nearly a 20% reduction in weekly COVID-19 cases [32]. These findings highlight the importance of widespread masking to potentially reducing infection risk, particularly at a time when hospital resources were under significant strain [33–36].

Although PPE is lower than source control in the hazard hierarchy according to Fig. 1.1, it remains an important defence against transmissions of pathogens through the air [7, 9]. During the COVID-19 pandemic, protection from inhalation of infectious aerosols was especially crucial to healthcare workers and immuno-compromised individuals. However, surging demand led to widespread shortages of PPE at a time of critical need [37, 38], and the resulting unavailability was linked with increased risk of infection among healthcare workers [39–41]. Additionally, perceived lack of PPE supply was associated with declines in the psychological well-being of healthcare workers [42–44]. The combined effects of infection risk and increased work pressure placed a physical and mental strain on healthcare workers, contributing to increased time off work and overall stress on health services [45–47]. Lost productivity by health workers during such critical periods can lead to reduced quality and availability of care; challenges that could have been mitigated through proper preparedness, including but not limited to maintaining adequate PPE stocks.

In North America, the N95 respirator, regulated by the National Institute for Occupational Safety and Health (NIOSH), is regarded as the gold standard for respiratory protection against airborne transmission of disease. However, shortages during the pandemic prompted emergency use authorizations permitting the importation of the Chinese standard KN95 mask [48]. While how well the N95 mask protects an individual has been well documented in literature, only one study characterized KN95 masks, which became widespread in North America due to aforementioned PPE supply shortages earlier in the

pandemic [48, 49]. The protection offered by surgical masks has also been well studied, demonstrating noticeably less protection than the N95 largely attributed to poorer fit allowing air to bypass the mask entirely through gaps. During the pandemic, public health authorities recommended improving surgical mask fit by ‘tying’ the ear loops and ‘tucking’ the excess mask material [50]. Overall, previous studies on the protective efficiency of KN95 and the ‘tied-and-tucked’ surgical masks on adults remain limited, particularly in regards to particle-size characteristics.

Despite children typically presenting milder symptoms when infected with COVID-19 [51], they have also been observed to shed comparable viral loads as adults [52]. Moreover, public health agencies, such as the Public Health Agency of Canada [27] and the World Health Organization (WHO) [53] recommended masking children over the age of 5, especially in places where COVID-19 was spreading rapidly. Furthermore, several cohort studies were carried out during the pandemic linking mask mandates in schools with a reduction in COVID-19 transmission compared to ones with no mask mandate [54–56].

Although child masking is important, few studies have examined the source control [57, 58] and inward protection efficiency [26] of different facial masks worn on children. Due to significant differences in facial dimensions, masks designed for adults often fit poorly when donned on a child, leading to reduced performance [59]. This degradation likely varies by mask geometry and understanding these effects can guide recommendations for child masking. Overall, no present study has characterized and compared the fitted efficiency of both larger adult sized and smaller child sized masks when used by children.

1.1 Research Objective and Thesis Outline

During regular human breathing, particles are predominately generated with diameters below $10\mu\text{m}$ [6], with the majority concentrated in the sub-micrometer range [60, 61]. Considering the limitations understanding of face mask performance for filtering aerosols in this size regime, experiments were designed to address the following objectives:

- 1) Assess the protective efficiency of KN95 and tied and tucked surgical masks relative to N95 masks and regularly worn surgical face masks when worn by adults breathing normally.
- 2) Quantify the source control efficiency of child and adult sized surgical, CA-N95, KN95, and N95 masks when worn by children under typical breathing conditions.
- 3) Quantify the protective efficiency of child and adult sized surgical, CA-N95, KN95, and N95 masks when worn by children under typical breathing conditions.

The remainder of this thesis is organized as follows: Chapter 2 defines the three mask classifications, reviews current methods of testing mask performance, and describes the mechanics of facial coverings. Chapter 3 outlines the experimental methodology used to evaluate mask performance. Chapter 4 presents findings on the protective efficiency of

tested masks worn by adults. Chapters 5 and 6 examine the source control and protective efficiencies, respectively, of both adult sized and child sized masks donned on a pediatric head form under typical breathing conditions. Finally, Chapter 7 summarizes key findings and presents recommendations for future research on this topic.

Chapter 2

Background

2.1 Face Mask Classifications

In general, face masks worn for mitigating airborne transmission of diseases fall under three broad categories, shown in Fig. 2.1. Listed in typical order of increasing effectiveness these are: non-medical masks (Fig. 2.1a), surgical masks (Fig. 2.1b), and filtering facepiece respirators (FFR) (Fig. 2.1c) [62].

Non-medical masks are typically made from everyday fabrics [62, 63], and may be homemade or commercially produced, often outside of existing regulatory frameworks. In response to the COVID-19 pandemic, some standards were introduced for non-medical masks, such as the American ASTM F3502-21 [64] and European CWA 17553 [65]. However, use of these standards is voluntary and adoption by manufacturers is uncertain. Although non-medical masks typically have poorer material filtration [66, 67], they were recommended early in the pandemic for the public to preserve limited supplies of surgical masks and FFRs for healthcare and other frontline workers [68, 69]. Given the variability and lack of standardized performance among non-medical masks, the present work focuses on certified barriers, that is, face masks manufactured in accordance with recognized regulatory standards.

Surgical masks typically consist of three or four layers: an inner moisture-absorbing layer, an outer hydrophobic layer, and one or two middle particle filtration layers [63, 67]. Table 2.1 summarizes key properties of different standards governing surgical masks. These include bacterial filtration efficiency (BFE), measuring the material’s ability to remove bacterial particulates, material filtration efficiency (MFE), measuring the efficiency of the material in aerosol removal, and pressure drop associated with breathability by quantifying flow resistance across the mask material [19, 70, 71]. These metrics are assessed under sealed conditions, ensuring the test airflow passes exclusively through the mask material, thereby not accounting for the impact of leakage from gaps around the barrier when worn in practice. While ASTM level 2 and 3 masks have identical characteristics, as listed in Table 2.1, level 3 masks are more splash resistant to synthetic blood. The European EN 14683:2025 standard also includes splash resistance for some mask classes. This provides protection from penetration of liquid splashes through the mask but is less relevant to the

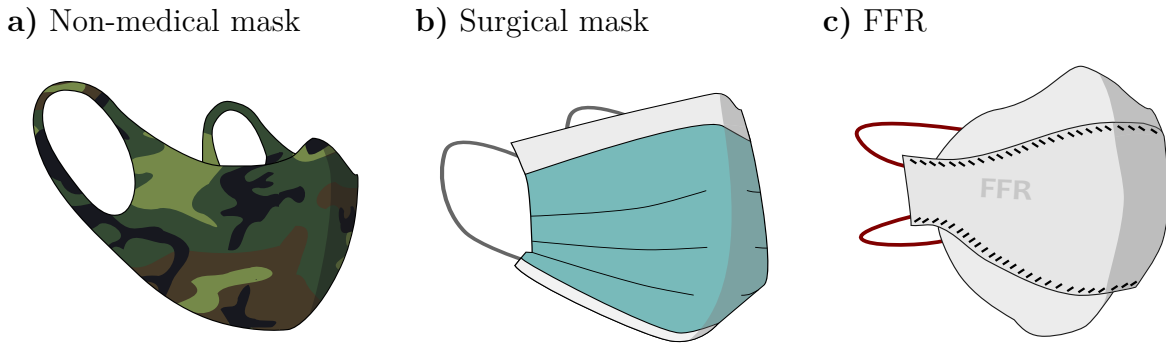


Figure 2.1: The classifications of face masks for mitigating airborne transmission of disease.

Table 2.1: Select parameters for standards of surgical masks.

Region	Standard	Class	BFE	MFE	Pressure drop
China	YY 0469-2023 [75]	-	$\geq 98\%$	$\geq 80\%$	$< 60 \text{ Pa cm}^{-2}$
Europe	EN 14683:2025 [76]	type I	$\geq 95\%$	-	$< 40 \text{ Pa cm}^{-2}$
		type II	$\geq 98\%$	-	$< 40 \text{ Pa cm}^{-2}$
		type IIR	$\geq 98\%$	-	$< 60 \text{ Pa cm}^{-2}$
United States	ASTM F2100-25 [77]	level 1	$\geq 95\%$	$\geq 95\%$	$< 49 \text{ Pa cm}^{-2}$
		level 2	$\geq 98\%$	$\geq 98\%$	$< 59 \text{ Pa cm}^{-2}$
		level 3	$\geq 98\%$	$\geq 98\%$	$< 59 \text{ Pa cm}^{-2}$

Table 2.2: Select parameters for standards of filtering facepiece respirator (FFR).

Region	Standard	Class	MFE	Pressure drop	
				Inspiratory	Exhalatory
Canada	CSA Z94.4.1:21 [78]	CA-N95	$\geq 95\%$		
		CA-N99	$\geq 99\%$	$\leq 343 \text{ Pa}$	$\leq 245 \text{ Pa}$
		CA-N100	$\geq 99.97\%$		
China	GB 2626-2019 [79]	KN90	$\geq 90\%$	$\leq 170 \text{ Pa}$	$\leq 170 \text{ Pa}$
		KN95	$\geq 95\%$	$\leq 210 \text{ Pa}$	$\leq 210 \text{ Pa}$
		KN100	$\geq 99.97\%$	$\leq 250 \text{ Pa}$	$\leq 250 \text{ Pa}$
Europe	EN 149:2001+A1:2009 [80]	FFP1	$\geq 80\%$	$\leq 210 \text{ Pa}$	
		FFP2	$\geq 94\%$	$\leq 240 \text{ Pa}$	$\leq 300 \text{ Pa}$
		FFP3	$\geq 99\%$	$\leq 300 \text{ Pa}$	
United States	42 CFR Part 84 [81]	N95	$\geq 95\%$		
		N99	$\geq 99\%$	$\leq 343 \text{ Pa}$	$\leq 245 \text{ Pa}$
		N100	$\geq 99.97\%$		

mitigation of disease transmission through airborne particles.

While non-medical and surgical masks are primarily intended for source control, FFRs are typically designed to protect the user [72, 73]. FFRs generally consist of hydrophobic inner and outer layers to protect the filter from moisture and a middle electrostatically charged filtration layer supported by a structural layer [66, 74]. Table 2.2 summarizes relevant performance metrics for various FFR standards. The CA-N95, KN95, FFP2, and N95 FFR classes, which offer comparable material filtration, were widely adopted during the COVID-19 pandemic to curb transmission [63]. Compared to surgical masks, FFRs place greater emphasis on fit [67], despite filtration characteristics in Tables 2.1 and 2.2 being generally similar. Furthermore, surgical mask standards evaluate bacterial filtration efficiency, reflecting their origin in medical settings, whereas FFR standards are broader in scope and originate as a controls to improve general workplace safety.

Pressure drop testing methods differ between surgical mask and FFR standards. All

standards tabulated in Table 2.1 measure the differential pressure across a 4.9 cm^2 sample of surgical mask material at a flow rate of 8 L min^{-1} , expressing airflow resistance as pressure drop per unit area. In contrast, FFR standards measure differential pressure for both inhalation and exhalation across the full mask area with the perimeter sealed ensuring no leakage. The Canadian CSA Z94.4.1:21, Chinese GB 2626-2019, and American 42 CFR Part 84 specify flow rate of 85 L min^{-1} for both exhalation and inhalation pressure drops. The European EN 149:2001+A1:2009 uses flow rates of 30 L min^{-1} and 95 L min^{-1} for inhalation and 160 L min^{-1} for exhalation. Moreover, maximum inhalation pressure drop requirement using 30 L min^{-1} in EN 149:2001+A1:2009 is lower than what is tabulated in Table 2.2 at 60 Pa, 70 Pa and 100 Pa for FFP1, FFP2, and FFP3 masks respectively.

Table 2.3 summarizes observational studies [82, 84, 85] and surveys [83, 86, 87] of mask wearing preferences during the COVID-19 pandemic. Caballero *et al.* [84], which observed persons in four Spanish cities noted a significant increase in FFR usage from 13.7% in July 2020 to 27.6% in March 2021, suggesting a shift in preferences over the course of the pandemic attributed to greater availability and public awareness on superior filtration of FFRs. Across all tabulated studies, a significant proportion of the population demonstrated a preference for surgical masks. Weighted average results of mask preferences in Table 2.3 suggest an approximate distribution of $\sim 40\%$ for non-medical masks, $\sim 50\%$ for surgical masks, and $\sim 10\%$ for FFRs, respectively. While these suggest a preference for

Table 2.3: Surveys and observational studies of masking preferences in China, the European Union, and North America during the COVID-10 pandemic

Study	Scope	Sample size	Mask classification		
			Non-medical	Surgical	FFR
Barrios <i>et al.</i> [82]	US Students observed in universities with mask mandates (August 2020 to November 2020)	14,704	72.1%	25.7%	1.9%
Bertges <i>et al.</i> [83]	Surveyed US residents (April 2020 to May 2021)	619	39.6%	28.8%	31.6%
Caballero <i>et al.</i> [84]	Persons observed in 4 Spanish cities (July 2020 and March 2021)	4,889	24.6%	54.1%	21.3%
Deschanvres <i>et al.</i> [85]	Persons observed in Western France (June 2020 to July 2020)	1,892	43.2%	56.8%	-
Mouliou <i>et al.</i> [86]	Surveyed service sector workers in mainland Greece (November 2021)	4,107	20.5%	63.4%	13.8%
Pan <i>et al.</i> [87]	Pedestrians surveyed in Chinese public spaces (July 2020 to August 2020)	6,003	2.0%	85.5%	9.4%

certified masks (i.e. surgical mask and FFR), the authenticity of these masks, particularly in observational studies, remains uncertain and may inflate distribution in their favor.

2.2 Methods of Evaluating Masks

Given the critical role of face masks in times of widespread disease transmission, it is essential to understand the mechanisms governing filtration of airborne aerosols. When evaluating the overall effectiveness of masks, the following parameters are considered: apparent filtration efficiency (η_{AFE}) is the source control reduction of exhaled particles from an infected individual wearing a mask, inward protection efficiency (η_{IPE}) is the protection of a mask-wearer from inhalation of airborne particles, material filtration efficiency (η_{MFE}) is the reduction in particles of the mask material assuming a perfect seal, and finally pressure drop (ΔP) across the mask when worn which is associated with its breathability. In this section the relevance of each of these parameters is emphasized and present methods of mask evaluation are reviewed.

2.2.1 Source Control

During the recent COVID-19 pandemic, universal masking recommendations were made stressing the higher efficacy of source control in mitigating disease transmission [88–90]. On the hierarchy of controls, this approach is placed higher than personal protection [9], allowing for a reduction in potentially infectious aerosols emitted by symptomatic and asymptomatic individuals alike [88]. Mask mandates played a critical role in the overall reduction of COVID-19 [30–32], however, the wide selection of face masks available raises the question of the effectiveness of the different types.

Apparent filtration efficiency is estimated by comparing exhaled particles before and after wearing of a mask. The source control apparent filtration efficiency is typically estimated mechanistically by donning a mask on a manikin [19, 57, 91–98], with fewer studies utilizing human subjects [58, 99, 100]. While mechanistic studies do not account for the wide variation in face structures existing in the population, these have the advantage of greater control and reproducibility [95]. On the other hand, studies using human subjects are more difficult to conduct, and unless the sample size is large and varied, do not provide a representative sample of a population. Furthermore, individual experience with mask use, such as healthcare workers who have been trained on the proper wearing of respirators, can affect results [101, 102]. However, within a well defined study scope, use of human subjects can reasonably capture variations in mask fit otherwise not accounted for in mechanistic studies.

To simulate human exhalation in the mechanistic manikin studies, some employ a constant airflow [91, 95, 96, 98], while others employ a more physiologically accurate cyclical breathing pattern [19, 57, 92–95, 97]. Lindsley *et al.* [95] measured mask apparent filtration efficiency using constant exhalation and cyclical breathing at flow rates representative of both regular and heavy breathing. Results were generally comparable across the test cases,

though high flow rate cyclical breathing demonstrated higher apparent filtration efficiencies, which was attributed to recirculation of particles within the mask volume. However, the study was limited to only four replicates for each trial, making it difficult to draw robust statistical conclusions. As a result, the impact of breathing pattern on apparent filtration efficiency remains uncertain.

Flow visualization of exhaled aerosols presented in Pieris *et al.* [97] show that masks can redirect the exhalation jet backwards and/or upwards. Thus, particle measurements taken in front of the mouth in both the masked and unmasked conditions can result in an overestimation of apparent filtration efficiency. This may explain the high apparent filtration efficiency by some studies where the exhaled particle measurements are taken at the mouth [57, 91, 98, 99]. In fact, Goodge *et al.* [57] calculated significantly lower efficiencies when sampling at eye-level compared to mouth level, which may be justified by the redirection of the jet upwards towards mask gaps near the nose. To reduce such bias, measuring exhaled particles measurements at a location of higher dispersion is recommended. Moreover, sampling measurements at or near steady state particle levels within a test volume can further improve estimate accuracy for apparent filtration efficiency.

Few studies have estimated the source control effectiveness of child masking [57, 58]. Goodge *et al.* [57] used a manikin based on child measurements to estimate apparent filtration efficiency of various masks. However, the use of a rigid manikin does not realistically represent the mask-face interface, thus can affect the estimated apparent filtration efficiency [103–105]. Moschovis *et al.* [58] measured particles exhaled from children aged between 3-17 years old under various exhalatory conditions, including speaking, breathing, and sneezing in both masked and unmasked conditions. Overall, in both discussed studies of source control efficiency of child masking, only cloth and surgical masks were evaluated, whereas FFRs such as the N95 or KN95 mask types were not included. Additionally, no study estimates the apparent filtration efficiency of adult-sized masks when worn by children. These gaps represent an opportunity for further investigation of the source control effectiveness of face masks when worn by children.

2.2.2 Personal Protection

In addition to source control, masks protect the wearer from inhaling potentially infectious particles. This is particularly important during disease outbreaks involving airborne transmission, especially to healthcare workers and immunocompromised individuals [7, 9, 37, 38]. Several studies have quantified the reduction of particle exposure when a mask is worn. Moreover, the inward protection efficiency has been both estimated mechanistically using a manikin [91, 92, 96, 98, 106] and by using human subjects [26, 49, 107–111]. The advantages and limitations of both methods discussed in Section 2.2.1 similarly apply to the estimation of inward protection efficiency.

Human subjects are more commonly employed in testing of inward protection efficiency than apparent filtration efficiency due to existing standardized methods for estimation of the inward leakage of a mask. In the United States, Occupational Safety and Health Administration (OSHA) regulations requires workers who may be regularly exposed to

harmful particles to wear a well-fitting respirator and undergo yearly fit testing, which may be either qualitative or quantitative [112]. The OSHA quantitative fit test procedure estimates inward protection efficiency by comparing particle measurements within the volume enclosed by the mask and face with those in the ambient (Fig. 2.2a). The test requires that, for a user wearing a half-mask FFR, the particle concentration surrounding air must be at least 100 times that within the FFR. It is important to note that this test is typically conducted on users wearing an individually fitted respirators and therefore does not reflect the variability in fit by the general public, where annual fit testing is not conducted. Several studies, both mechanistic and human, utilize a similar sampling approach as the OSHA quantitative fit test to quantify the inward protection efficiency of a mask [26, 49, 96, 107–111]. However, measuring particles within the volume enclosed by the mask and face can raise issues as the sampling flow rate is quite large relative to the space enclosed by the mask and face and the inhalation volume. Thus, it is expected that the sampling flow rate will impact the measurement. Another approach to estimate inward protection efficiency is by comparing the number of particles inhaled in the masked case versus the no mask case (Fig. 2.2b) [91, 92, 98, 106]. This approach is only performed in mechanistic studies as it is not practical to measure inhaled aerosols in a human subject. Overall, the author is not aware of studies determining the impact of differences between both methods used for estimating inward protection efficiency.

During the COVID-19 pandemic, public health authorities in the United States issued emergency authorizations permitting the import of Chinese-standard KN95 masks to alleviate shortages in PPE supply [48]. Despite widespread adoption across North America, at the time of writing, the author is only aware of the study by Duncan *et al.* [49] that has estimated the inward protection efficiency of KN95 masks. However, results of that study correspond to a median particle diameter of $0.131\text{ }\mu\text{m}$, highlighting a gap in the literature

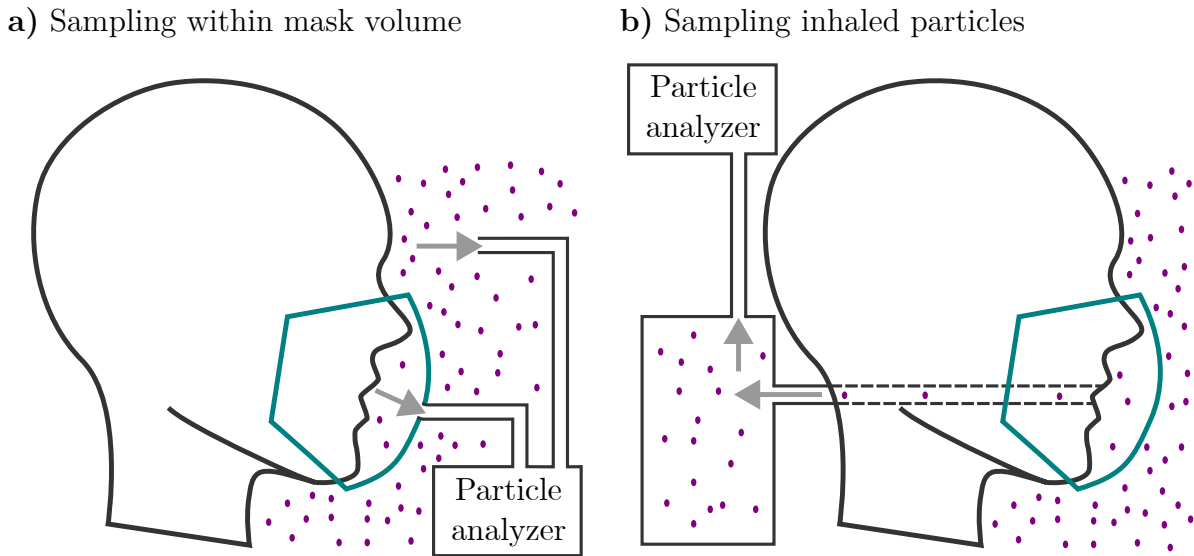


Figure 2.2: The two methods in literature for estimating inward protection efficiency. Figure adapted from Mittal *et al.* [25].

regarding size-resolved measurements of inward protection efficiency. Furthermore, it is generally established that the N95 mask offers more protection than the surgical mask, largely due to a better face seal in the former [49, 106, 107, 109–111]. To improve surgical mask fit, donning using the “tie and tuck” method has been suggested [50, 91, 108], though the amelioration in effectiveness across different particle sizes remains poorly characterized.

A significant research gap is the limited data on the protection of masks on children. Van der Sande *et al.* [26] investigates the inward protection efficiency of a homemade, surgical, and FFP2 masks on adults and children between 5 to 11 years old. Findings suggest a significant degradation in mask protection when adult-sized masks are donned by children, attributed to a poorer fit. However, no study compares the particle size specific inward protection efficiency of adult and child-sized masks worn by children.

2.2.3 Material Filtration

The filtration characteristics of the mask material depends on factors such as the material property, the utilized aerosol, and the face velocity. When testing for material filtration efficiency, mask material is typically the independent variable. The N95 mask material is engineered to filter with greater efficiency than a cloth mask, largely due to differences in fiber thickness, lower fiber density in the cloth mask, and a stronger electrostatic charge on the N95 mask [66]. The velocity and type of particles passing through the material can be controlled between studies, and also have a significant impact on overall filtration performance [1, 113, 114].

A test flow rate of 85 L min^{-1} is prescribed by the NIOSH standard for the N95 mask [81], representing a conservative estimate of breathing at a high work rate [81, 114–118]. Other comparable standards, such as the Chinese KN95, the European FFP2, and Canadian CA-N95, measure material filtration at similar flow rates (85 L min^{-1} or 95 L min^{-1}) [78–80, 115]. These flow rates are designed for testing at worst-case conditions, providing a lower bound for the filtration efficiency of a mask material, and are not intended to represent normal breathing conditions for an average person during regular use. However, it is not flow rate that dictates the filtration characteristics of a material but rather the face velocity through the mask filter material (u_f) [1]. This quantity is defined as the flow rate (Q_{test}) divided by the filter test surface area (A_{test}), as shown in Eq. 2.1.

$$u_f = \frac{Q_{test}}{A_{test}} \quad (2.1)$$

The NIOSH N95 standard is widely used for testing mask material filtration efficiency. To meet this guideline, the test area and flow rate are typically adjusted to achieve compliant face velocities in the range of 4 cm s^{-1} to 11 cm s^{-1} [96, 119–123]. Another approach involves sealing the tested face mask onto a manikin or clamping it to a plate fitted with an exhalation tube, and use the constant flow rate of 85 L min^{-1} outlined in the NIOSH testing protocol [118, 124, 125]. The advantage of this setup is that it accounts for the variations in face velocities that occur due to the different mask designs.

Furthermore, other standards have been used to determine test face velocity. For example, Bagheri *et al.* [126] uses a face velocity of 2 cm s^{-1} , in line with the ASTM F2299 standard used for testing surgical masks and more representative of normal breathing [115]. In contrast, Shah *et al.* [19] does not rely on a standard for testing material filtration. Rather, regular human tidal exhalation through a tube with a diameter of 2.5 cm is used. This results in a mean face velocity 35 cm s^{-1} per exhalation, a value far higher than face velocities associated with heavy breathing across a full mask area [115].

Another key methodological difference that can affect the estimation of material filtration is the choice of test particles [1]. Existing standards include different recommendations for what particulates can be used, with the most common being aerosolized NaCl [78, 115, 127]. Consequently, the majority of studies measuring material filtration efficiency use NaCl particles [96, 113, 119–123, 128]. These test particles are often neutralized to establish an equilibrium bipolar charge distribution, thereby preventing overestimation and improving consistency of material filtration estimates [129, 130].

Some standards also provide instructions for testing using oil-based particles. For instance, ISO 16900-1:2019 [127] and EN 149:2001+A1:2009 [80] allow for the use of corn and paraffin oils, respectively, as a test aerosol. Rengasamy *et al.* [125] compared the effects of neutralized NaCl particles and corn oil on material filtration efficiency, finding that results using the latter being lower, and thus more conservative, than the former. Based on this, it is expected that material filtration characteristics from Shah *et al.* [19] and Pieris *et al.* [97] using neutrally charged olive oil provide a more conservative estimate than results from studies employing NaCl.

Rengasamy *et al.* [118] tested masks using different American standardized methodologies, including the NIOSH N95 standard, ASTM 2299, and ASTM F2101, varying the face velocity based on each method’s specifications. Different test aerosols, such as NaCl, aqueous bacterial, aqueous viral, and polystyrene latex aerosols were used. Particle properties and face velocities varied across standards, explaining the resulting differences in material filtration efficiencies. Furthermore results suggest that the NIOSH guideline provides the most conservative filtration efficiency among tested American standards.

2.2.4 Pressure Drop

Pressure drop across the face mask is associated with airflow resistance, and serves as a measure of breathability, with lower values indicative of easier inhalation or exhalation [131]. Both surgical mask and FFR standards described in Section 2.1 assess airflow resistance across the mask material under sealed conditions. Shah *et al.* [19] and Konda *et al.* [128] measure pressure drop under sealed conditions, though with differing flow rates or mask test areas than the standards.

Since this thesis focuses on real-world mask use, measuring airflow resistance under sealed conditions overlooks the significant impact of leakage on actual comfort. Material pressure drop alone does not reflect actual mask breathability when donned. For instance, a loosely fitting mask with high material pressure drop may still feel comfortable, as a

significant portion of the flow leaks through gaps at the mask-face interface. With that in mind, Arumuru *et al.* [70] and Yao *et al.* [71] both assessed breathability of various masks worn on an adult manikin. While both studies use tidal breathing patterns, the former employed parameters reflective of normal breathing, while the latter simulated breathing under heavy work.

To date, the author is not aware of any studies that quantify the air resistance of masks when donned on children. This is a significant gap, as poor breathability has been cited to cause children, who are generally more sensitive to discomfort than the general population, to remove their face masks [132]. Thus, insights into which mask types are easier to breathe through may aid in improving mask compliance among children.

2.3 Modeling the Mechanics of Mask Efficiency

Given the critical role of face masks in reducing airborne transmission of disease, understanding the mechanisms behind the efficiency of a mask donned by an individual, i.e. fitted mask efficiency, is crucial for the design of an effective masks. As shown in Fig. 2.3, there are two pathways for flow, $Q_{(out\ or\ in)}$, to exit/enter the mask during an individual exhalation/inhalation, respectively. The first is through leakage from around the gaps around the mask-face interface, Q_{leak} , and the second is through the mask material, Q_{mask} . Thus the flow out/in of the individual can be expressed using Eq. 2.2.

$$Q_{(out\ or\ in)} = Q_{leak} + Q_{mask} \quad (2.2)$$

Given that the majority of exhaled particles are under $1\mu\text{m}$ in size [60, 61], these

a) Outward

b) Inward

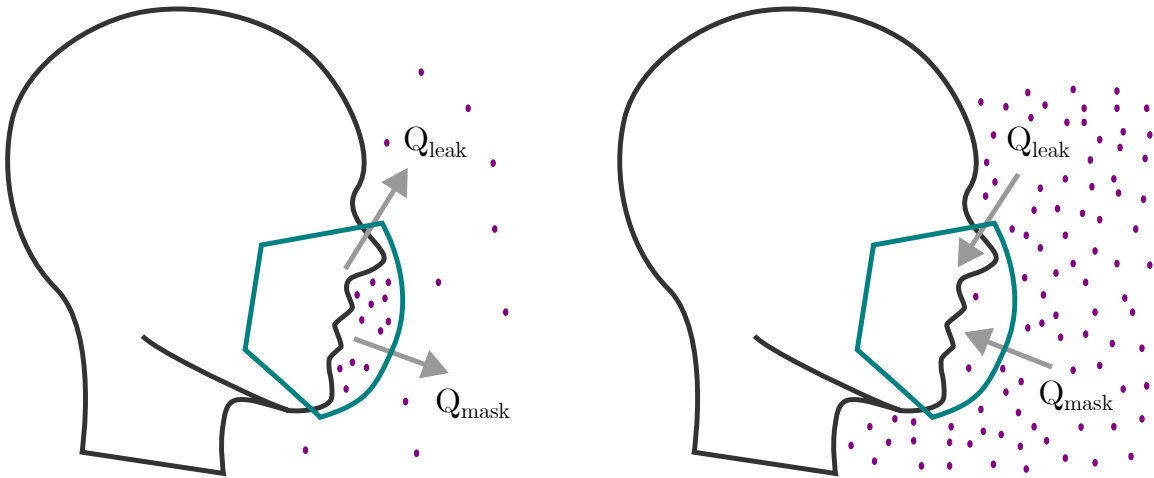


Figure 2.3: Flow paths going inwards and outwards from a mask. Figure adapted from Mittal *et al.* [25].

small-scale aerosols act as faithful flow tracers, having a Stokes' number well below 1 at regular breathing conditions. Thus, Eq. 2.2 can be expressed in terms of the number of particles, n . Therefore, for particles exiting or entering the area enclosed by the mask and the face, $n_{(out\ or\ in)}$, these can either leak in through gaps in the mask-face interface, n_{leak} , or go through the mask material, n_{mask} . Of the latter, a certain proportion of the particles will be filtered out when passing through the material; this is referred to as the material filtration efficiency, η_{MFE} , of a mask. Eq. 2.3 describes the total number of particles having passed the filter material or leaked through gaps as

$$n_{(out\ or\ in)} = n_{leak} + \left(1 - \frac{\eta_{MFE}}{100\%}\right) \times n_{mask}. \quad (2.3)$$

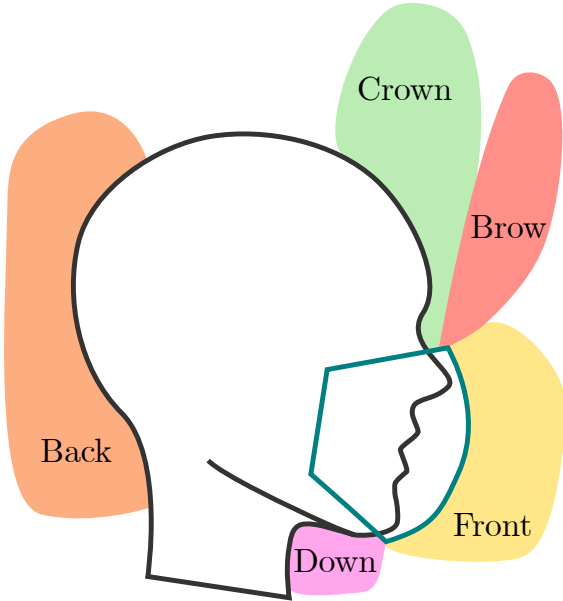
With the above in mind, fitted mask efficiency can be estimated by comparing the reduction in particles relative to the no-mask case ($\eta_{MFE,NM} = 0\%$ and $n_{(out\ or\ in),NM} = n_{leak,NM}$), yielding:

$$\eta_{AFE,IPE} = 100\% \times \left(1 - \frac{n_{leak,M} + \left(1 - \frac{\eta_{MFE}}{100\%}\right) \times n_{mask,M}}{n_{leak,NM}}\right), \quad (2.4)$$

where subscripts M and NM refer to the mask and no mask cases, respectively.

Based on Eq. 2.4, two key factors affect the overall efficiency when masks are worn. The

a) Side view



b) Front view

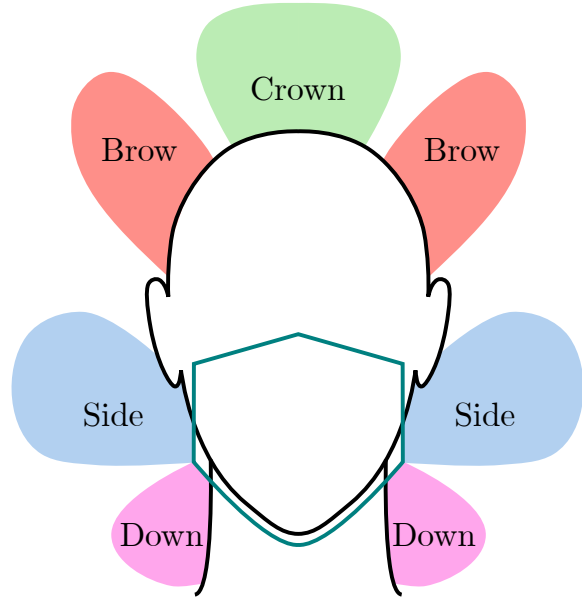


Figure 2.4: General diagram of the main flow penetration locations of a mask when worn. Figure adapted from Mittal *et al.* [25] and Viola *et al.* [133].

first is the impact of leakage, both inward protection and apparent filtration efficiencies deteriorate when $n_{leak,M}$ approaches $n_{leak,NM}$. Moreover, a poorly fitting mask is expected to redirect flow through gaps around the mask-face interface rather than through the filter material and vice-versa for a well-fitting mask. The second factor affecting overall fitted mask efficiency is material filtration efficiency, the influence of which increases with reduced leakage and better mask fit.

Fig. 2.4 illustrates the six general flow penetration locations of a mask fitted on a head. In Eqs. (2.3) and (2.4), the term $\left(1 - \frac{\eta_{MFE}}{100\%}\right) \times n_{mask,M}$ corresponds to flow through the front of the mask, and is subject to five basic mechanisms contributing to the overall material filtration efficiency of a filter: interception, inertial impaction, diffusion, gravitational settling, and electrostatic attraction [1]. Moreover, these deposition mechanisms vary in strength with respect to various factors including particle size, the type of filter material, and the flow velocity going through the filter medium.

Among the five mechanisms, gravitational settling is not expected to play a major role for the smaller-scale particles going through a mask as the stronger velocity of tidal breathing dominates over the effects of particle settling. The four remaining relevant filtration mechanisms are depicted in Fig. 2.5, adapted from Mittal *et al.* [25]. Interception (Fig. 2.5a) occurs when a particle closely following the streamlines impacts with the filter fiber due to its finite radius, this largely occurs in particle sizes above $0.1 \mu\text{m}$. Impaction (Fig. 2.5b) typically affects particles larger than $1 \mu\text{m}$, and happens when the inertia of the particle is large enough for it to not follow the streamlines (i.e. $Stk \gtrsim 1$). Diffusion (Fig. 2.5c) results from Brownian motion and is more significant in the collection of smaller scale particles,

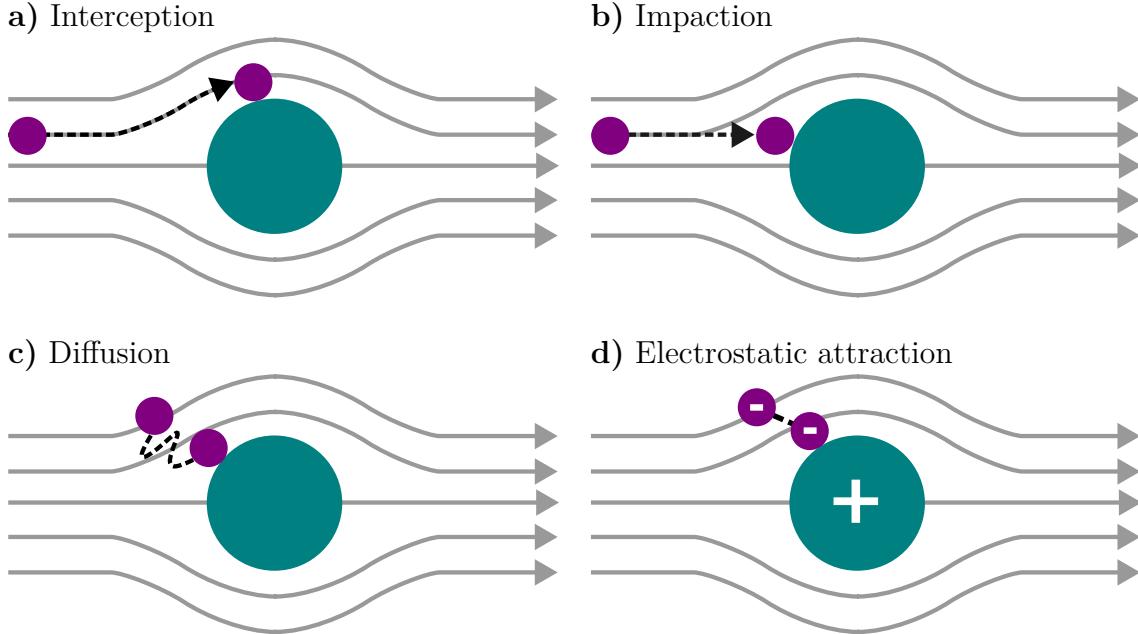


Figure 2.5: Common particle deposition mechanisms over a single fiber within the mask material. Figure adapted from Mittal *et al.* [25].

particularly those with diameters on the order of $0.1\text{ }\mu\text{m}$ or less. Its effectiveness is governed by the Peclet number of a particle, with a smaller value indicating greater diffusion. Finally, electrostatic attraction (Fig. 2.5d) occurs when either the filter fiber, the test particles, or both carry a charge, and is of particular importance in filtration of nanoscale particles [25, 134].

Thus, material filtration efficiency is a combination of the different particle deposition mechanisms. Combining the effects of individual mechanism efficiencies to derive a general expression for material filtration efficiency is shown in Eq. 2.5 from Hinds [1]

$$\eta_{MFE} = 100\% \times \left(1 - \left(1 - \frac{\eta_{interception}}{100\%} \right) \times \left(1 - \frac{\eta_{impaction}}{100\%} \right) \times \left(1 - \frac{\eta_{diffusion}}{100\%} \right) \times \left(1 - \frac{\eta_{electrostatic}}{100\%} \right) \right). \quad (2.5)$$

Given that particles harboring pathogens that transmit through the air can span a wide size range, from approximately $0.05\text{ }\mu\text{m}$ to $500\text{ }\mu\text{m}$ [135], all of the discussed filtration mechanisms may contribute to pathogen carrying particle capture, depending on specific factors such as particle size, physicochemical properties, and velocity. Furthermore, Drewnick *et al.* [113] observed a trend in which material filtration decreases with increasing face velocity for smaller particle sizes ($d_p \lesssim \mathcal{O}(10^{-1})\text{ }\mu\text{m}$), while increasing for larger particle sizes ($d_p \gtrsim \mathcal{O}(10^{-1})\text{ }\mu\text{m}$). This trend is attributed to the varying efficiency of filtration mechanisms with face velocity. As face velocity increases, mechanisms that primarily affect smaller particles, such as electrostatic attraction and diffusion, become less efficient, whereas impaction, which affects larger particles, becomes more effective. The opposite trend occurs with decreasing face velocity [1, 113].

Unlike the front flow, which is filtered through the mask material, the other locations depicted in Fig. 2.4 are associated with gaps around the mask-face interface that can significantly reduce fitted mask efficiency [136]. The term $n_{leak,M}$ in Eq. 2.4 corresponds to leakage through these five remaining leakage locations. A poor fit preferentially redirects flow towards these gaps. Conversely, a well-fitting mask minimizes unfiltered flow by reducing leakage.

To provide a measure of the degree of mask fit, the percentage of total particles leaking through the gaps at the mask-face interface (ζ) can be defined relative to the no mask reference case ($\zeta = 100\% \times \frac{n_{leak,M}}{n_{leak,NM}}$). With this definition, Eq. 2.4 can be manipulated to derive an expression of the proportion of particles leaking through gaps in the mask-face interface as

$$\zeta = 100\% \times \left(1 - \frac{\eta_{AFE,IPE}}{\eta_{MFE}} \right). \quad (2.6)$$

The equation above only accounts for particles that act as faithful flow tracers, as such does not account for particles with stokes numbers of order unity or larger. However, the scope of this work is limited to conditions where the above equations apply, using smaller scale particles at regular tidal breathing velocities, thus resulting in Stokes numbers several order of magnitudes below one. For cases with larger particles or greater velocities, a more

general interpretation of Eq. 2.6 accounting for particles that do not faithfully follow flow (see, for example, Mittal *et al.* [25]) should be considered.

Overall, high face mask effectiveness can be achieved by considering the two major factors influencing fitted filtration efficiency. The first is by the selection of a filter with a high material filtration efficiency and the second is the designing a mask geometry that minimizes leakage at the mask-face interface.

Chapter 3

Methodology

3.1 Mask Efficiency

Experiments were conducted in the Fluid Mechanics Research Laboratory at the University of Waterloo. Fig. 3.1 illustrates the experimental configurations used to quantify apparent filtration efficiency (Fig. 3.1a), inward protection efficiency (Fig. 3.1b), and material filtration efficiency (Fig. 3.1c). In each setup, upstream and downstream control volumes were denoted as 1 and 2, respectively. All efficiencies were estimated using Eq. 3.1, derived from an approach based on conservation of mass presented in Appendix A.

$$\eta_M = 100\% \times \left(1 - \frac{c_{ss,2,M}/c_{ss,1,M}}{c_{ss,2,NM}/c_{ss,1,NM}} \right) \quad (3.1)$$

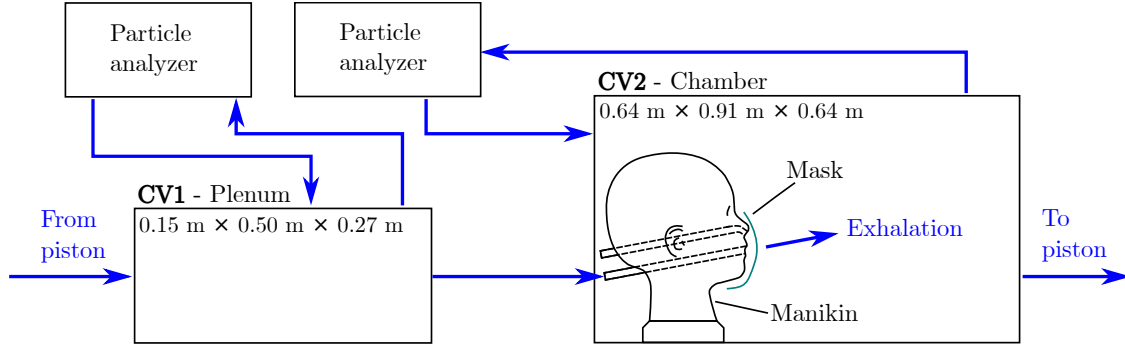
Filtration efficiency was computed by comparing test particle number concentrations from both mask (subscript M) and no-mask (subscript NM) configurations, the latter serving as a baseline case in the testing. Overall a mask efficiency of 100% indicates complete removal of particles, while 0% implies no filtration.

To estimate mask filtration efficiency, olive oil aerosols with diameters in the range of 0.2 μm to 1 μm were generated using a Laskin-style nozzle constructed following the design of Kähler *et al.* [137]. The size range is representative of a large segment of exhaled particles [6, 138–140] and has been shown to be able to harbor pathogen RNA, including that of COVID-19 and influenza viruses [6, 135, 141–144]. Olive oil was selected as the test aerosol because it does not degrade the synthetic mask materials and has been successfully used in prior studies [19, 97]. Its physical properties are comparable to those of corn oil, which is specified in ISO 16900-1:2019 [127]. In the sub-micron regime, olive oil droplets serve as passive flow tracers, with Stokes numbers under typical breathing conditions well below unity. Particle number concentration measurements were obtained using the Palas Promo LED 2000 aerosol spectrometer, which operates using optical light scattering and integrating photometer principles and is capable of measuring concentrations of up to $1.0 \times 10^6 \text{ particles cm}^{-3}$ at a volumetric sampling flow rate of 5 L min^{-1} . The instrument classifies particles into 128 logarithmically spaced bins per decade, yielding 91 size bins within the 0.2 μm to 1 μm range. The measured particle size distribution is presented in Fig. 3.2.

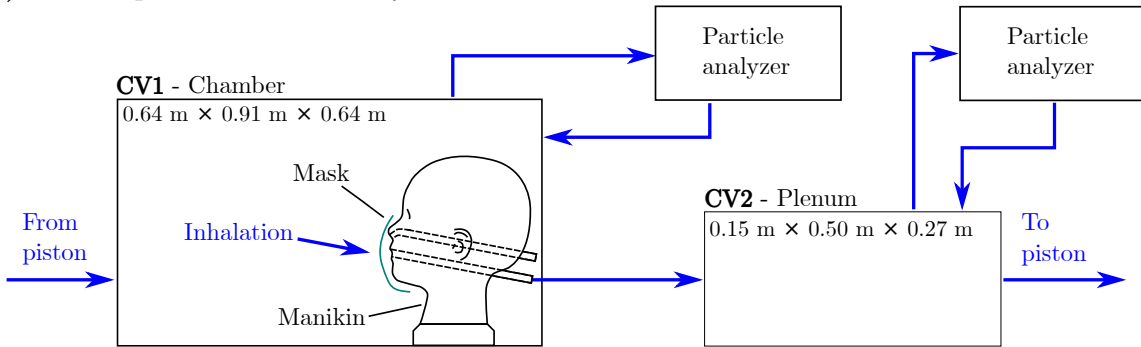
In all mask efficiency experiments, the steady state particle number concentration within control volume 1 ranged between $0.7 \times 10^5 \text{ particles cm}^{-3}$ to $1.4 \times 10^5 \text{ particles cm}^{-3}$. These concentrations are well below the $10^6 \text{ particles cm}^{-3}$ threshold at which particle coagulation becomes significant under experimental conditions [1]. Other aerosol processes, such as diffusion and gravitational deposition within the control volumes, are implicitly accounted for via the in-situ particle loss terms defined in Appendix A [1]. Furthermore, due to the stability of olive oil particles at room temperature, losses from evaporation are expected to be negligible [1, 19].

The piston-cylinder assembly used to simulate inhalation and exhalation is illustrated in Fig. 3.3. A linear traverse driven by a motor controller actuated the piston to replicate resting tidal volumes and breathing rates for adults [145, 146] and children [147]. Piston

a) Apparent filtration efficiency



b) Inward protection efficiency



c) Material filtration efficiency

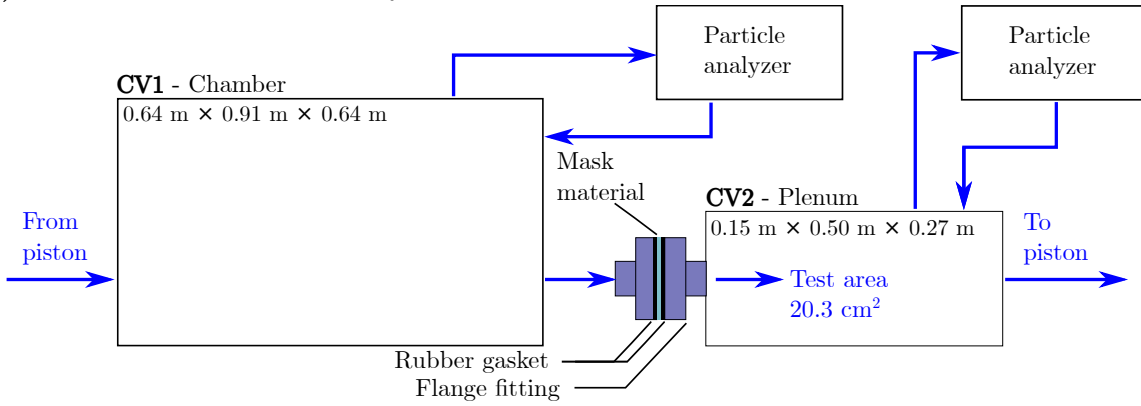


Figure 3.1: General setups used to estimate mask efficiency.

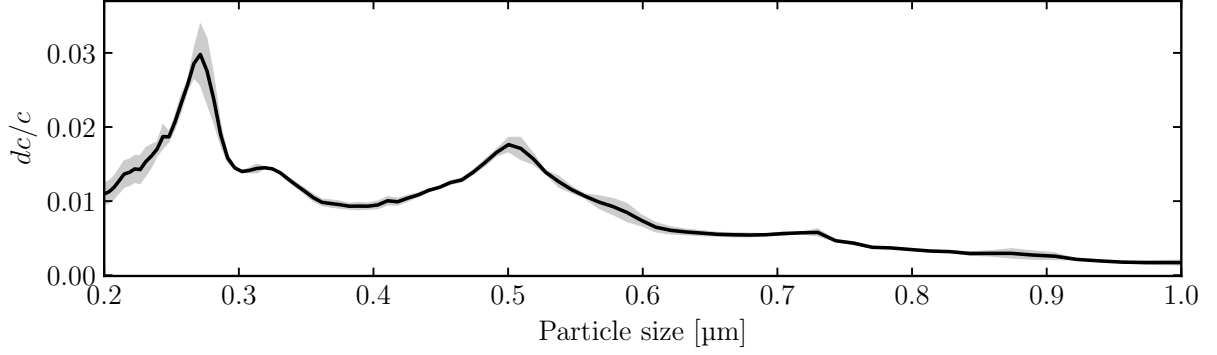


Figure 3.2: Size distribution of olive-oil particles generated by Laskin-style nozzle. Shaded areas show one standard deviation of 10 tests.

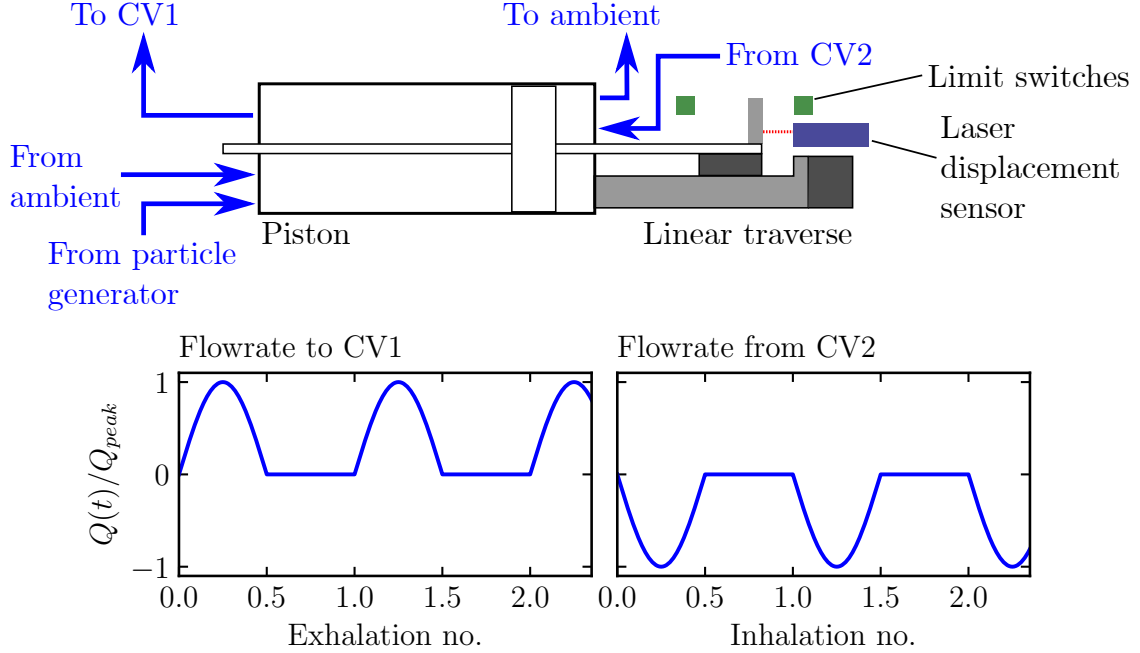


Figure 3.3: Piston assembly used to simulate human exhalation and inhalation.

position was tracked using a Wenglor CP24MHT80 laser displacement sensor, while airflow into and out of the control volumes were measured using two calibrated orifice-plate flow meters. Instantaneous piston position, breath count, flow rates, and particle generator pressure were recorded with a National Instruments DAQ USB-6259. Two limit switches positioned at stroke endpoints tracked breath count. The switch triggered at the end of the piston shaft retraction activated a solenoid that initiated particle generation from the Laskin-style nozzle, thereby synchronizing aerosol seeding with the breathing cycle.

Fitted mask efficiency was evaluated using a medium NIOSH adult manikin [148] and a child manikin modeled from facial measurements of 7 year old Dutch children [149]. To maintain a physiologically representative mask-skin interface, both head forms were fitted

with a soft silicone elastomer skin with a shore hardness of 00-20 [103–105].

The general testing procedure for all filtration metrics is summarized as follows. Prior to each test, the plenum and chamber were purged of residual particles. For fitted mask efficiency measurements (Figs. 3.1a and 3.1b), the unmasked manikin was placed within the sealed chamber, and for material filtration efficiency measurements (Fig. 3.1c), the mask holder was connected without a mask. Testing began with a 10 minute sampling of background particle number concentrations without aerosol generation. Subsequently, particle generation commenced, and control volume 1 was seeded with aerosols from the Laskin-style nozzle via the piston. Particles were then drawn from control volume 1 to control volume 2, passing through the manikin or mask material clamp. Testing continued until particle number concentrations reached steady state, after which particle size distributions were measured for 30 minutes in both control volumes. The procedure was repeated with the tested barriers either fitted on the manikin or secured in the holder. Filtration efficiency for each tested mask was computed using Eq. 3.1 with uncertainty estimated as the variability between repeated trials. Specific details on the experimental procedure used to estimate apparent filtration and inward protection efficiencies are provided in Chapters 4–6.

As discussed in Chapter 2, material filtration efficiency can vary with face velocity [1, 113, 114]. To account for this, the average volumetric flow rate in Fig. 3.1c was adjusted to yield mean face velocities of 1.6 cm s^{-1} and 1.5 cm s^{-1} through the custom mask holder to represent conservative estimates of the face velocities corresponding to adult and child breathing, respectively. The inner diameter of the mask holder was 50.8 mm. Further discussion on the determination of face velocities is provided in Appendix B. Estimation of mask material filtration efficiency employed an approach based on the conservation of mass consistent with that used for inward protection efficiency, as outlined in Appendix A.

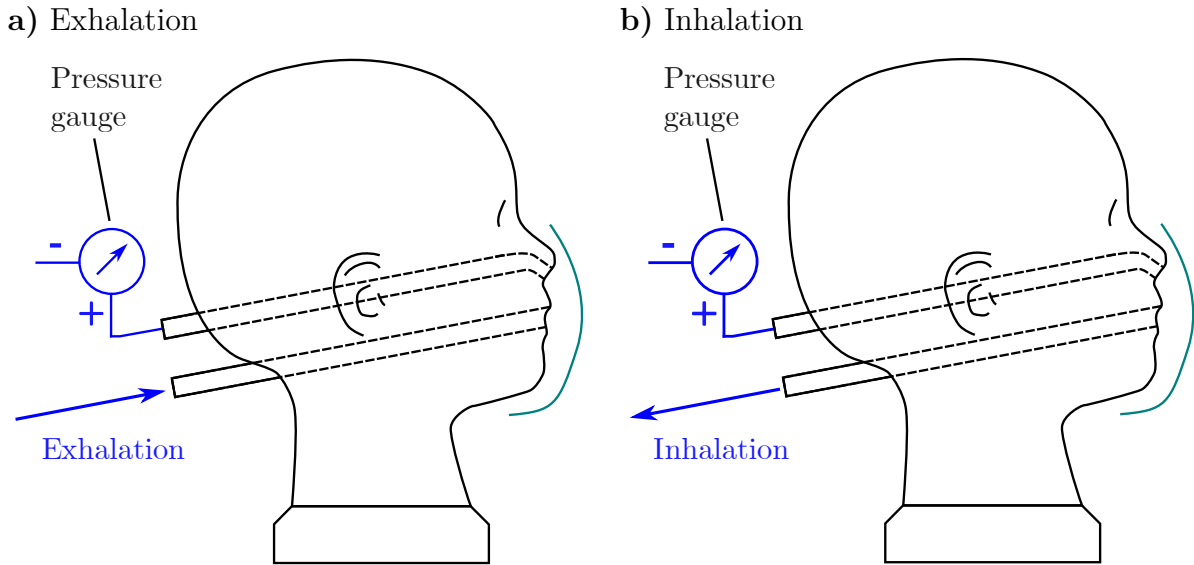


Figure 3.4: Experimental setup for measurement of pressure drop across a fitted mask.

3.2 Pressure Drop

Fig. 3.4 depicts the setup used to assess pressure drop during simulated child breathing, as detailed in Chapters 5 and 6. The child manikin, fitted with the test barrier, was connected to the breathing apparatus via the oral line. A Setra model 239 differential pressure transducer connected to the nasal port was used to measure pressure within the volume enclosed by the mask and face relative to the ambient. Each trial consisted of 78 child breathing cycles (roughly 3 minutes). Subsequently, peak pressure drops were extracted for each cycle and averaged to obtain a trial mean. Testing was repeated 10 times for each barrier to capture variability due to mask fit. 95% confidence intervals of the mean peak differential pressures were estimated using Eq. C.1, which incorporates contributions from both repeat trial variability and instrument accuracy to measurement uncertainty.

3.3 Flow Visualization

In Chapter 5, flow visualization of the exhalation through the tested barriers was conducted using the setup illustrated in Fig. 3.5. To enable clear visualization of exhaled flow, the chamber was seeded to particle concentrations significantly higher than those used in filtration efficiency measurements. Prior to each test, the manikin was fitted with the selected mask, and the test area was cleared of residual particles. Visualization was

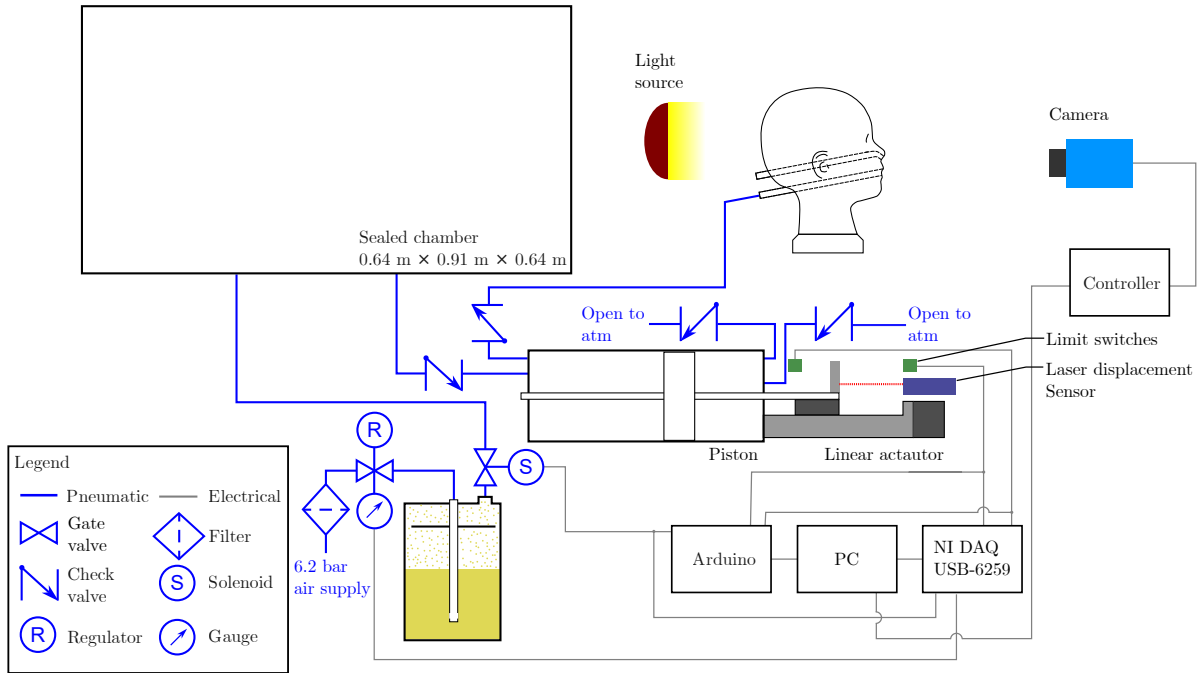


Figure 3.5: Experimental setup used to visualize leakages from exhalation around the mask-face interface. Figure is adapted from Pieris *et al.* [97].

performed from both front and side views, with careful attention paid to maintaining consistent mask fit between perspectives. Image acquisition was realized using a 5.5 Megapixel LaVision Imager sCMOS CLHS camera equipped with a Nikon 50 mm lens. A backlight was positioned behind the manikin to illuminate exhaled particles. The image capture sequence was synchronized with breathing cycle via a limit switch triggered at the end of the exhalation stroke. Images were captured at 25 Hz and post-processed using LaVision DaVis 10 software, where frames nearest to peak exhalation were averaged over 11 cycles.

Chapter 4

Inward Protection of Adult Masking

Parts of this chapter have been adapted from

EL KHAYRI, H. *et al.* 2025 Study of the inward protection efficiency of various facial masks. *Aerosol Science and Technology* 1–12. [DOI](#).

4.1 Introduction

During the recent COVID-19 pandemic, demand for personal protective equipment surged, causing shortages and endangering doctors, nurses, and other essential workers [37, 38]. While the NIOSH certified N95 filtering face-piece respirator is the standard for personal protection in North America, limited supply resulted in emergency use authorizations by the U.S. Food and Drug Administration to import Chinese standard KN95 FFR to help alleviate the strain in supply [48].

Both N95 and KN95 standards require a filtration of 95% of NaCl particles at 85 L min^{-1} through the material [150]. Similar requirements for ASTM compliant surgical masks exist, being categorized into three barrier levels, from the lowest filter efficiency at level 1 to the highest at levels 2 and 3 [151, 152]. However, because of gaps in the mask-face interface, the apparent inward protection efficiency offered by a mask can be lower than its reported material filtration efficiency (e.g, Grinshpun *et al.* [109]).

Additionally, during the pandemic, surgical masks were prevalent as a relatively affordable masking option. Due to a looser fit of surgical masks compared to N95 or KN95 alternatives, some health authorities recommended a “tie and tuck” method to improve mask fit [50], whereby a knot is made using the elastic ear loops in which excess material is tucked in. Other suggestions to improve fit include the use of nylon hosiery over the mask and around the back of the head to push the mask more firmly in place, and double masking; the tie and tuck method, however, carries the distinction of not requiring any additional material other than single surgical mask to implement [91, 108].

The aim of the present chapter is to quantify the inward protection efficiency for aerosol particles ranging from $0.2 \mu\text{m}$ to $1 \mu\text{m}$ for the KN95 and the tied and tucked surgical mask, two interventions that have proliferated greatly during the recent COVID-19 pandemic, relative to the N95 and regularly worn surgical mask.

4.2 Experiment Detail

A detailed schematic of the experimental setup is provided in Fig. 4.1. The soft-skinned medium NIOSH head form is used to test physiologically realistic masking conditions for adults [103–105]. Tests were performed using the manikin placed upright in the sealed chamber. The manikin inhalation parameters are based on regular adult tidal breathing and are listed in Table 4.1.

Fig. 4.2 shows all configurations considered in the study, namely, no-mask, as well as

Table 4.1: Adult inhalation properties with 95% confidence interval

Parameter	Value	Unit
Inhalation rate (h_{inh})	14.3 ± 0.2	inhalation min^{-1}
Inhalation volume (V_{inh})	582.1 ± 39.2	mL inhalation $^{-1}$

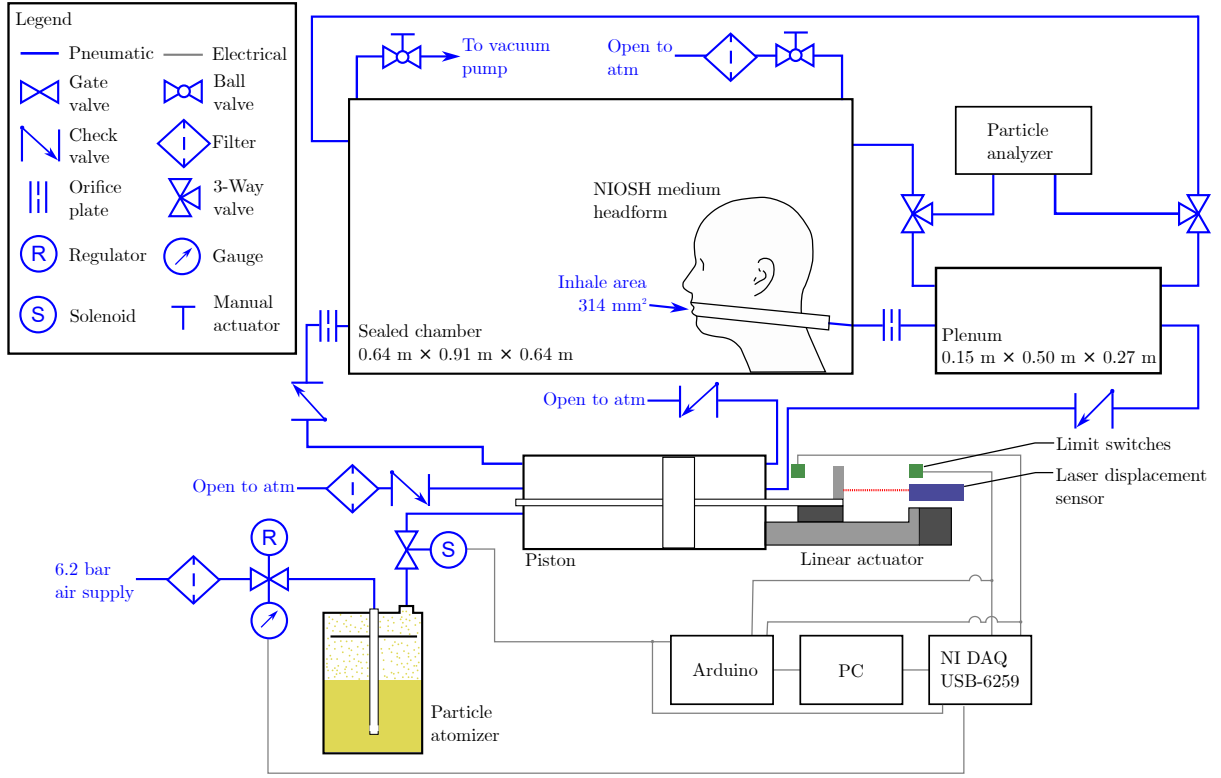


Figure 4.1: Experimental setup used to measure mask inward protection efficiency on an adult manikin. In this configuration, the sealed chamber is control volume ‘1’ and the plenum is control volume ‘2’. Figure is adapted from Pieris *et al.* [97].

N95, a KN95, and ASTM level 3 surgical masks. Furthermore, the surgical mask was tested with normal donning and using the “tie and tuck” method [50]. Aside from the tied and tucked surgical mask, all mask application procedures followed manufacturer-specified donning protocol.

Based on the methodology outlined in Section 3.1, the employed testing procedure can be summarized as follows. The unmasked manikin was connected to the inhalation line to the plenum and placed in the sealed chamber. A blower was then used to replace the air in both the chamber and plenum with clean filtered air drawn in from the ambient through a HEPA filter. Initial measurements of background particle number concentration were conducted for the first 140 cycles (approximately 10 minutes) with no particle injection into the system. Subsequently, particle injection was initiated, and continuous measurements were performed in the chamber for 1710 cycles (approximately 2 hours), to ensure that steady-state conditions were reached for at least 30 min. After the concentration measurements in the chamber were complete, measurements were performed in the plenum for approximately 1700 cycles (approximately 2 hours), including at least 30 minutes of steady-state measurements for each run. The above procedure was then repeated with the inhaling manikin fitted with one of the facial coverings. The employed methodology required switching of sampling locations from the chamber to the plenum due to the availability of only one particle

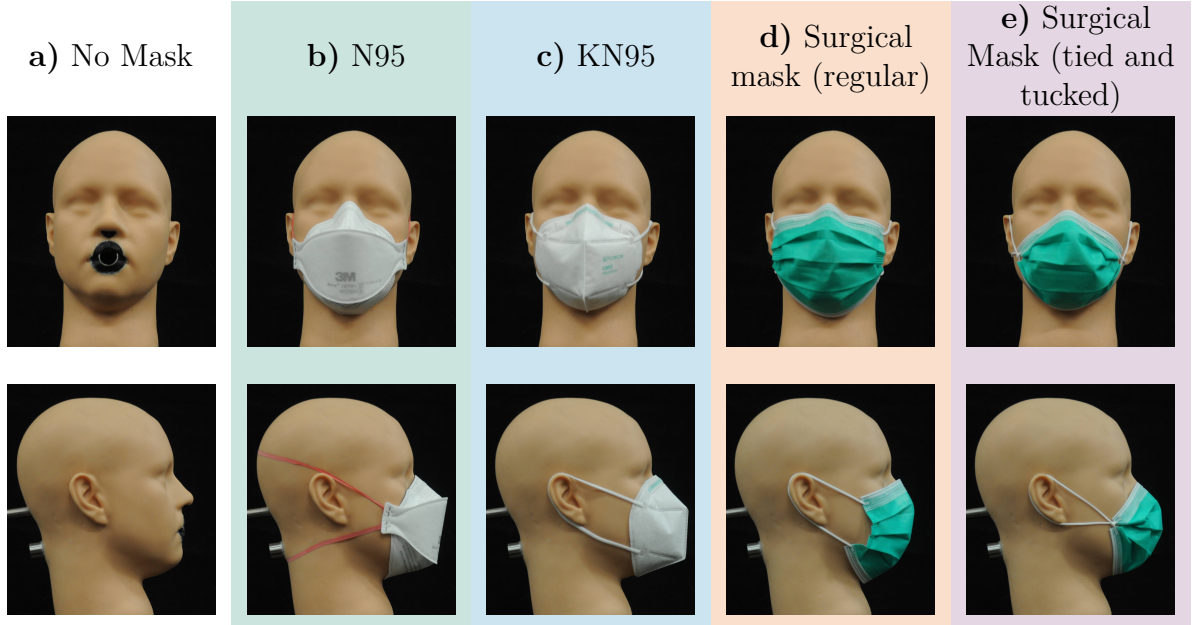


Figure 4.2: Front (top) and side (bottom) views of adult Medium NIOSH manikin wearing tested masks for inward protection efficiency.

analyzer at the time of testing. The measurement duration was identified via shakedown testing, which involved separate trials conducted to confirm the stability and repeatability of experiments. These tests involved extended sampling periods in both the plenum and chamber to ensure steady-state conditions did not change appreciably over the specified test durations.

Fig. 4.3 shows particle number concentration time histories normalized by chamber steady state particle number concentration for each case. The observed exponential increase and approach to steady state particle number concentrations in the chamber is in agreement with the form of the analytical solution to Eq. A.1. The same trend is observed for the measurements in the plenum following the initial transient due to the switch of the measurement location (marked by the hatched region). The results illustrate that steady state is reached in each control volume for at least the last 0.5 hours of sampling, marked in Fig. 4.3. It can be seen from the steady state particle number concentrations levels in the plenum that the N95 FFR produces the most significant reduction in particle number concentration in the plenum compared to the no-mask case, implying the highest inward protection efficiency. This is followed by the KN95 and the two variations of the surgical masks.

4.3 Results

The inward protection efficiency, η_{IPE} , along with material filtration efficiency, η_{MFE} , are shown Fig. 4.4. The results show minor variation in the inward protection efficiency

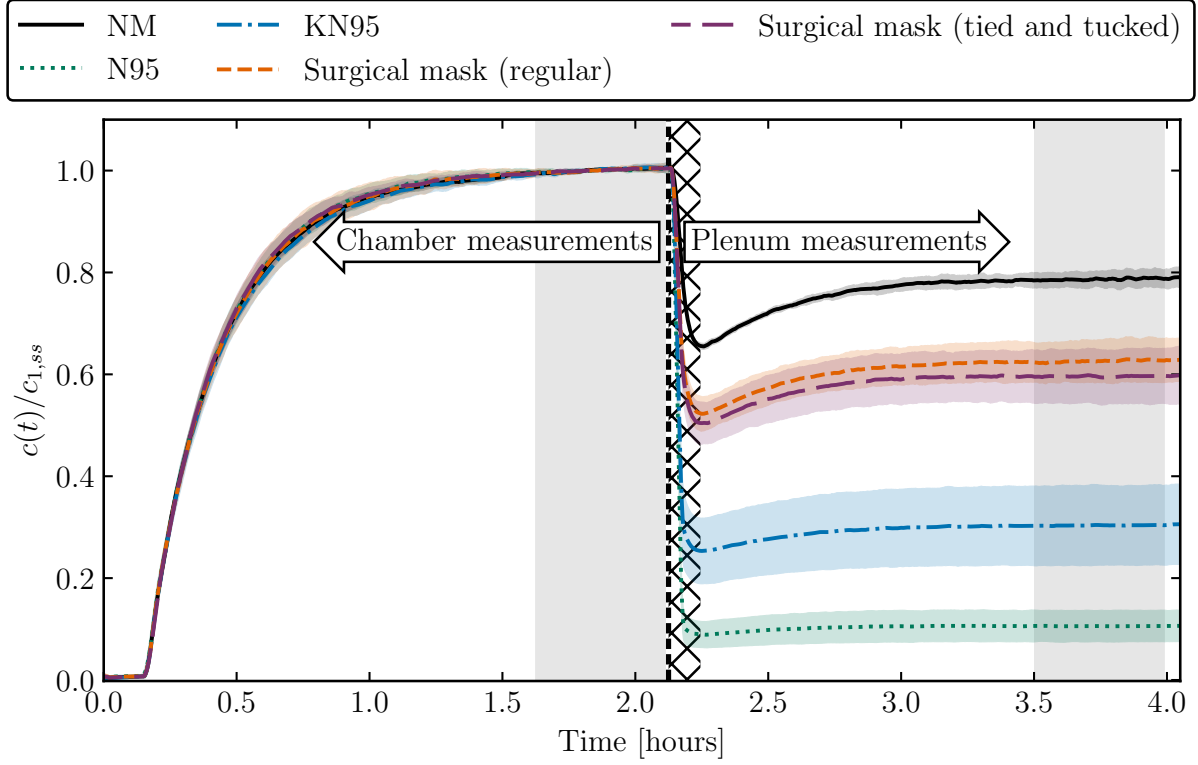


Figure 4.3: Temporal evolution of particle number concentrations normalized by chamber steady state particle number concentration using the setup depicted in Fig. 4.1. Shaded areas show one ensemble standard deviation of 10 tests. Measurements left of the vertical black dashed line show measurements at the chamber and right of it are measurements at the plenum. The gray bands show the sampling time spans for calculation of inward protection efficiency, and the hatched area is a transitional period occurring due to switching of sampling location. Chamber steady state particle concentrations ranged from 0.7×10^5 particles cm^{-3} to 1.1×10^5 particles cm^{-3} .

across the tested particle size range, with a slight decrease in apparent efficiency seen for decreasing particle size. The ensemble mean inward protection efficiency, $\bar{\eta}_{IPE}$, is presented in Table 4.2, where the N95 mask has the highest inward protection efficiency ($86.5 \pm 2.5\%$), followed by KN95, tied and tucked ASTM 3 surgical mask, and regularly worn ASTM 3 surgical mask at $61.5 \pm 6.0\%$, $24.2 \pm 4.6\%$, and $20.4 \pm 3.9\%$, respectively.

The observed variation in the apparent inward protection efficiency within the test ensemble is attributed primarily to deviations in mask fit from test to test. This is indirectly confirmed by observing the notably smaller variation in the measurements pertaining to the no-mask case in Fig. 4.3 compared to those with a given mask type. For the inward protection efficiency estimates in Table 4.2, the larger standard deviation observed in the KN95 of 9.5% suggests that the mask model used is more sensitive to variations in mask fit than the other tested masks. The N95 case has the smallest standard deviation for inward protection efficiency during testing (3.9%), indicating a lower sensitivity to variations in

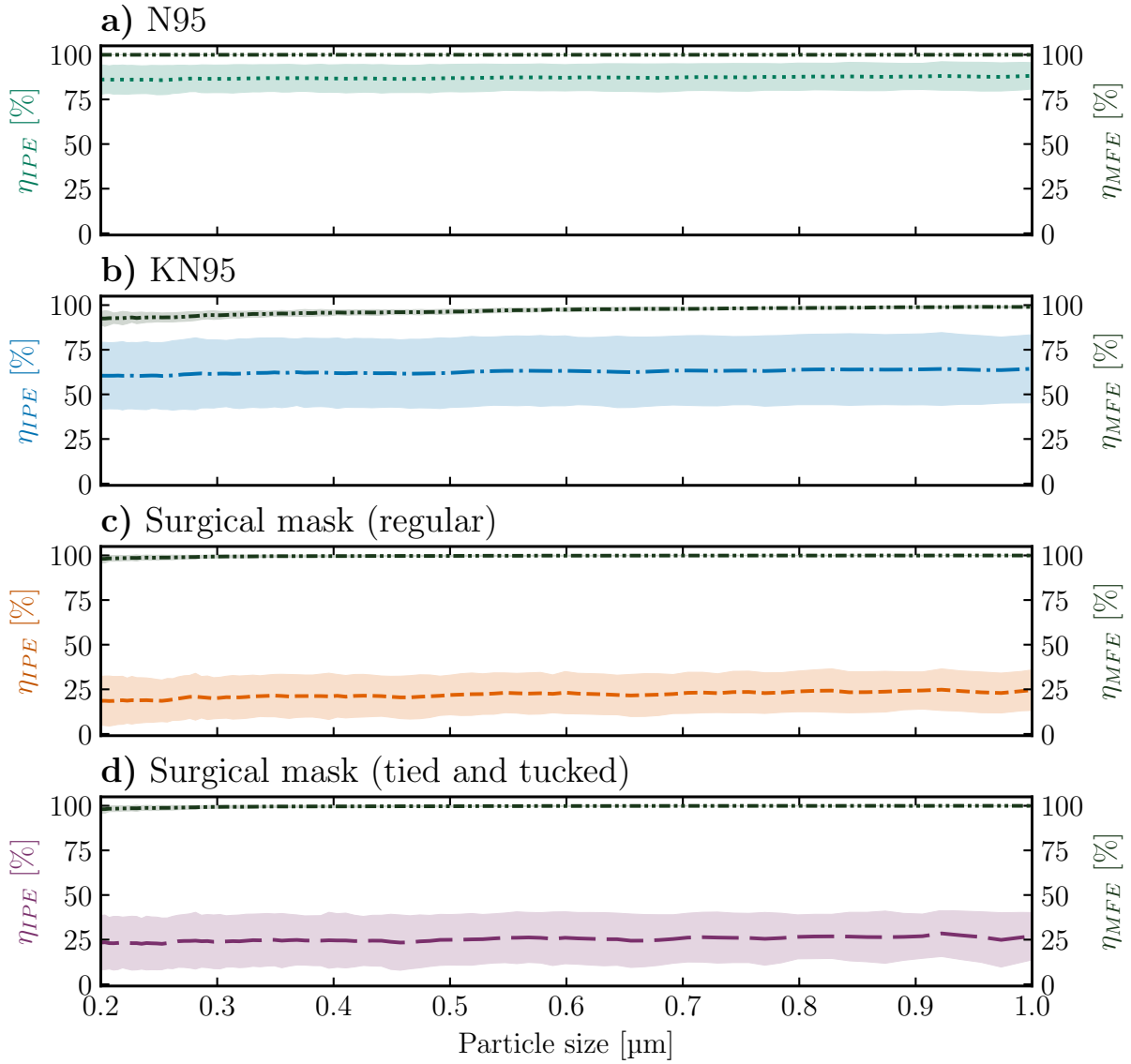


Figure 4.4: Inward protection efficiency and material filtration efficiency with respect to particle size of tested masks on adult manikin. A face velocity of 1.6 cm s^{-1} is used for material filtration efficiency based on adult breathing characteristics. Shaded areas indicate standard deviations of 10 samples for inward protection efficiency and 6 for material filtration efficiency.

mask fit.

Across the measured particle size range, the material filtration efficiency for the N95 is at or near 100%, while the surgical mask has a material filtration above 95%. Meanwhile, the KN95 material filtration efficiency drops slightly for smaller particle sizes. For all the mask types tested, the material filtration efficiency is notably larger than the inward protection efficiency for all particle sizes. Further, for particle diameters above approximately $0.4 \mu\text{m}$,

Table 4.2: Ensemble mean inward protection efficiency of masks fitted on medium NIOSH adult manikin with 95% confidence interval.

Test Case	$\bar{\eta}_{IPE}[\%]$
N95	86.5 ± 2.5
KN95	61.5 ± 6.0
Regularly worn surgical mask	20.4 ± 3.9
Tied and tucked surgical mask	24.2 ± 4.6

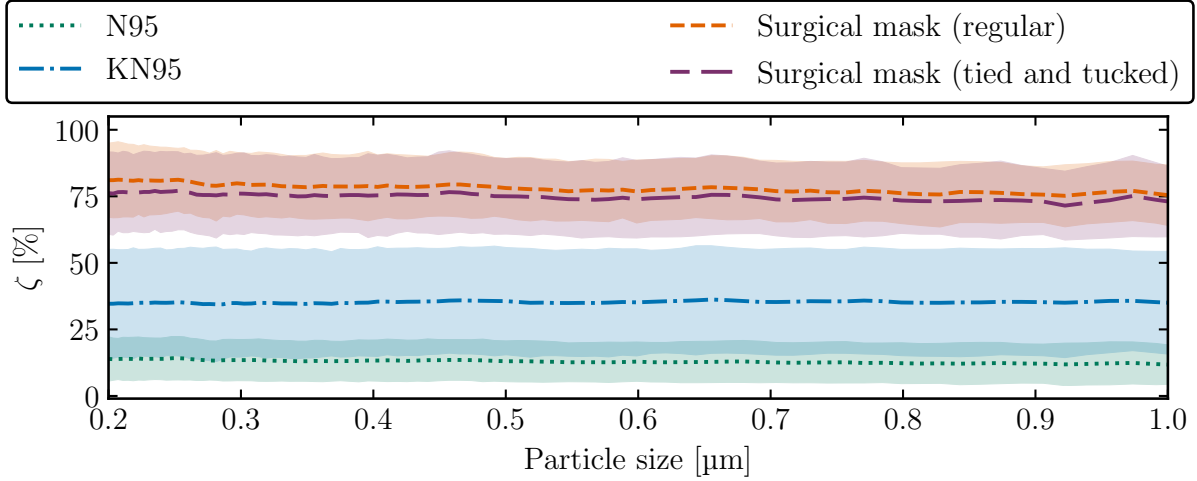


Figure 4.5: Inward leakage through gaps in the mask-face interface with respect to particle size tested on the adult manikin. Shaded areas indicate two standard deviations from the mean.

the material filtration efficiency is comparable across different mask types, contrasting with the notable differences in the inward protection efficiency between different masks (Fig. 4.4). These observations indicate that leakages are the primary factor determining the inward protection efficiency.

Having quantified both material filtration and inward protection efficiencies (Fig. 4.4), the mask leakage, ζ , can be estimated using Eq. 2.6. Fig. 4.5 shows the leakage estimate with respect to particle size for each mask. The masks from lowest to highest overall leakage based on Fig. 4.5 are the N95, KN95, and both surgical mask cases.

4.4 Discussion

The notable difference between the apparent inward protection efficiency of the tested barriers and their material filtration efficiencies points to the deleterious effect of leakages known to impact mask performance [109, 153]. For the tested masks there is an inverse correlation between leakage and inward protection efficiency as presented in Table 4.2.

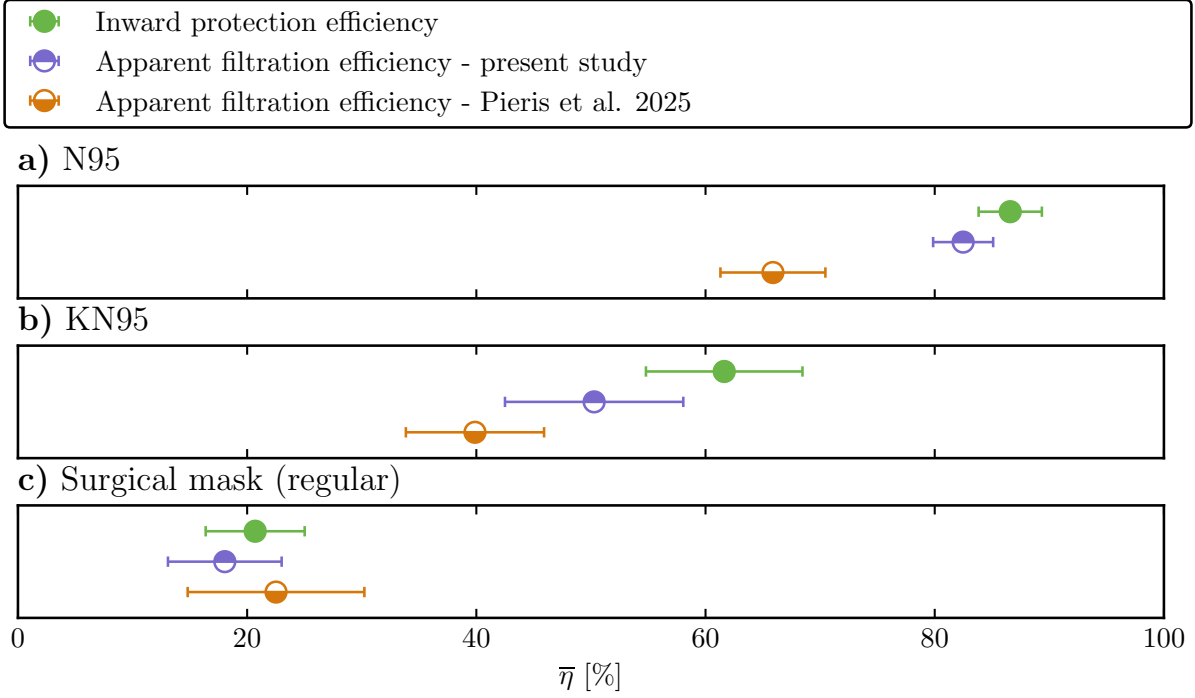


Figure 4.6: Mean inward protection efficiency compared with mean apparent filtration efficiencies from both the present study and Pieris *et al.* [97]. Error bars are 95% confidence intervals from the mean.

Furthermore, the effects of tying and tucking the surgical mask on leakage show no statistically significant decrease in leaked particles ($72.8 \pm 5.4\%$ versus $67.7 \pm 6.4\%$), indicating that this method does not result in much improvement of surgical mask fit. The surgical mask in this study has a higher leakage than those reported in both Grinshpun *et al.* [109] and Pushpawela *et al.* [154]. On the other hand, the N95 leakage rate in this study is roughly comparable to the data reported in Pushpawela *et al.* [154] and nearly double what that is reported by Grinshpun *et al.* [109].

Masks not only provide protection, but also act as a source control measure by reducing the number of particles exhaled by an individual. It is thus of interest to compare the associated efficiency metrics. In Fig. 4.6, inward protection efficiency is compared to the source control apparent filtration efficiencies of the N95, KN95, and regularly worn surgical masks on the manikin. Results from the present study, obtained using the methodology outlined in Chapter 3, are shown alongside those reported by Pieris *et al.* [97], wherein a comparable experimental setup was used. For the two FFRs evaluated (N95 and KN95), inward protection efficiency exceeded outward apparent filtration efficiency. However, the relative difference between the two fitted mask efficiencies is smaller than those reported by Pieris *et al.* [97]. Overall, for the N95 case, present results contradict those by Koh *et al.* [92], where regularly worn N95 respirators provided lower inward ($\sim 25\% - 35\%$) than outward apparent filtration efficiency ($\sim 40\% - 50\%$). Notably, the reasons for such difference were not explored in that study. For all the barriers tested, the present results show comparable

inward and apparent filtration efficiencies, with the former being consistently higher within the uncertainty bounds. For the surgical mask, such an observation agrees with Koh *et al.* [92] and Pan *et al.* [96] in finding no significant difference between inward protection and apparent filtration efficiencies for this mask type.

The ability of estimate average inward protection efficiency for a given mask type and the associated statistical variation in population is of particular interest for risk assessment and modeling of disease spread. This has proved a challenging task due to lack of data for some types of barriers, inconsistent and non-standardized testing methodologies, and variability in the physical properties of similar mask types. Fig. 4.7 shows results reported from other studies of inward protection efficiency. Studies plotted in blue indicate the use of human subjects, while those in red utilized manikins to evaluate protective efficiency. Few studies were found for the tied and tucked surgical mask and KN95, none of which presented protection with respect to particle size; regardless these agree with trends observed in this work, confirming that the KN95 has lower efficiency than the N95 but higher than the regularly worn surgical mask. The protection of a surgical mask is not significantly improved using the “tie and tuck” method, contradicting findings from Clapp *et al.* [108]. For the N95 and regularly worn surgical mask, significant variations in reported data for inward protection efficiency from different studies are observed, pointing to the necessity for a standardized approach and detailed reporting of the mask models used and testing methodologies employed. For example, in the United States and Canada, the ASTM F2100 standard is commonly used to categorize surgical masks into three categories, from level 1 with the lowest material filtration and level 2 and 3 having the highest and equal material filtration [151, 152]. In contrast, pseudo-surgical face coverings can have significantly lower material filtration efficiencies compared to any of the certified surgical masks. Additionally, future studies should verify certification of face masks tested when applicable as the existence of fraudulent masks can skew final results [150].

Computing the ensemble mean inward protection efficiency of data presented in Fig. 4.7 for particle sizes between $0.2\text{ }\mu\text{m}$ to $1\text{ }\mu\text{m}$ allows for a comparison of the present results with the broader literature. Mean ensemble inward protection efficiencies, across studies (excluding present work results), is 92.2% for N95 masks and 47.6% for surgical masks with standard application, with standard deviations of 12.3% and 16.1%, respectively. The provided statistical metrics were obtained by weighting data from different studies based on study sample size. Overall, this places the present results reported in Table 4.2 within two standard deviations of the mean ensemble inward protection efficiencies for both N95 and surgical mask. For the purpose of risk assessment and modeling with 95% confidence limits, including present work data into these population statistics produces a mean ensemble inward protection range of [67.9%, 100%] and [12.5%, 79.6%] for N95 and surgical masks, respectively. The lower bound represents a worst-case mean inward protection efficiency and the average of this range being a reasonable mean expectation for inward protection provided by these masks.

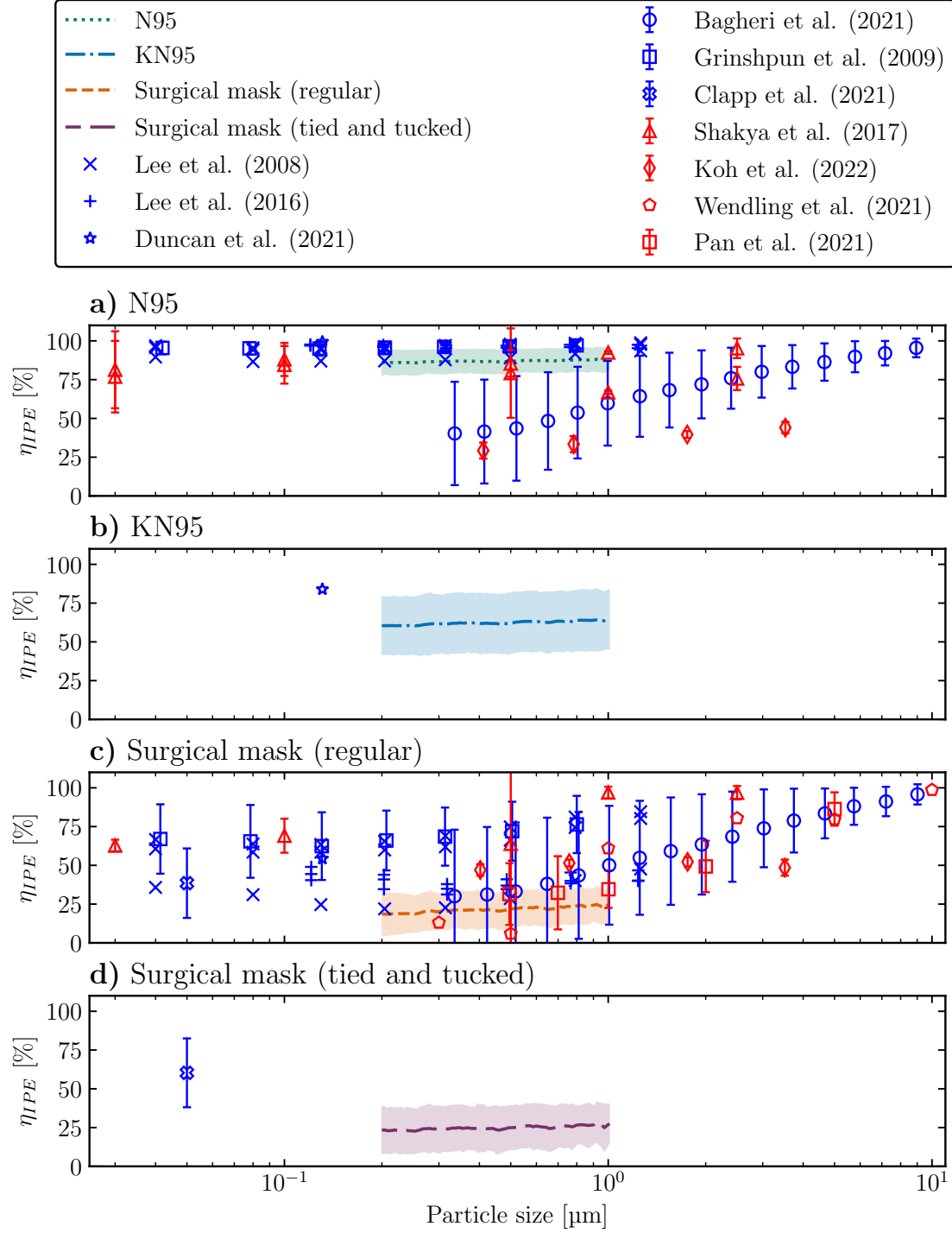


Figure 4.7: Inward protection efficiency from the present work plotted alongside results from other studies evaluating inward protection efficiency for masks tested on adult manikin. Red plots indicate the study was conducted using manikins and blue indicates the use of human subjects. Error bars and shaded area indicate two standard deviations.

4.5 Concluding Remarks

Experimentally determined inward protection efficiencies for four facial mask variations for particles in the $0.2\text{ }\mu\text{m}$ to $1\text{ }\mu\text{m}$ range were presented in this chapter. Results demonstrate significant impact of leakage in mask efficiency, exhibiting a considerable decrease from the material filtration by a mask. Tested N95 masks provides the highest mean inward protection efficiency ($86.5 \pm 2.5\%$) followed by KN95 masks ($61.5 \pm 6.0\%$), despite both standards requiring a similar material filtration efficiency. The surgical mask worn regularly exhibits the lowest mean inward protection efficiency ($20.4 \pm 3.9\%$) and is improved by a not statistically significant amount through use of the “tie and tuck” method ($24.2 \pm 4.6\%$). For both N95 and KN95 mask types, inward protection efficiency was higher than outward filtration efficiency. For the surgical mask, inward protection and outward filtration efficiencies were comparable across the tested particle size range. A quantitative comparison of the data for inward protection efficiency from this work and other studies shows a high degree of variability in measurements of inward protection efficiency. This highlights the importance of verifying and specifying mask certification in future studies. Statistical analysis of the available results, including those from the present work was performed, weighting data based on the statistical sample size reported in each study. The obtained ranges of mean inward protection efficiency are $[67.9\%, 100\%]$ and $[12.5\%, 79.6\%]$ for N95 and surgical masks, respectively, and can be used as a guide for future risk population assessment and modeling investigations.

Chapter 5

Source Control Efficiency of Child Masking

5.1 Introduction

Mask wearing generally is more favored as a source control mechanism than a measure for personal protection due to its greater effectiveness in reducing community transmission [9, 88, 93]. However, variations in mask fit and material can significantly affect fitted mask filtration efficiency [25].

Despite the effectiveness of various facial masks as source control devices having been well documented for adults [19, 92, 95, 97], just a few studies have considered the reduction of exhaled particles for children [57, 58]. This is despite recommendations made during the pandemic by public health agencies such as the WHO and Health Canada encouraging the masking of children as young as 5 years old [27, 53]. While children tend to present milder symptoms of COVID-19 when infected [51], they have been observed to shed similar viral loads as adults [52]. With that in mind, child masking remains important for reducing community airborne transmission of diseases. Moreover, studies have shown schools that introduced mask mandates during the pandemic saw a reduction in COVID-19 transmission [54–56].

Discomfort, including poor mask breathability, has been cited as a factor causing children to remove their face masks [132]. This suggests focusing only on mask effectiveness when assessing available options for child masking is not best practice for everyday use. Although general mask comfort is a subjective metric, relative breathability can be quantified by the pressure drop across the mask which depends on mask fit and material resistance to exhalation [19, 70].

In this chapter, the aim is to quantify the source control apparent filtration efficiency for aerosol particles ranging from $0.2\mu\text{m}$ to $1\mu\text{m}$ for adult and child versions of the KN95, CSA certified CA-N95, and ASTM level 3 surgical masks and the N95 respirator on a manikin representative of a 7 year old child. The fit of each mask is evaluated both quantitatively by comparing against the material filtration efficiency and qualitatively through flow visualization techniques. Finally, the breathability of the tested masks is measured through pressure drop across each mask during exhalation; this being especially important due to children being more sensitive to mask comfort.

5.2 Experiment Details

A diagram of the experimental setup is shown in Fig. 5.1. Testing was performed using a head form representative of 7 year old children based on measurements by Goto *et al.*

Table 5.1: Child exhalation properties with 95% confidence interval

Parameter	Value	Unit
Exhalation rate (h_{exh})	26.4 ± 0.3	exhalations min^{-1}
Exhalation volume (V_{exh})	234.0 ± 23.8	ml exhalation $^{-1}$

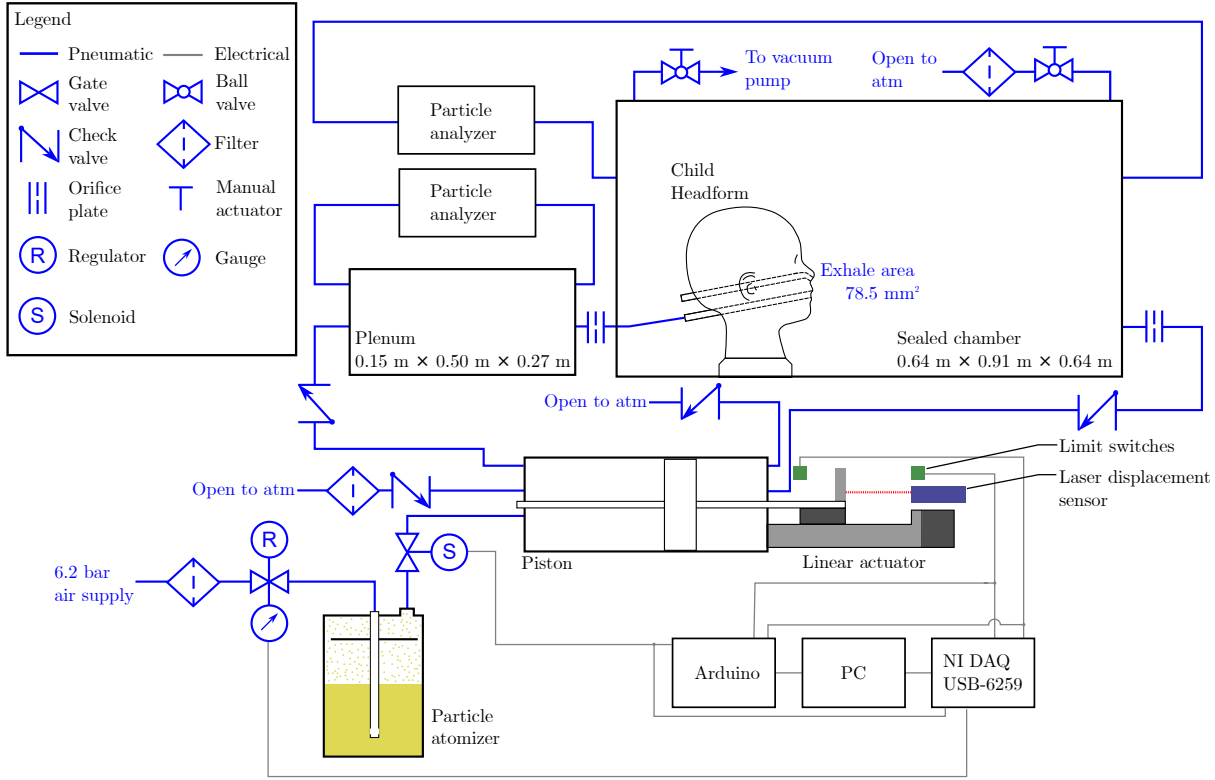


Figure 5.1: Experimental setup used to measure mask apparent filtration efficiency on a child manikin. In this configuration, the plenum is control volume ‘1’ and the sealed chamber is control volume ‘2’. Figure is adapted from Pieris *et al.* [97].

[149]. The manikin was placed in a sealed chamber and connected to a piston pump via a plenum. Breathing occurred at the manikin mouth with the nasal line sealed to prevent particle leakage through the nose. The exhalation of a 7 year old child was approximated as a half-wave sine curve, with both tidal volume and exhalation rate based on measurements from Roy *et al.* [147]. Measured exhalation properties are presented in Table 5.1.

Fig. 5.2 shows all masking configurations considered in the study, namely, no-mask, N95, and child, adult, and modified adult versions of the CA-N95, KN95, and ASTM level 3 surgical masks. The loose fit of certain adult masks is apparent in Figs. 5.2e–5.2h. Moreover, it can be observed that mask geometry and the tension created by the ear loops holding it in place are important factors for mask fit. These factors can be seen to have an adverse effect on adult mask fit. Thus, it is of interest to isolate the impacts of these two factors on the overall apparent filtration efficiency. Therefore, modified adult masks (Figs. 5.2i–5.2k) are considered, with ear loops adjusted to achieve the same tension as that on the child masks on the child manikin. Since the N95 does not have a child equivalent, it was not tested using this modification.

The modified adult masks were created by first aligning each adult CA-N95, KN95, and surgical mask with its corresponding child version. The ear loop attachment points on the child mask were then marked on the adult version. Preliminary testing showed that ear

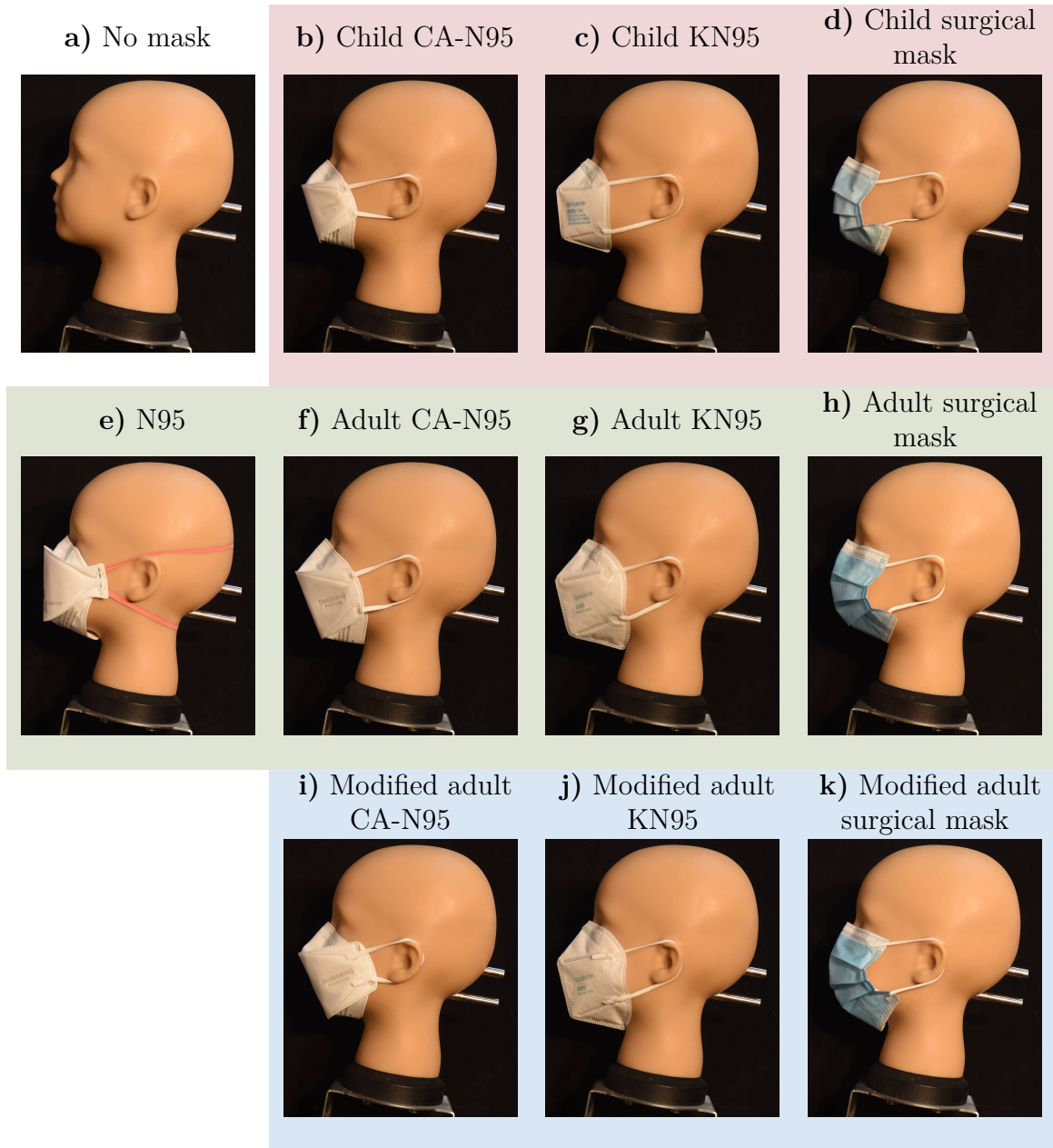


Figure 5.2: Side views of child manikin wearing tested face masks

loop stiffness was the same for adult and child versions for both CA-N95 and KN95 but not surgical masks. Thus, for the CA-N95 and KN95, the ear loops were detached and reattached onto the marked positions, ensuring the child ear loop length on the modified mask matched the child version. For the surgical mask, child ear loops were transferred directly onto the adult mask geometry and attached to the marked location.

The following procedure was used for testing apparent filtration efficiency. The child manikin equipped with the tested barrier (or without one) was placed in the chamber and connected to the exhalation line. Before each trial, a blower was used to replace the air

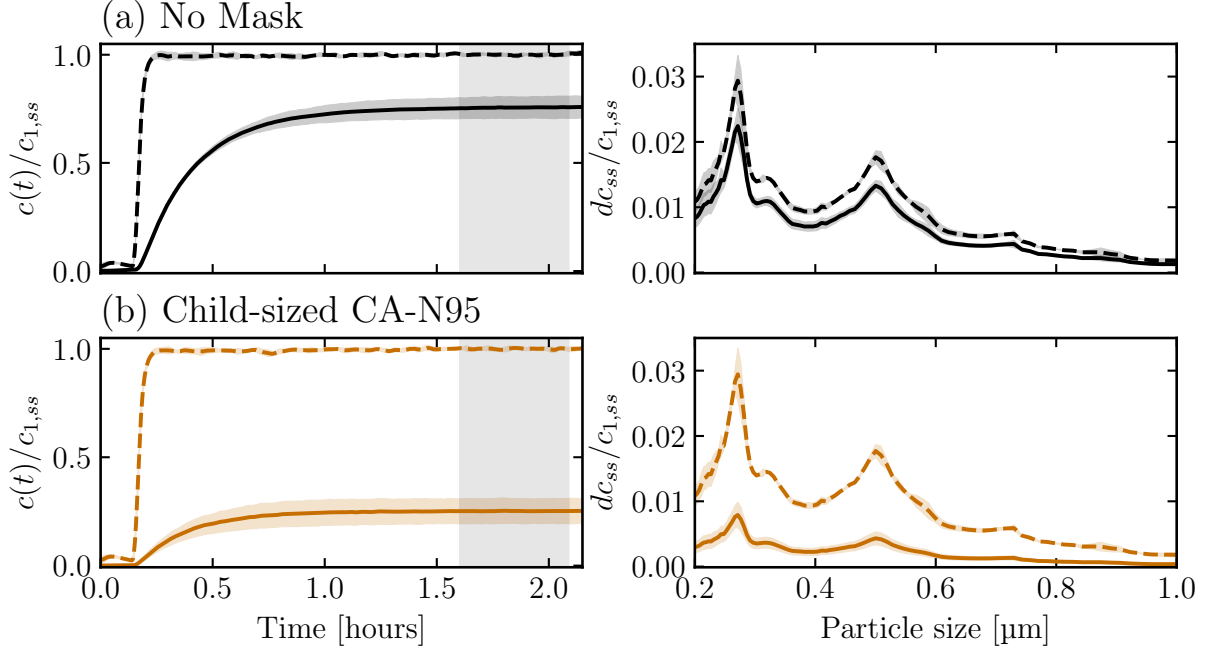


Figure 5.3: Temporal evolution (left) and steady state size distribution (right) of particle number concentrations in the no mask and child-sized CA-N95 cases normalized by plenum steady state particle number concentration using the setup depicted in Fig. 5.1. Solid lines are measurements in the chamber and dashed lines are measurements in the plenum. Shaded areas show one ensemble standard deviation of 10 tests. The gray band in the time history plots show the steady state sampling time span for calculation of apparent filtration efficiency. Steady state particle number concentrations in the plenum ranged from 0.9×10^5 particles cm^{-3} to 1.3×10^5 particles cm^{-3} .

in the chamber with clean filtered air drawn in from the ambient through a HEPA filter, and air was blown into the plenum to purge it of particles. Afterwards, testing began with 260 cycles of background particle count measurements (approximately 10 minutes). Then, particle generation was activated and measurements were taken for another 3120 cycles (approximately 2 hours), ensuring steady state particle number concentrations in both control volumes was reached for at least 30 minutes. Testing of the aforementioned masking cases was done in 10 randomized cohorts for statistics.

Fig. 5.3 shows the particle number concentration time histories and steady state particle size distributions in both the plenum and the chamber for both the no-mask and child-sized CA-N95 cases. Overall, the plotted temporal evolution align well with expected numerical solutions to Eqs. (A.1) and (A.4) observed in Fig. A.2. Steady state levels are sampled for at least 30 minutes in both control volumes with the gray-shaded region indicating the time window of data used to estimate apparent filtration efficiency using Eq. 3.1.

In addition to estimating apparent filtration efficiency, leakage was assessed quantitatively using Eq. 2.6 to calculate the proportion of leaking particles and qualitatively using the flow visualization procedure described in Section 3.3.

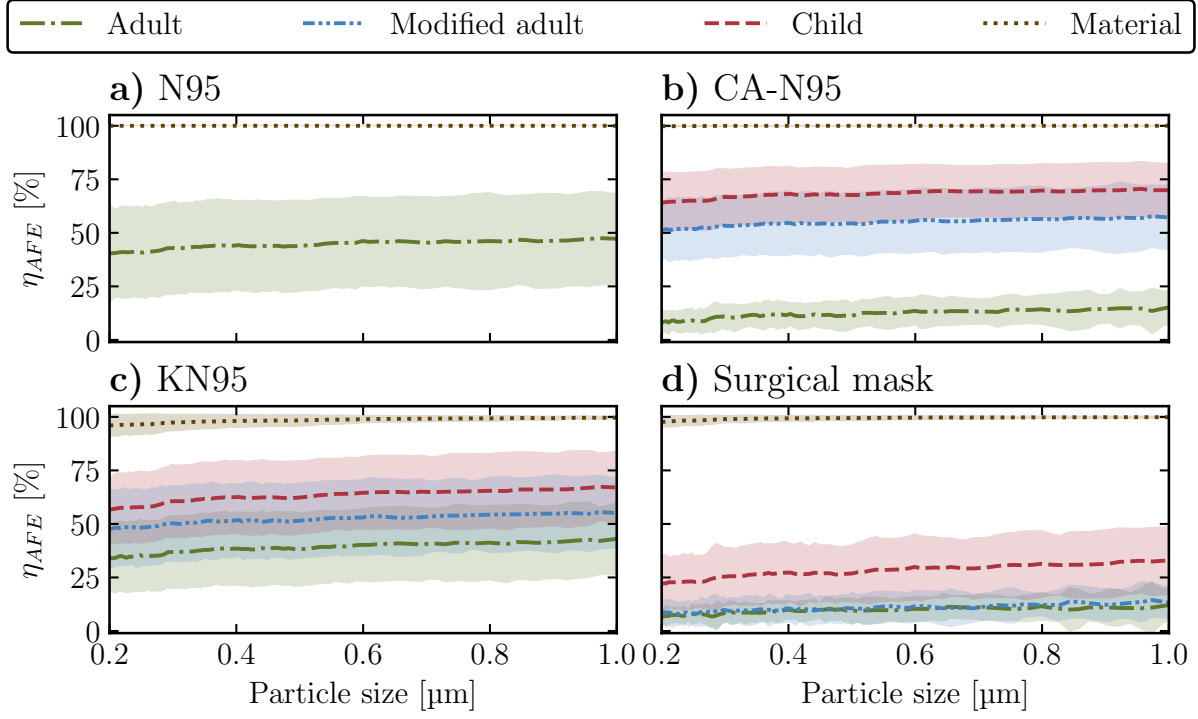


Figure 5.4: Apparent filtration efficiency and material filtration efficiency with respect to particle size of tested masks on child manikin. A face velocity of 1.5 cm s^{-1} is used for material filtration efficiency based on child breathing characteristics. Shaded area indicate two standard deviations of 10 samples for apparent filtration efficiency, 10 samples for material filtration efficiency of the KN95 and surgical mask, and 5 samples for material filtration efficiency of the N95 and CA-N95.

Furthermore, relative exhalatory breathability of tested masks for children was quantified by measuring differential pressure across the mask following the methodology in Section 3.2.

5.3 Results

Particle-size specific estimations of apparent and material filtration efficiencies are plotted in Fig. 5.4. Across all tested configurations, the material filtration efficiency remains close to 100%, indicating that mask materials effectively remove sub micron particles across the examined size range. In contrast, apparent filtration efficiencies are substantially lower than the material filtration efficiency, underscoring the significant effect of leakage around the mask seal. Overall, the child-sized CA-N95 and KN95 masks exhibit the highest apparent filtration efficiencies. A significant reduction in source control efficiency is observed for adult-sized masks relative to corresponding child-sized variants. The modified adult versions of the CA-N95 and KN95 demonstrate intermediate apparent filtration efficiencies between the child and adult masks. Among tested masks, the adult-sized CA-N95 as well as adult

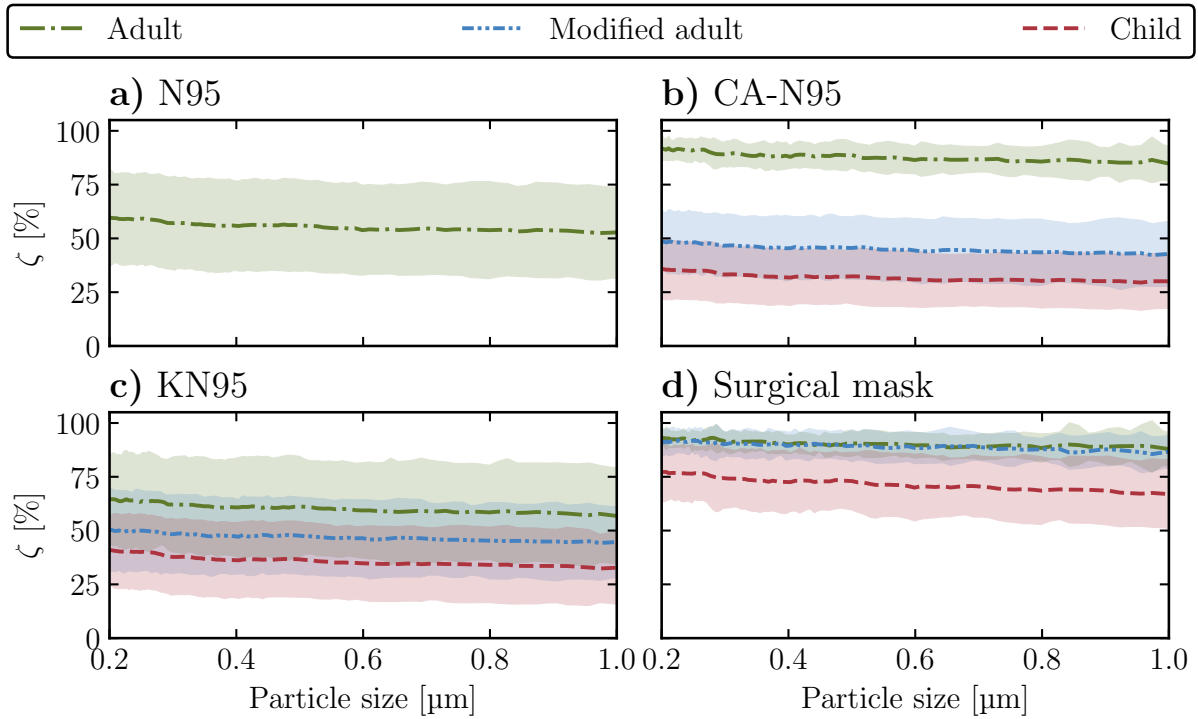


Figure 5.5: Outward leakage through gaps in the mask-face interface with respect to particle size tested on the child manikin. Shaded areas indicate two standard deviations from the mean.

and modified adult surgical masks exhibit the lowest performances.

The proportion of particles leaking through gaps around the mask-face interface computed using Eq. 2.6 is presented in Fig. 5.5. Overall, the adult-sized masks exhibit the highest leakage for each mask type, reflecting poorer fit on the child manikin relative to the child-sized variants. Furthermore, increasing the ear loop tension on adult-sized masks results in a reduction of leakage for the CA-N95 and the KN95, but not for the surgical mask.

Four primary leakage areas in the front view flow visualizations (Fig. 5.6) are identified: two lateral jets from gaps near the cheek directed outward and upward, and two downward jets emanating from gaps near neck and jaw. In the side view visualizations (Fig. 5.7), two leakage paths are observed: one directed upwards from gaps near the nasal region and another downward from near the chin. Overall, the prominence of these leakage flows vary with mask fit.

The best-fitting masks, the child-sized CA-N95 and KN95, exhibit little leakage in the front view (Figs. 5.6b and 5.6c). However, in the side view, a distinct upward jet from the nasal region and faint downward wisps are observed (Figs. 5.7b and 5.7c). In contrast, the child-sized surgical mask has two lateral puffs from the cheek area (Fig. 5.6d), with a smaller upward jet observed in the side view (Fig. 5.7d).

Observations for the modified adult and adult surgical masks confirm poor fit on the

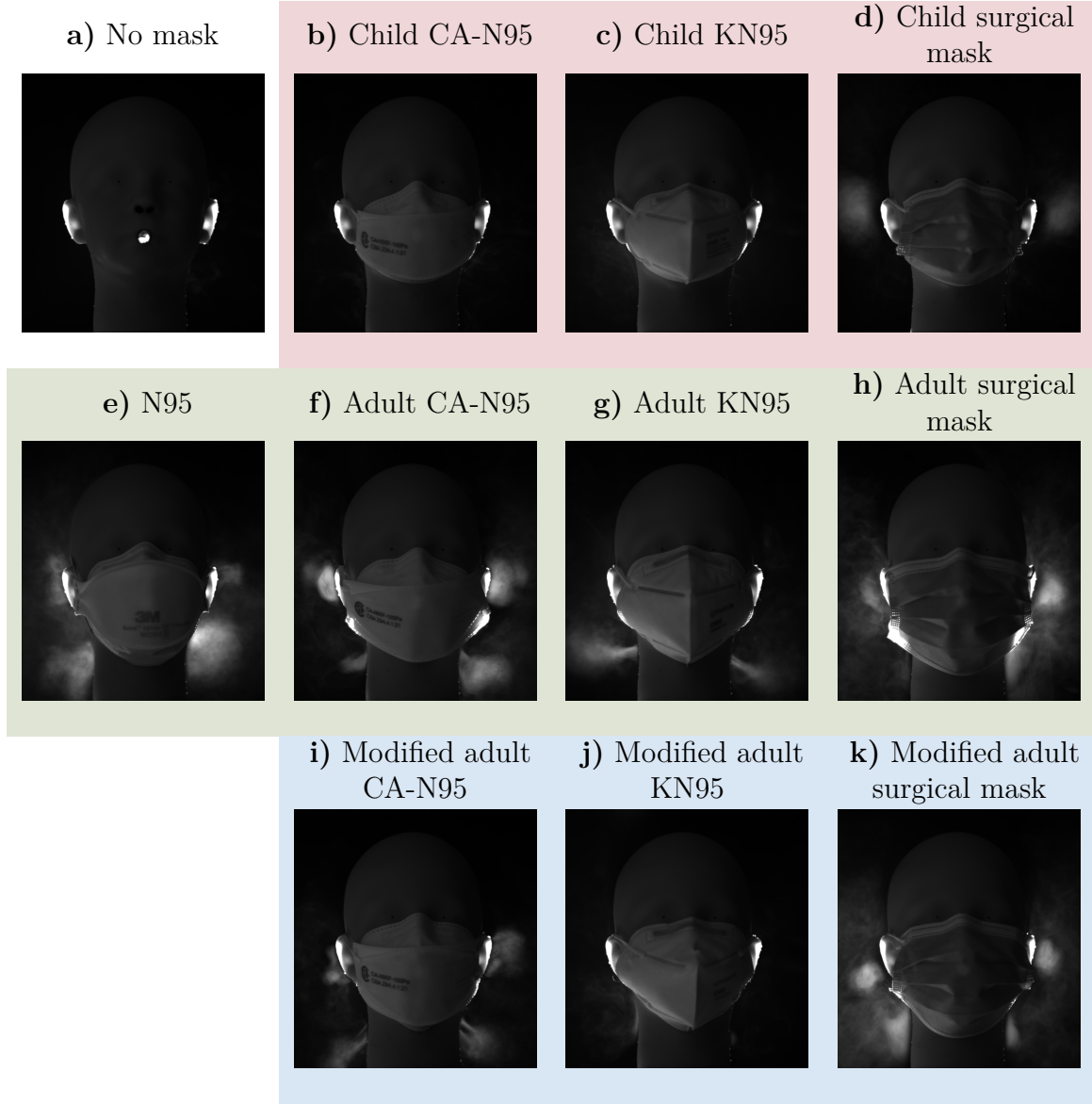


Figure 5.6: Front view flow visualizations of exhaling child manikin wearing tested face masks. Images are an average taken closest to peak exhalation flow of 11 exhalations.

child manikin, with particles leaking laterally and downwards showing a great degree of dispersion (Figs. 5.6h and 5.6k).

For all KN95 masks, the primary leakage is seen in the side view, with prominent upward jets from the nasal region and wisps moving downwards from the chin (Figs. 5.7c, 5.7g, and 5.7j). In the front view, lateral leakage from the cheek area is minimal across KN95 variants (Figs. 5.6c, 5.6g, and 5.6j). Finally, the N95 mask shows significant lateral leakage in the front view (Fig. 5.6e), whereas in the side view visualization reveals little to no leakage (Fig. 5.7e).

The mean peak pressure drops plotted against mean ensemble apparent filtration efficien-

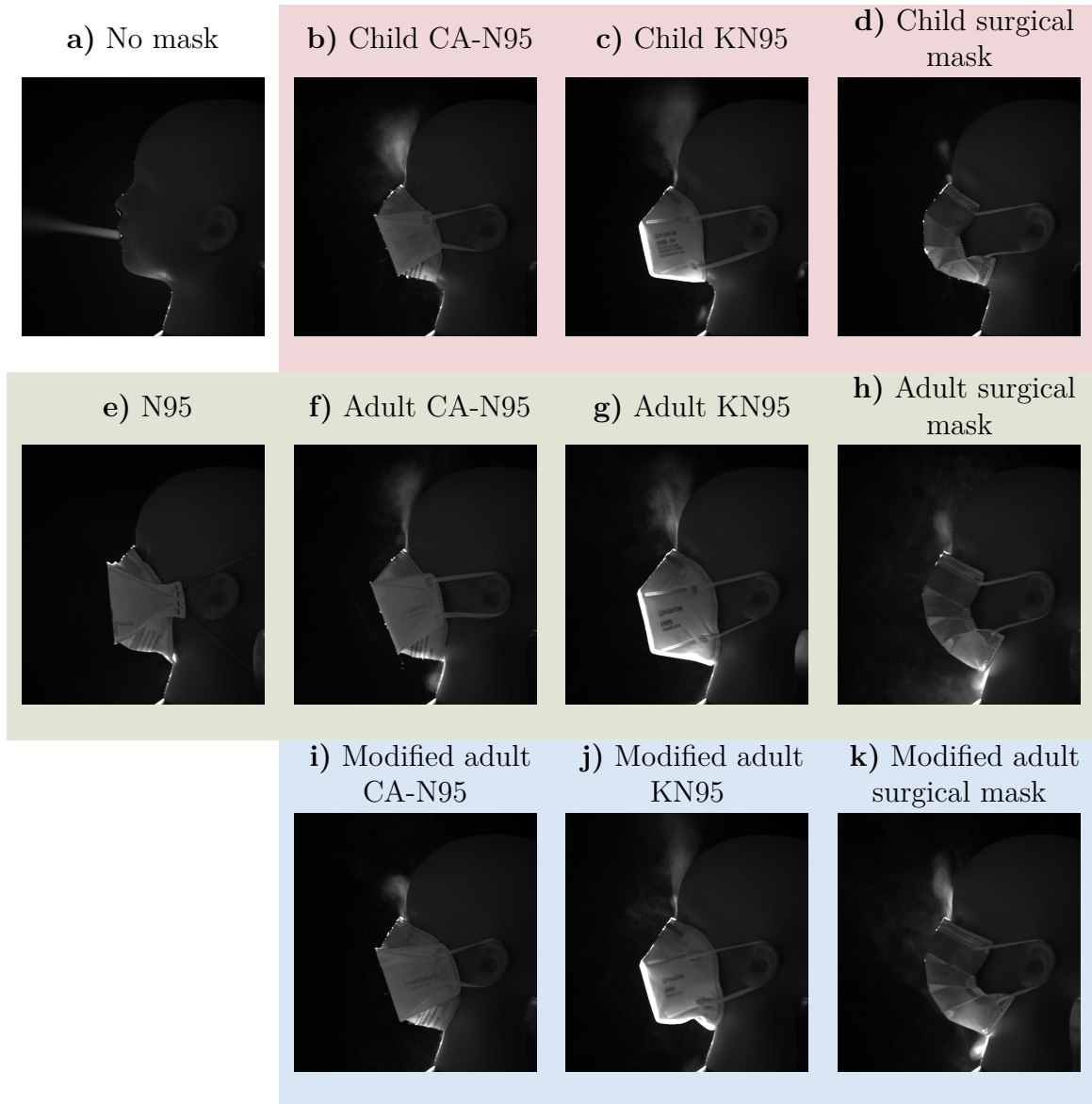


Figure 5.7: Side view flow visualizations of exhaling child manikin wearing tested face masks. Images are an average taken closest to peak exhalation flow of 11 exhalations.

cies for the tested masks are presented in Fig. 5.8. The results suggest that breathability can vary substantially between masks even in cases where no statistically significant differences are observed in mean apparent filtration efficiency. Overall, a positive correlation between apparent filtration efficiency and peak pressure drop is evident. For poorly fitting masks, the presence of large gaps around the mask-face interface enable significant pressure relief reflected by the low pressure differential measured for the adult-sized CA-N95 and modified and unmodified adult surgical masks.

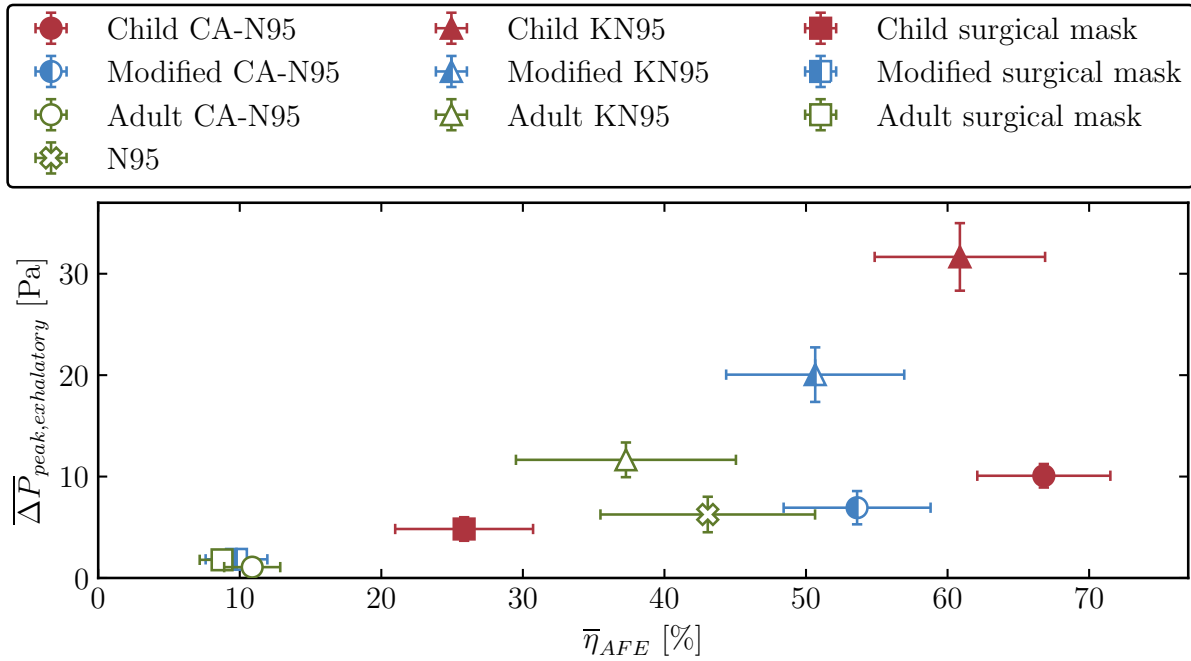


Figure 5.8: Mean peak exhalatory pressure drop of masks fitted on the child manikin with respect to mean apparent filtration efficiency. Error bars are 95% confidence intervals of the mean.

5.4 Discussion

The results presented in Figs. 5.4, 5.5, and 5.8 demonstrate that child-sized variants of a mask, where available, exhibit higher mean apparent filtration efficiency compared to their corresponding adult-sized versions worn on a child. This improvement is largely attributed to a reduction in gaps at the mask-face interface. Among tested face masks, the child-sized CA-N95 and KN95 demonstrate the highest apparent filtration efficiency and correspondingly the lowest overall leakage. Notably, the reduction in apparent filtration efficiency from child version to adult version is greater for the CA-N95 than for the KN95. This observation suggests that the conical mask geometry of the adult KN95 is better suited for the smaller facial dimensions of children. This is further corroborated by the front flow visualizations in Figs. 5.6f and 5.6g, where the adult KN95 shows significantly reduced lateral leakage out from cheeks than the adult CA-N95 respirator.

As shown in Fig. 5.8, the KN95 masks exhibit higher peak pressure drops compared to other masks with similar mean ensemble apparent filtration efficiencies. While no statistically significant differences in mean apparent filtration efficiency are observed between the modified adult and child versions of the KN95 and CA-N95 or between the adult version of the KN95 and the N95, the KN95 consistently exhibits a higher pressure drop across each of the three pairs. In fact, all tested versions of the KN95 mask demonstrate mean peak pressure drops equal to or greater than any other mask type.

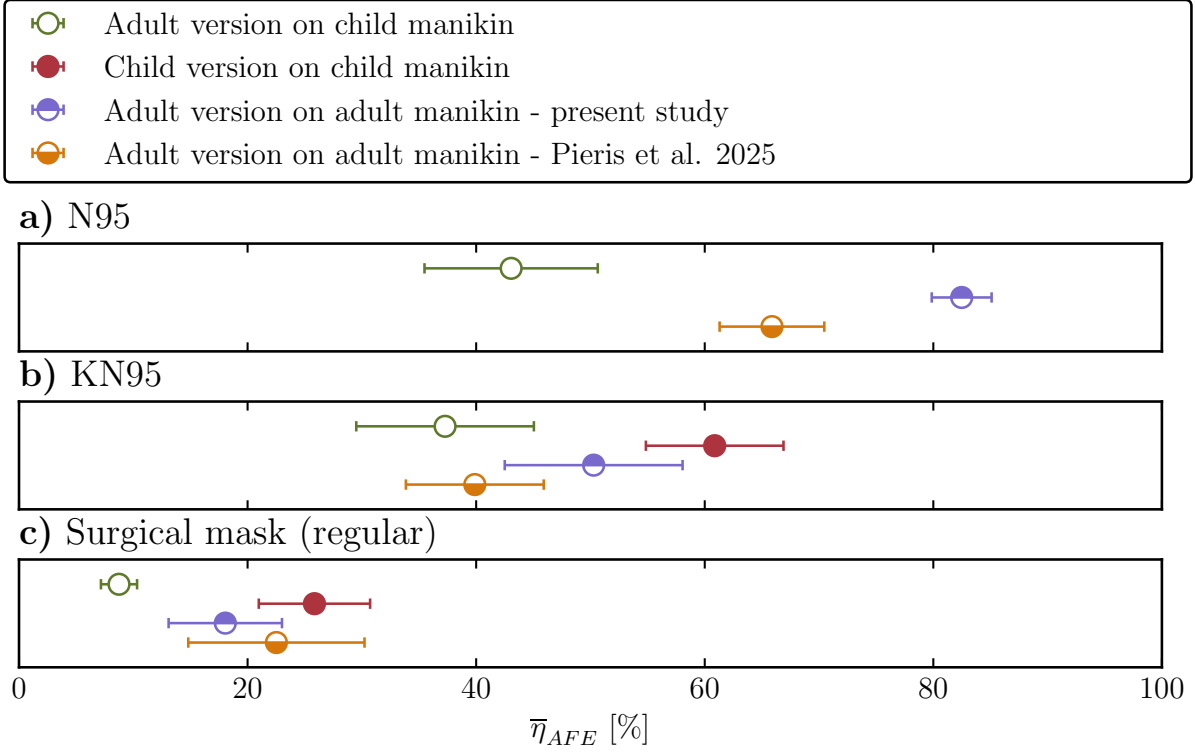


Figure 5.9: Mean apparent filtration efficiency of masks fitted on child and adult manikins. Error bars indicate 95% confidence intervals from the mean.

Exhalatory breathing resistance of masks fitted on adult head forms have previously been reported in Arumuru *et al.* [70] and Yao *et al.* [71]. Trends observed by Yao *et al.* [71] are consistent with present results, wherein FFRs appropriately-sized for the test manikin demonstrate greater exhalatory resistance than surgical masks. In contrast, Arumuru *et al.* [70] reported the opposite trend, with surgical masks exhibiting higher exhalatory resistance compared to the tested FFRs, which is attributed to the surgical mask used obstructing airflow close to the exhalation line compared to the N95 used in that study.

On the child head form, the adult versions of tested masks produce a looser seal and increased leakage compared to child-sized variants. The resulting decrease in apparent filtration efficiency is driven primarily by two properties crucial to maintaining a proper seal: mask geometry and ear loop tension. Modifying adult masks to increase the latter improved apparent filtration efficiency, however, the performance of modified masks remained below that of corresponding child-sized masks. Given that ear loop tension are matched between the child and modified adult versions, remaining differences in apparent filtration efficiency are attributed to suboptimal mask geometry. This effect is particularly evident for the modified adult surgical mask, where the adverse impact of poorly fitting mask geometry negates any positive effects from tightening the ear loops, resulting in no statistically significant improvement from the unmodified adult variant.

The influence of head form size on mask performance was assessed by comparing apparent

filtration efficiency obtained for masks on the child head form with those on the adult head form. Apparent filtration efficiencies of the adult-sized KN95, surgical mask, and N95 worn on a medium NIOSH adult manikin were estimated using the same methodology outlined in Chapter 3 and a comparable experimental procedure in Pieris *et al.* [97]. Fig. 5.9 presents the mean apparent filtration efficiency from these studies alongside relevant results on the child manikin. A significant degradation in apparent filtration efficiency is noted for both the N95 and adult surgical masks when fitted on the smaller child head form relative to when they are evaluated on the adult manikin. On the other hand, the present results show that the performance of the adult-sized surgical and KN95 masks on the adult head form is comparable to that of the child-sized variant on the child manikin.

Results strongly suggest that apparent filtration efficiency is primarily leakage-driven, further evidenced by the significant difference between fitted mask and material filtration efficiency noted in Fig. 5.4. Flow visualizations in Figs. 5.6 and 5.7 provide qualitative indications of the leakage points for each tested mask and further corroborate the critical role of leakage in apparent filtration efficiency. With material filtration efficiencies being near or at 100% for all tested masks, the observed degradation in apparent filtration efficiency can be attributed almost entirely to leakage. Therefore, minimizing leakage should be prioritized over material filtration performance when selecting from among the tested face masks to achieve highest apparent filtration efficiency.

Although the N95 is generally regarded as the gold-standard in respiratory protection, results in Fig. 5.9 highlight a significant degradation in apparent filtration efficiency when this respirator is worn by a child. Unlike other tested masks, the N95 does not have a certified child-specific version, as current regulatory standards do not account for pediatric use [155]. Given the significant leakage from the N95 mask donned on a child head-form, it is expected that a smaller, better-fitting version could enhance apparent filtration efficiency.

5.5 Concluding Remarks

The source control apparent filtration efficiency of various masks donned on a child manikin in the $0.2\mu\text{m}$ to $1\mu\text{m}$ size range was determined experimentally. The results highlight the significant role of leakage in apparent filtration efficiency, exhibiting a significant drop from material filtration efficiency. Where available, the child versions of the tested masks outperform the adult versions due to a more tightly fitting seal around the mask-face interface. Furthermore, to separate the impacts of mask geometry from ear loop tension, the adult masks were modified to have ear loop tensions similar to the child versions of masks. The results for the modified adult CA-N95 and KN95 fall between those of the child and adult versions. However, there is no statistically significant difference in apparent filtration efficiency between the regular and modified adult surgical masks, indicating that the effects of poorly fitting mask geometry negate positive effects from tightening the ear loops. Overall, child variants of the CA-N95 and KN95 demonstrated the highest apparent filtration efficiency, while the adult CA-N95 as well as the modified and unmodified adult versions of the surgical mask performed the worst. Furthermore, comparing with results of

adult-sized masks on the adult head form, it is found that the child-sized surgical mask on the child manikin offers similar filtration to the adult-sized version on the adult manikin whereas the child KN95 respirator on the child manikin demonstrate varying degrees of improvement from adult-sized KN95 on the adult head form. Finally, measurements of peak pressure drop indicate that masks with similar apparent filtration efficiencies can have markedly different pressure drops. Notably, the two highest filtering respirators, the child-sized CA-N95 and KN95, show the former demonstrating a greater differential pressure than the latter. In fact, all KN95 variants exhibited a relative breathability less than or equal to other tested masks.

Chapter 6

Inward Protection of Child Masking

6.1 Introduction

Protecting children from airborne transmission of disease is particularly important in school settings, where prolonged indoor contact facilitates transmission. During the COVID-19 pandemic, implementation of mask mandates in schools was associated with reduced disease spread [54–56]. While masking can be a source control measure, it can also reduce a wearer’s exposure to infectious aerosols, thereby contributing to overall mitigation efforts.

Standards for FFRs were originally developed to protect workers from occupational exposure to airborne hazards. The recent pandemic, however, prompted wider adoption of respirators across the population, including among children, as a measure to limit the spread of COVID-19. In response to increased demand for child-appropriate respiratory protection, some manufacturers have produced smaller, child-sized mask variants. Despite this shift, existing FFR standards rely on protocols more representative of adult users, without consideration of pediatric facial anatomy or breathing patterns.

To the best knowledge of the author, Van der Sande *et al.* [26] is the only study to directly assess the personal protection of face masks on children, reporting a substantial decline in protective performance of adult-sized masks when donned by children relative to when worn by adults. This is attributed to the presence of significant gaps around the mask-face interface. Overall results of that study point to the importance of proper fit in ensuring effective user protection and underscore a gap in the current research regarding the protective performance of pediatric mask variants, especially when compared to the standard adult versions.

With the above in mind, the aim of the present chapter is to quantify the inward protection efficiency of adult and child versions of the KN95, CSA certified CA-N95, and ASTM level 3 Surgical Masks and the N95 respirator for aerosol particles ranging from 0.2 μm to 1 μm on a manikin representative of a 7 year old child. Furthermore, given the sensitivity of children to mask comfort [132], the inspiratory pressure drop of tested masks is measured to provide a relative measure of breathability.

6.2 Experiment Details

A schematic of the experimental setup used for estimation of inward protection efficiency is presented in Fig. 6.1. The masks tested are shown in Fig. 5.2, fitted on the same child manikin described in Chapter 5. Breathing was simulated through the manikin mouth, with the nasal line sealed to prevent particle leakage into the mask-face volume. Inhalation

Table 6.1: Child inhalation properties with 95% confidence interval

Parameter	Value	Unit
Inhalation rate (h_{inh})	26.0 ± 0.3	inhalation min^{-1}
Inhalation volume (V_{inh})	224.0 ± 33.3	ml inhalations $^{-1}$

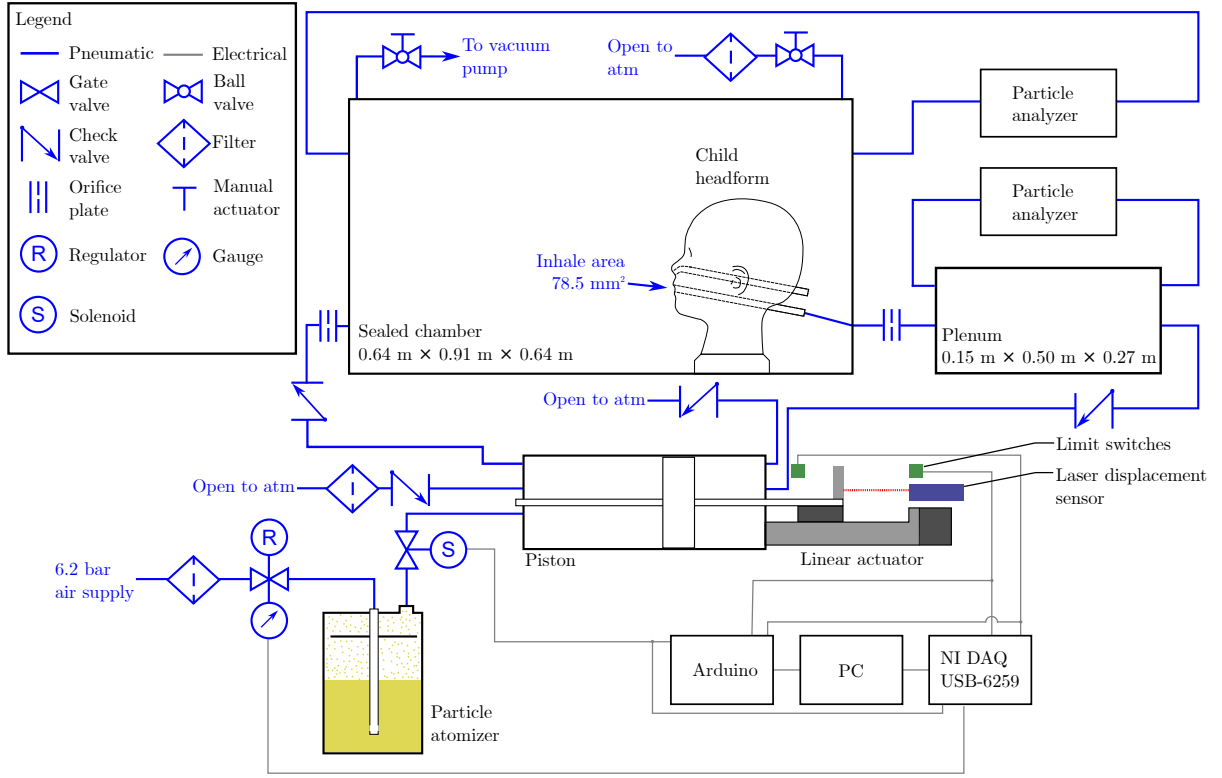


Figure 6.1: Experimental setup used to measure mask inward protection efficiency on a child manikin. In this configuration, the sealed chamber is control volume ‘1’ and the plenum is control volume ‘2’. Figure is adapted from Pieris *et al.* [97].

was modeled as a half-wave sine curve, following the breathing characteristics of 7 year old children reported by Roy *et al.* [147]. Measured inhalation characteristics are provided in Table 6.1.

Overall, the experimental procedure for testing inward protection efficiency is as follows. The child head form was equipped with the tested barrier, placed in the sealed chamber, and connected to the plenum through the inhalation line. Before each test, the chamber air was replaced with air filtered through a HEPA filter, and the plenum was purged of residual particles using a blower. Testing began with measurements of initial background particle number concentration for the first 260 inhalation cycles (approximately 10 minutes) with no particle injection into the system. Subsequently, particle injection was initiated for 3120 cycles (approximately 2 hours), ensuring that steady state particle conditions were reached for at least 30 minutes.

The temporal evolution of measured particle number concentrations and steady state particle size distributions in both control volumes for the no mask and child-sized CA-N95 cases are shown in Fig. 6.2. The observed exponential increase in the time history plots indicate a temporal evolution and subsequent approach to steady state particle number concentrations in both control volumes consistent with expected numerical solutions to Eqs. (A.1) and (A.2) depicted in Fig. A.3. The gray band indicates the 30 minute time

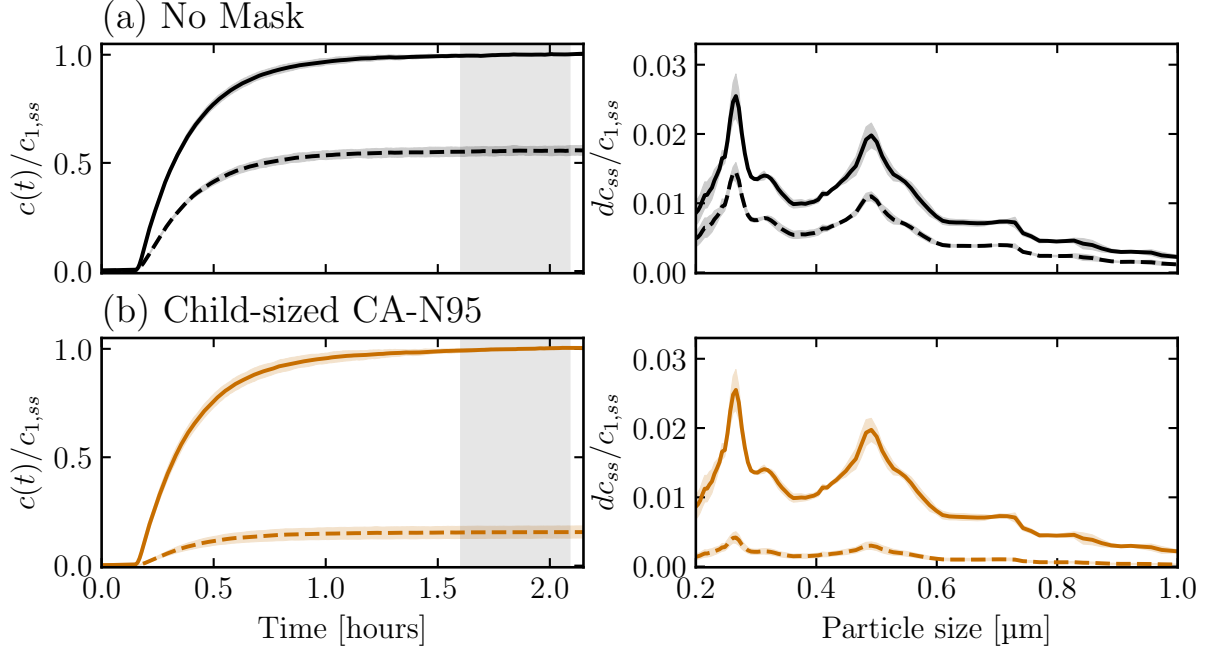


Figure 6.2: Temporal evolution (left) and steady state size distribution (right) of particle number concentrations in the no mask and child-sized CA-N95 cases normalized by chamber steady state particle number concentration using the setup depicted in Fig. 6.1. Solid lines are measurements in the chamber and dashed lines are measurements in the plenum. Shaded areas show one ensemble standard deviation of 10 tests. The gray band in the time history plots show the steady state sampling time span for calculation of inward protection efficiency. Steady state particle number concentrations in the chamber range from 0.9×10^5 particles cm^{-3} to 1.4×10^5 particles cm^{-3} .

window of data used to estimate inward protection efficiency using Eq. 3.1.

In addition to estimating inward protection efficiency, relative inspiratory breathability of tested barriers for children was quantified using the methodology outlined in Section 3.2.

6.3 Results

Inward protection and material filtration efficiencies with respect to particle size are presented in Fig. 6.3. Overall, child-sized masks consistently outperform adult versions when both are available. Among tested masks, the child CA-N95 offers the highest protection, whereas both modified and unmodified adult surgical masks provide the lowest. Moreover, a significant disparity is observed between fitted mask efficiency and material filtration efficiency, consistent with findings from Chapters 4 and 5.

The proportion of particles leaking through mask gaps was estimated using Eq. 2.6 and is presented in Fig. 6.4. The results highlight that greater mask protection corresponds to reduced particle leakage, and, conversely, lower protection is associated with higher leakage.

Fig. 6.5 plots the mean peak inspiratory pressure drop with respect to ensemble average inward protection efficiency for tested barriers. Overall, masks exhibiting the greatest leakage (e.g. the adult-sized CA-N95 and both modified and unmodified adult surgical masks) demonstrate the lowest pressure drop. While this implies improved comfort, the reduced pressure differential is attributed to significant gaps in the mask-face interface that degrade inward protection. Furthermore, similar to the observations made in Chapter 5 for the exhalatory configuration, masks with similar inward protection can exhibit substantial variations in their measured differential pressure.

6.4 Discussion

It is observed in Fig. 6.3 that, where available, child-sized versions of masks offer greater protection than either modified or unmodified adult variants. This is attributed to the substantial reduction in leakage from gaps at the mask-face interface (Fig. 6.4). Furthermore, the adult-sized KN95 respirator maintains reasonable protective characteristics even when

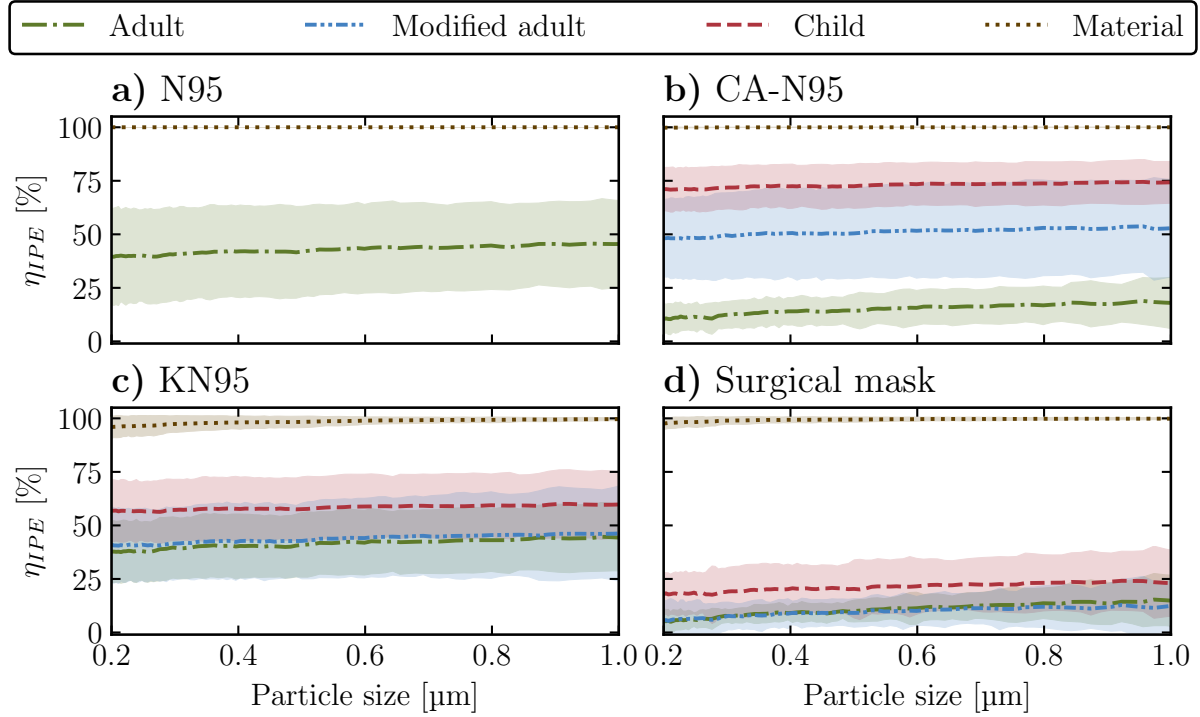


Figure 6.3: Inward protection efficiency and material filtration efficiency with respect to particle size of tested masks on child manikin. A face velocity of 1.5 cm s^{-1} is used for material filtration efficiency based on child breathing characteristics. Shaded areas indicate two standard deviations of 10 samples for inward protection efficiency, 10 samples for material filtration efficiency of the KN95 and surgical mask, and 5 samples for material filtration efficiency of the N95 and CA-N95.

worn on the child manikin. This mirrors observations from Chapter 5, and can be attributed to the conical geometry of the KN95, which enables it to achieve a more effective seal across varying head sizes. In contrast, the CA-N95 demonstrates a substantial decline in performance, from the child-sized respirator offering the greatest protection to the adult version demonstrating protection more comparable to the least effective barriers tested.

The modified adult mask variants were tested to isolate the effects of mask geometry and ear loop tension on inward protection efficiency. This adjustment improved the protective performance of the adult CA-N95, although its efficiency remained below that of the child-sized CA-N95. In contrast, the modified adult KN95 and surgical masks showed no significant improvement over their unmodified counterparts. For these two mask types, the results suggest that gaps at the mask face interface offset potential gains from increasing ear loop tension to match that of the child variants donned on the child manikin.

Fig. 6.6 compares the mean ensemble apparent filtration determined in Chapter 5 and inward protection efficiencies for masks tested on the child manikin. For all the cases, these two measures of mask efficiencies are similar within experimental uncertainty. Thus, for purposes of risk assessment and modeling of disease spread, these findings suggest inward protection and apparent filtration efficiencies of masks on children may be treated as approximately equivalent.

In Fig. 6.7, inward protection efficiencies from Chapter 4 are compared with relevant

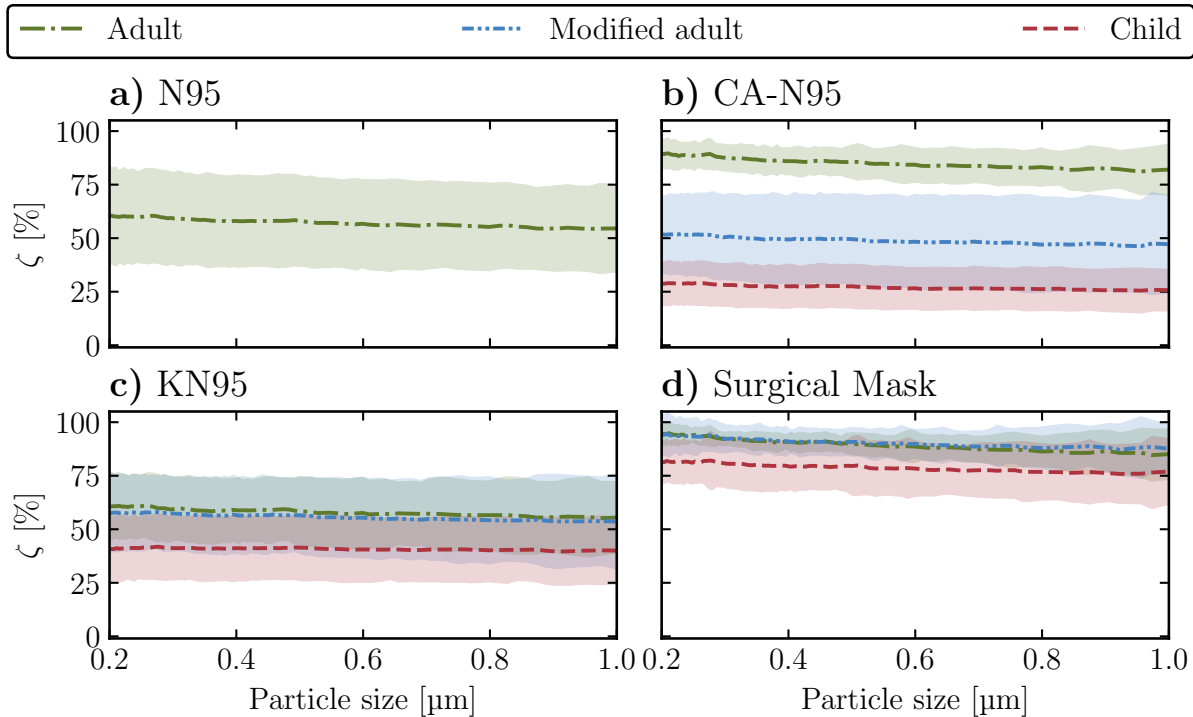


Figure 6.4: Inward leakage through gaps in the mask-face interface with respect to particle size tested on the child manikin. Shaded areas indicate two standard deviations from the mean.

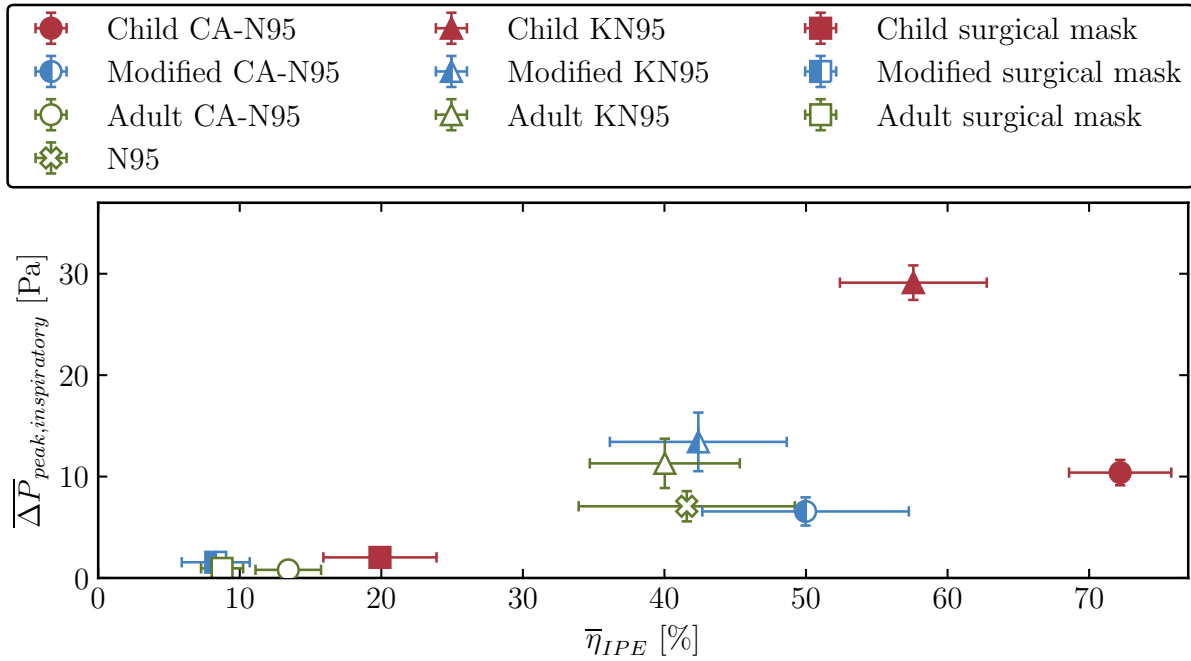


Figure 6.5: Mean peak inspiratory pressure drop of masks fitted on the child manikin with respect to mean inward protection efficiency. Error bars are 95% confidence intervals of the mean.

results from Fig. 6.3 to assess the influence of head form shape on mask performance. Where child-sized masks are available, their protective characteristics on a child manikin are similar to adult versions worn on an adult manikin. Consistent with Van der Sande *et al.* [26], adult-sized barriers provide substantially less protection when worn on a child head form compared to when worn on an adult. Notably, the N95 mask, which lacks a pediatric variant, provides roughly half the inward protection due to poor fit on the child manikin. By extrapolating KN95 and surgical mask results, a child-sized variant of the N95 mask can be expected to offer improved protection similar to that obtained on the adult manikin.

Fig. 6.5 shows that masks offering similar protection can have substantially different pressure drops. For example, the N95, modified adult CA-N95, and both modified and unmodified adult KN95 configurations exhibit no statistically significant differences in mean inward protection efficiency. However, the KN95 respirators demonstrate a higher mean peak pressure drop compared to the other two barriers. In fact, all KN95 type respirators demonstrate relative breathability that is lower than or equal to that of other tested barriers. Furthermore, the child-sized CA-N95, which provides the greatest protection among the tested face masks, exhibits measured mean peak differential pressures nearly a third of those measured for the less protective child KN95 respirator. This underscores that, although protection and pressure drop are often positively correlated, higher protection does not necessarily come at the cost of lower inspiratory breathability.

Overall trends for inspiratory breathing resistance observed in the present study are

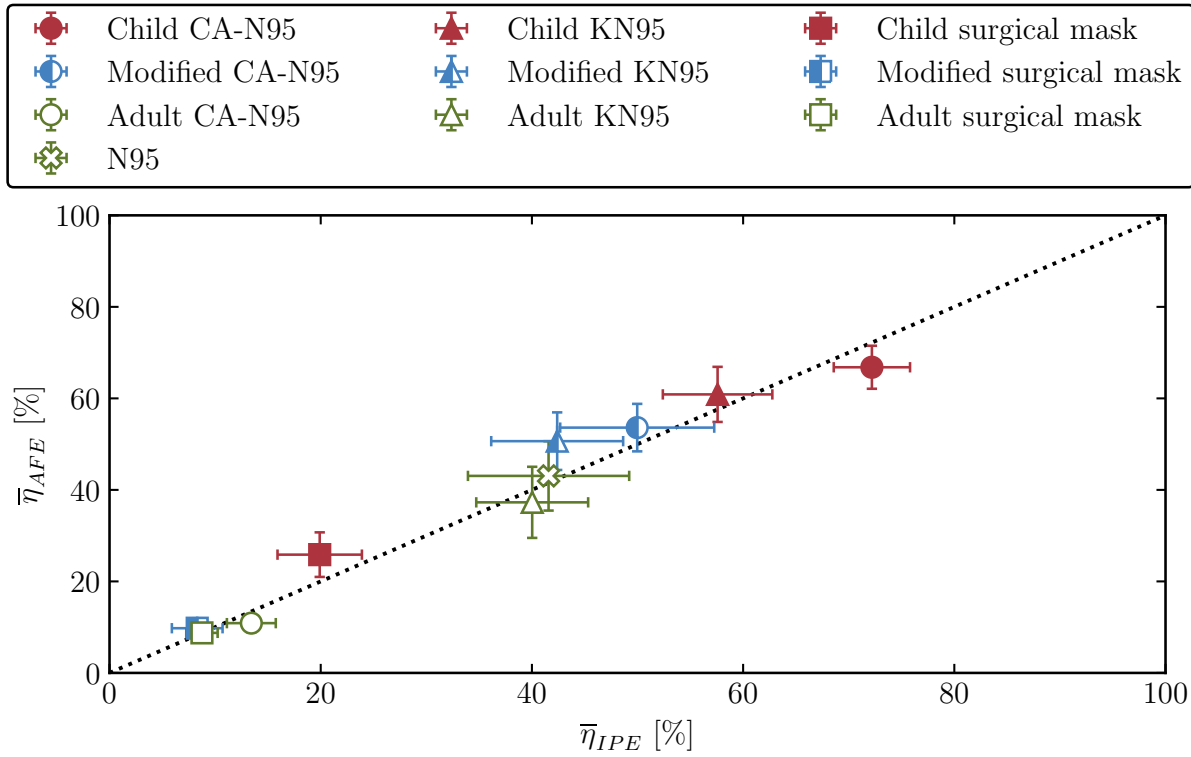


Figure 6.6: Mean apparent filtration efficiency from Chapter 5 plotted against mean inward protection efficiency. Dotted line is a reference line where $\bar{\eta}_{AFE} = \bar{\eta}_{IPE}$. Error bars are 95% confidence intervals of the mean.

consistent with those of Yao *et al.* [71], who tested on an adult manikin, noting that FFRs worn on the correctly sized manikin are less breathable than appropriately sized surgical masks. In contrast, results from Arumuru *et al.* [70] suggest the opposite trend, attributing the higher resistance of the surgical masks to airflow obstruction occurring closer to the breathing line compared to the tested N95. However, this explanation is not supported by the present findings in Fig. 6.5, where the KN95 respirator demonstrates a significantly higher peak differential pressure than surgical masks, despite its conical geometry positioning the mask surface farther from the inhalation location.

6.5 Concluding Remarks

Inward protection efficiencies in the $0.2\text{ }\mu\text{m}$ to $1\text{ }\mu\text{m}$ particle size range were experimentally determined for various masks on a manikin representative of a 7 year old child. Among tested barriers, the child-sized CA-N95 demonstrated the highest protection, followed by the child-sized KN95. Conversely, both modified and unmodified surgical masks provided the least protection due to the detrimental impact of leakage at the mask-face interface. Furthermore, mean peak inspiratory pressure drop was measured to provide a relative

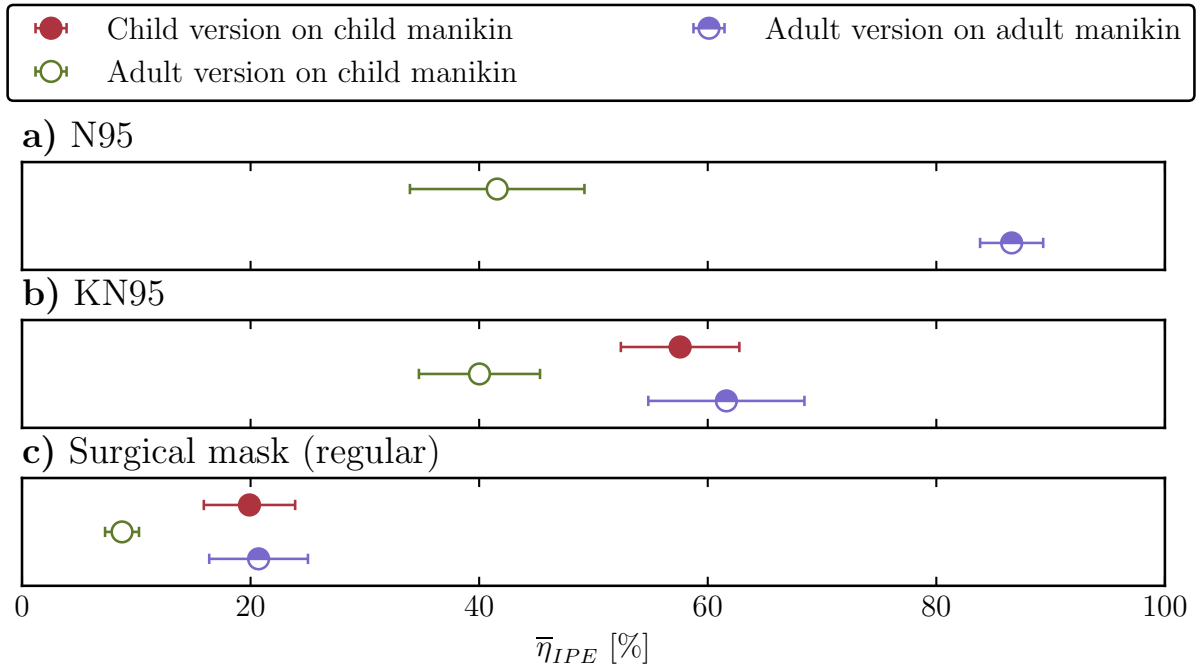


Figure 6.7: Mean inward protection efficiency of masks fitted on child and adult manikins. Error bars indicate 95% confidence intervals from the mean.

metric of breathability. The least protective masks demonstrated the highest breathability, reflecting a loose fit. Although the child-sized CA-N95 offered the highest protection, its mean peak inspiratory pressure drop was nearly a third of the less protective child-sized KN95, suggesting that increased protection does not necessarily compromise breathability. Comparisons with results from Chapter 5 indicate that source control and personal protective efficiencies of the tested barriers are roughly comparable for children. Furthermore, as demonstrated by comparisons with results from Chapter 4, same mask types appropriately sized for their intended users perform similarly, whereas adult-sized masks on the child head form exhibit a significant reduction in protective performance relative to when worn on an adult.

Chapter 7

Conclusions & Recommendations

7.1 Conclusions

In this thesis, an approach based on conservation of mass was used to characterize the inward protection efficiency of masks tested on adult and child head forms, as well as the apparent filtration efficiency of masks evaluated on the child head form. The experimental design replicated a physiologically realistic tidal breathing condition and mask-face interface, considering polydisperse aerosols with particle size ranging from $0.2\text{ }\mu\text{m}$ to $1.0\text{ }\mu\text{m}$. Furthermore, recognizing the higher sensitivity of children to mask breathability, both inspiratory and exhalatory pressure drops of tested masks were measured using the child manikin. Additionally, exhalatory leakage was visualized on the child manikin to identify leakage pathways and characterize dominant locations of gaps around the mask-face interface.

These results highlight degradatory effects of leakage on fitted mask efficiency. While material filtration efficiency was measured to be near or at 100% across the tested particle size range for the evaluated masks, fitted efficiencies were substantially lower. The pronounced disparity between material and fitted filtration efficiencies observed for all barriers is attributed primarily to gaps at the mask-face interface. Consequently, for mask types examined in this study, minimizing leakage should be prioritized over improvements in material properties when selecting masks for fitted filtration characteristics.

The inward protection efficiency of N95, KN95, and both regularly worn and tied and tucked surgical masks were tested on the adult manikin. The N95 respirator offered the highest protection ($86.5 \pm 2.5\%$), followed by the KN95 ($61.5 \pm 6.0\%$), whereas both regularly worn and tied and tucked surgical masks were the least effective ($20.4 \pm 3.9\%$ and $24.2 \pm 4.6\%$, respectively). The tie-and-tuck method for the surgical mask, which was recommended as a method to improve fit, showed a small, statistically insignificant improvement from the regularly worn surgical mask. Moreover, weighted population statistics of mean inward protection efficiency from the present work with the broader literature yield ranges of $[67.9\%, 100\%]$ and $[12.5\%, 79.6\%]$ for N95 and regularly worn surgical masks, respectively.

Both inward protection and apparent filtration efficiencies of adult, modified adult, and child variants of the KN95, CA-N95, and surgical masks, as well as the N95 respirator, were evaluated on the child manikin. Results indicate that both child-sized CA-N95 and KN95 masks provide the highest mean apparent filtration efficiencies ($66.8 \pm 4.7\%$ and $60.9 \pm 6.0\%$, respectively), with the difference not being statistically significant. However, only the adult-sized CA-N95 offered the highest mean inward protective efficiency ($72.2 \pm 3.6\%$). In contrast, the unmodified adult CA-N95 and both unmodified and modified adult surgical masks yielded the lowest mean source control efficiencies ($10.9 \pm 2.0\%$, $8.8 \pm 1.6\%$, and $9.8 \pm 2.2\%$, respectively), with no statistically significant differences across this group. Similarly, both unmodified and modified adult-sized surgical mask variants provided the lowest inward protection efficiencies ($8.3 \pm 2.4\%$ and $8.8 \pm 1.5\%$, respectively), again with no statistically significant difference between them. Overall, for all barriers tested on the child manikin, inward protective efficiency was found to be comparable to source control efficiency.

The degradatory effects of leakage is underscored by the substantial decline in filtration

characteristics of adult-sized masks donned on the child manikin relative to better fitting child-sized variants. This effect is less pronounced for the KN95, where the conical mask geometry enables a more effective seal across varying head sizes. This was further corroborated by flow visualization of exhalation out of the KN95 respirator, showing little lateral leakage through gaps near the head form cheeks for all mask sizes tested.

Modifying adult-sized masks on the child head form by tightening the ear loops to replicate the tension of child variants yielded mixed results. The modified CA-N95 showed an improvement in fitted filtration efficiencies relative to the unmodified adult variant. In contrast, the modified surgical mask demonstrated no improvement, indicating that the effects of poorly fitting mask geometry negate positive effects from tightening the ear loops. For the KN95 variants, the modification led to an increase in source control efficiency but not in inward protection.

Measurements of inspiratory and exhalatory peak pressure drop on the child manikin serve as relative indicators of mask breathability. Masks that fit poorly on the child head form, such as the adult surgical mask and adult-sized CA-N95, exhibited lower pressure drops due to significant leakage at the mask-face interface, which simultaneously degraded fitted filtration characteristics evaluated. Conversely, all KN95 respirators demonstrated peak pressure drops greater than or equal to any other tested barrier, suggesting greater breathing resistance. Notably, the child-sized CA-N95, despite showing leakage rates comparable to or lower than the child variant of the KN95, exhibited significantly greater breathability. Overall, for a given mask model, improved fit is generally associated with increased breathing resistance. However, comparisons across different mask types show that higher fitted filtration efficiency does not necessitate a compromise in breathability.

Comparing fitted mask efficiencies between the child and adult head forms further highlight the influence of head size and mask geometry. For surgical and KN95 masks, fitted filtration efficiency was comparable for variants donned on an appropriately sized manikins. Furthermore, adult-sized masks demonstrate a significant reduction in filtration characteristics when worn on the child manikin relative to the adult. This observation is particularly pertinent to the N95 respirator, for which no child-sized equivalent was available, and which provides approximately half the fitted filtration when evaluated on the child manikin.

7.2 Recommendations

Numerous questions remain regarding the mitigation of airborne hazards, including those associated with disease transmission. The experimental framework developed in the present work can be extended to support further investigations, including but not limited to the following:

- 1) As noted in Chapters 4–6, the fitted filtration efficiency of FFRs and surgical masks is primarily leakage driven. Given the significant role of mask geometry in reducing gaps around the mask-face interface, further studies are warranted to isolate geometric

effects. This could be achieved by comparing masks fabricated from the same material but differing in shape, thereby decoupling the geometric effects on fitted filtration efficiency from material properties. Furthermore, the broad variety of geometries among commercially available masks provides a basis to identify design features that consistently reduce leakage. Insights from such an investigation could guide a systematic optimization of mask design for improved fitted filtration efficiency, potentially through self-exploring experimental approaches [156–158].

- 2) Surgical masks consistently exhibited the lowest fitted filtration efficiency among tested barriers. Given their widespread use during the COVID-19 pandemic, strategies to improve surgical mask fit warrant further investigation. While the inward protection of the tied-and-tucked surgical mask was examined for adults in Chapter 4, other approaches such as nylon hosiery overlays, mask braces, ear loop tensioning straps, and double masking have been suggested to improve fit [91, 108, 159]. Evaluating these adjustments could provide further insight into strategies to improve surgical mask fit when donned on an adult. Furthermore, implementation of such configurations to adult-sized surgical masks worn by children could be particularly beneficial, considering the more effective pediatric variants may not always be available.
- 3) According to the hierarchy of hazard controls presented in Chapter 1, engineering controls are generally more effective than administrative and personal protective equipment at reducing population-level risk. Examples of this control include increased building ventilation and installation of air purification systems [15–19]. The approach based on the conservation of mass described in Appendix A can be extended to evaluate the effectiveness of such controls in limiting aerosol exposure. Combined, the efficiencies of tested engineering controls together with the present mask performance results could provide a basis to develop integrated mitigation strategies for airborne transmission of disease.
- 4) As discussed in Section 2.3, the type of test aerosol used in filtration efficiency measurement can influence results. Airborne pollutants originating from sources such as wildfire smoke [160–162] fossil fuel combustion [163–166], armed conflict [167–169], and allergens [170, 171] differ in particle size distribution and physicochemical properties. Extending the experimental methodology developed for Chapters 4 and 6 to testing these aerosol types would enable a broader assessment of mask effectiveness against a wider range of airborne hazards.
- 5) Flow visualization of exhaled air was conducted in Chapter 5, aiding in identifying key leakage pathways out of various face masks. However, due to increased experimental complexity, similar visualization was not performed for inspiratory flow in Chapters 4 and 6, and the inward leakage routes remain unclear. Therefore, developing a methodology to visualize inhaled particle trajectories through a mask would provide valuable insight into inward leakage and support the design of more effective personal protective equipment.

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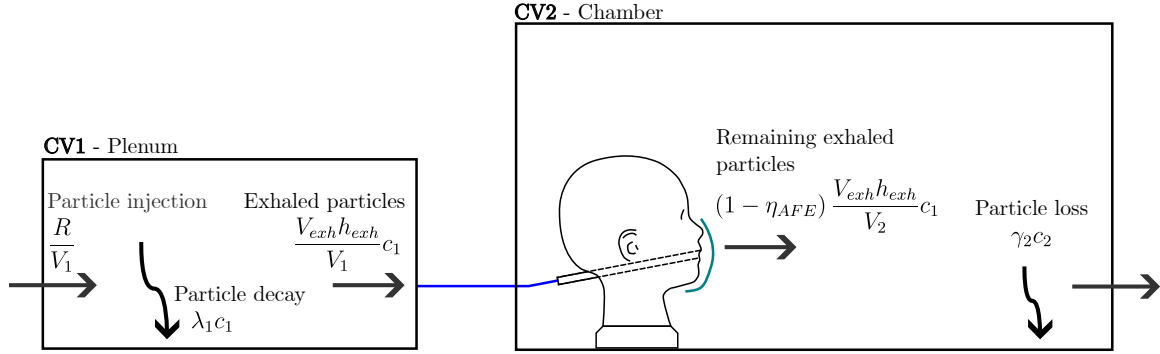
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Appendices

Appendix A

Derivation of Mask Efficiency

a) Apparent filtration efficiency



b) Inward protection efficiency

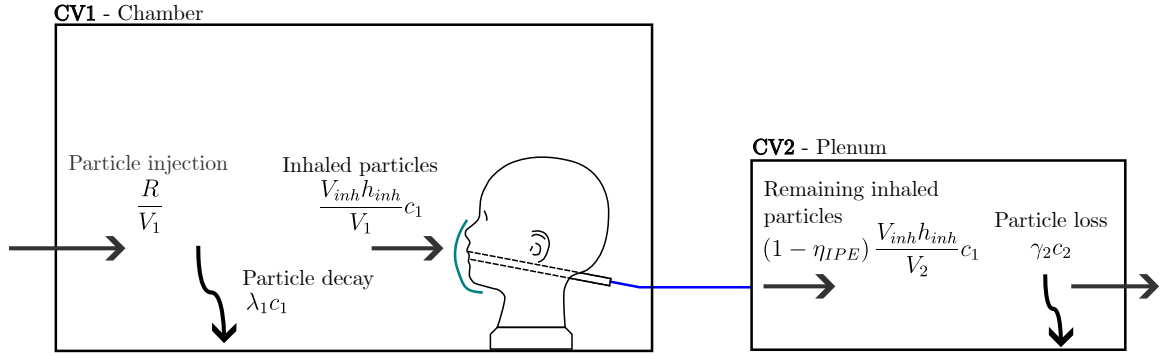


Figure A.1: Approach based on the conservation of mass used to determine apparent filtration efficiency and inward protection efficiency

Fig. A.1 illustrates the control volume analysis used to estimate apparent filtration and inward protection efficiencies. The essential variables involved in the approach based on the conservation of mass within the two control volumes are c being the particle number concentration (particles m^{-3}), V is the volume of a given control volume (m^3), λ_1 is the particle number concentration decay rate in control volume 1 (s^{-1}), reflecting the combined effects of in-situ particle removal processes, γ_2 is the particle number concentration loss rate in control volume 2 (s^{-1}), accounting for both in-situ particle decay and removal by outflow, R is the particle injection rate (particles s^{-1}), and t is time (s). Subscripts 1 and 2 correspond to properties in the respective control volumes. For apparent filtration efficiency, V_{exh} and h_{exh} refer to the exhalation tidal volume (L exhalation^{-1}) and rate (exhalation s^{-1}), respectively, and for inward protection efficiency, V_{inh} and h_{inh} refer to the inhalation tidal volume (L inhalation^{-1}) and rate (inhalation s^{-1}), respectively. The rate of change of particle number concentration with respect to time in the two control volumes is

expressed as

$$\frac{dc_1}{dt} = \frac{R}{V_1} - \frac{V_{exh,inh}h_{exh,inh}}{V_1}c_1 - \lambda_1c_1 \quad (\text{A.1})$$

$$\frac{dc_2}{dt} = (1 - \eta) \frac{V_{exh,inh}h_{exh,inh}}{V_2}c_1 - \gamma_2c_2. \quad (\text{A.2})$$

The following assumptions are made in the derivation of Eqs. (A.1) and (A.2):

- 1) Particles are assumed to be well-mixed such that the steady state number concentrations measured at the sampling location is representative of the control volume.
- 2) Air density (ρ_a), kinematic viscosity (ν_a), particle injection rate (R), decay rate in control volume 1 (λ_1), loss rate in control volume 2 (γ_2), and fitted mask efficiency ($\eta_{AFE, IPE}$) remain constant during each experimental run.

At steady state particle number concentrations within both control volumes, Eqs. (A.1) and (A.2) can be expressed as

$$0 = \frac{R}{V_1} - \frac{V_{exh,inh}h_{exh,inh}}{V_1}c_{ss,1} - \lambda_1c_{ss,1} \quad (\text{A.3})$$

$$0 = (1 - \eta_{AFE, IPE}) \frac{V_{exh,inh}h_{exh,inh}}{V_2}c_{ss,1} - \gamma_2c_{ss,2}. \quad (\text{A.4})$$

Where $c_{ss,1}$ and $c_{ss,2}$ in Eqs. (A.3) and (A.4) are the steady state particle number concentrations in the respective control volumes.

Furthermore, Eq. A.4 can be rearranged to

$$1 - \eta = \left(\frac{\gamma_2 V_2}{V_{exh,inh}h_{exh,inh}} \right) \frac{c_{ss,2}}{c_{ss,1}}. \quad (\text{A.5})$$

It is noted that the efficiency of the no-mask case is 0%. Additionally, the loss rate in control volume 2 (γ_2), the volume of control volume 2 (V_2), the exhalation/inhalation tidal volume ($V_{exh,inh}$), and exhalation/inhalation rate ($h_{exh,inh}$), do not vary significantly between tests. Thus, for a given mask M, the equation for mask efficiency becomes

$$\eta = 100\% \times \left(1 - \frac{c_{ss,2,M}/c_{ss,1,M}}{c_{ss,2,NM}/c_{ss,1,NM}} \right). \quad (\text{A.6})$$

Moreover, the above equation can be expressed on a particle-size bin basis, where dc_{ss} is steady state number concentration of particles of diameter d_p :

$$\eta(d_p) = 100\% \times \left(1 - \frac{dc_{ss,2,M}/dc_{ss,1,M}}{dc_{ss,2,NM}/dc_{ss,1,NM}} \right). \quad (\text{A.7})$$

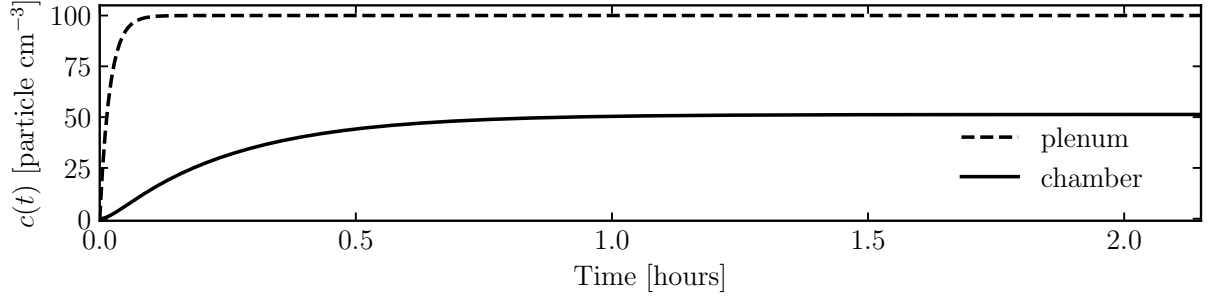


Figure A.2: Modeled particle number concentration based on parameters representative of the source control efficiency experimental setup. In this configuration the plenum is control volume 1 and the chamber is control volume 2. Plotted time histories were derived by numerically integrating Eqs. (A.1) and (A.2) using $V_1 = 20$ L, $V_2 = 370$ L, $V_{exh} = 0.5$ L, $h_{exh} = 1560$ exhalation h^{-1} , $R = 102\,000$ particles h^{-1} , $\lambda_1 = 12$ h^{-1} , $\gamma_2 = 4.1$ h^{-1} , and $\eta_{AFE} = 0\%$

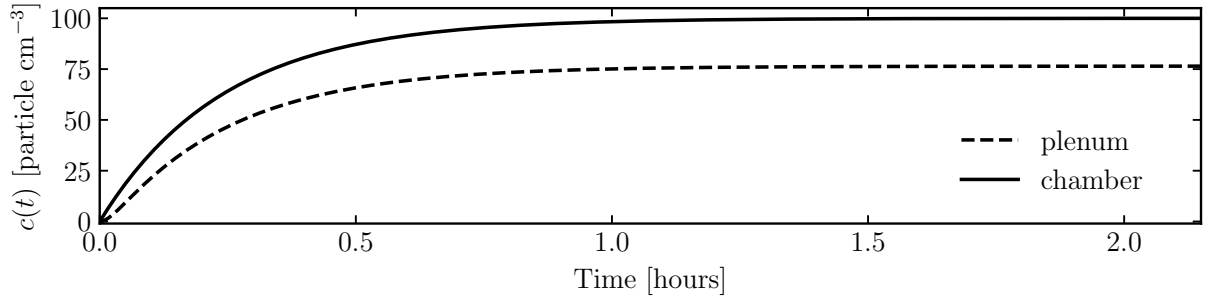


Figure A.3: Modeled particle number concentration based on parameters representative of the inward protection efficiency experimental setup. In this configuration the chamber is control volume 1 and the chamber is control volume 2. Plotted time histories were derived by numerically integrating Eqs. (A.1) and (A.2) using $V_1 = 370$ L, $V_2 = 20$ L, $V_{inh} = 0.5$ L, $h_{inh} = 1560$ inhalation h^{-1} , $R = 152\,000$ particles h^{-1} , $\lambda_1 = 2$ h^{-1} , $\gamma_2 = 51$ h^{-1} , and $\eta_{IPE} = 0\%$

Due to significant variability in particle generation from the Laskin-style nozzle between tests, steady state particle number concentration measurements in control volume 1 were incorporated to improve the accuracy of mask efficiency estimates (note, $c_{ss,1} = \frac{R}{V_{exh,inh}h_{exh,inh} + V_1\lambda_1}$). If generation were consistent, Eq. A.6 could be simplified to rely solely on measurements from control volume 2.

Eqs. (A.1) and (A.2) numerically integrated based using experimental parameters representative of the setups depicted in Fig. A.1 are shown in Figs. A.2 and A.3.

Appendix B

Determination of Face Velocity

Table B.1: Calculation of mean tidal face velocities of tested face masks using Eq. 2.1 with adult breathing parameters ($\bar{Q}_{test} = 273 \text{ mL s}^{-1}$)

Mask type	$\bar{A}_{test} [\text{cm}^2]$	$\bar{u}_f [\text{cm s}^{-1}]$
N95	235	0.9
KN95	210	1.0
Surgical mask	170	1.6

Table B.2: Calculation of mean tidal face velocities of tested face masks using Eq. 2.1 with child breathing parameters ($\bar{Q}_{test} = 206 \text{ mL s}^{-1}$)

Mask type	$\bar{A}_{test} [\text{cm}^2]$	$\bar{u}_f [\text{cm s}^{-1}]$
N95	235	0.9
adult-sized CA-N95	215	1.0
child-sized CA-N95	175	1.2
adult-sized KN95	210	1.0
child-sized KN95	150	1.4
adult-sized surgical mask	170	1.4
child-sized surgical mask	135	1.5

Mean face velocity ($\bar{u}_f$) is calculated using Eq. 2.1, based on average volumetric flow rate per breath ($\bar{Q}_{test}$) for child and adult breathing parameters in Tables B.1 and B.2, respectively. This calculation assumes no leakage and does not account for the consequent reduction in face velocity during inhalation and exhalation.

The most conservative, and thus highest, face velocity is selected, as increased face velocities are associated with a reduction in material filtration efficiency in the sub micrometer particle size range [113, 114]. In both Tables B.1 and B.2, this corresponds to the mask with the smallest surface area. Therefore, face velocities of 1.5 cm s^{-1} and 1.6 cm s^{-1} are selected for testing material filtration efficiency under child and adult breathing conditions, respectively.

Appendix C

Uncertainty Estimation

Uncertainties were estimated with 95% confidence intervals using the n^{th} -order uncertainty method of Moffat [0]. For a given quantity, a , its associated uncertainty, ε_a , is computed as the root sum squared of its individual error components, as shown in Eq. C.1. Moreover, while it is not feasible to account for all possible sources of error, the most significant contributors were included in the uncertainty analysis.

$$\varepsilon_a = \sqrt{\sum_{i=1}^n \varepsilon_i^2} \quad (\text{C.1})$$

The uncertainty of a derived quantity a , from measured quantities b_i through a known relationship, i.e. $a = f(b_1, b_2, \dots, b_n)$, is estimated using equation Eq. C.2.

$$\varepsilon_a = \sqrt{\sum_{i=1}^n \left(\frac{\partial f}{\partial b_i} \varepsilon_{b_i} \right)^2} \quad (\text{C.2})$$

Alternatively, for scenarios where the uncertainty of derived quantities was too complex to derive through Eq. C.2, the method of sequential perturbation was used [0]. This approach can be summarized as follows:

- 1) Calculate the derived quantity a without accounting for uncertainty.
- 2) For each i , compute the positive perturbation of the derived quantity a_i^+ using $b_i + \varepsilon_{b_i}$.
- 3) For each i , compute the negative perturbation of the derived quantity a_i^- using $b_i - \varepsilon_{b_i}$.
- 4) Estimate the contribution of each b_i by averaging $|a_i^+ - a|$ and $|a_i^- - a|$.
- 5) Determine the uncertainty of the derived quantity, ε_a , using Eq. C.1.

Overall, Table C.1 summarizes the maximum uncertainty estimates and derivation methodologies for the quantities presented in this work.

Table C.1: Maximum uncertainty estimates for measured and derived quantities. A 95% confidence interval is used to express uncertainties.

Parameter	Chapter 4	Chapter 5	Chapter 6	Unit	Method
h_{exh}	-	± 0.3	-	$\frac{\text{exhalation}}{\text{min}}$	Repeated trial variability
h_{inh}	± 0.2	-	± 0.3	$\frac{\text{inhalation}}{\text{min}}$	Repeated trial variability
$\overline{\Delta P}$	-	± 2.9	± 2.6	Pa	Eq. C.1
V_{exh}	-	± 23.8	-	$\frac{\text{mL}}{\text{exhalation}}$	Sequential perturbation
V_{inh}	± 39.2	-	± 33.3	$\frac{\text{mL}}{\text{inhalation}}$	Sequential perturbation
$\bar{\zeta}$	± 6.4	± 7.0	± 6.8	%	Eq. C.2
$\bar{\eta}_{AFE}$	-	± 6.9	-	%	Repeated trial variability
$\bar{\eta}_{IPE}$	± 6.0	-	± 6.8	%	Repeated trial variability
$\bar{\eta}_{MFE}$	± 0.5		± 1.1	%	Repeated trial variability