Impact of Self-Contained Breathing Apparatus on Air Gaps in Structural Firefighting Personal Protective Equipment

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Background: Air acts as an insulator and in excess can lead to heat stress in some applications, such as in structural firefighting turnout suits (Griefahn et al., 2012). Air gaps, which can be defined as the volume of air occupied between the body and clothing or between clothing layers, are essential for thermal protection (Havenith, 1999). Air gaps within a multi-layer firefighting turnout suit work to slow heat transfer from the fireground environment to the skin. However, excess air gaps can lead to heat stress as they also reduce the body's ability to lose excess metabolic heat (Havenith, 1999). Therefore, an optimized balance in air gap thickness must be struck when donning the full turnout ensemble, including personal protective equipment (PPE) such as the self-contained breathing apparatus (SCBA), which provides essential air way protection (Griefahn et al., 2012).

Research demonstrates the SCBA's negative impact on firefighters' physiological strain due to the addition of significant weight (Bakir & Tochihara, 2016). The SCBA may also interfere with personal protective clothing (PPC) fit in areas where it is synched and places a weight-bearing load on the body (Figure 1). However, no work has quantified this direct affect. While essential for respiratory protection, current designs significantly hinder firefighter mobility and increase the difficulty of performing job-related tasks (McQuerry, 2020). This cumbersome load leads to quicker onset of heat stress which, over an extended period, can result in increased cardiovascular strain, the leading cause of acute firefighter fatalities (NFPA, 2022; Cheung et al., 2010). Therefore, it is important for researchers to better understand the impact of SCBA design on air gaps within the full systems firefighting ensemble to optimize the fit, physiological comfort, and protection.

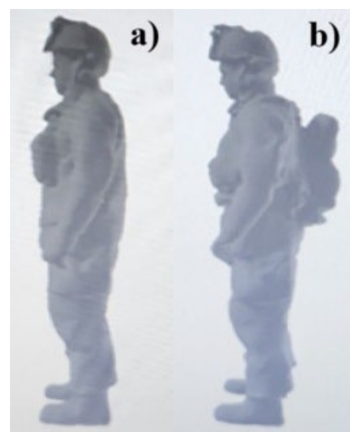

Figure 1. Side view of firefighter participant in (a) turnout suit and (b)

Some studies have evaluated the impact of SCBA on the overvall thermoregualtion of firefighters via the interaction of ventilation (McQuerry et al., 2016), thermal insulation (Bouskill et al., 2002), and heat flux (Fu et al., 2013). Even so, a large gap in the literature still exists regarding how the SCBA affects air gaps and ease allowances. Therefore, the purpose of this research was to determine the impact of the SCBA on the fit of structural firefighting PPC. Ease allowance is directly related to the air volume between garment layers and may affect the amount of heat transferred through the clothing system (Bouskill et al., 2002).

Method: A sample of 11 active-duty male firefighters were recruited to participate in this study. Participants were informed of the IRB-approved study protocol and signed an informed consent form upon arrival to the test session. Participants were then body scanned in each of the three garment configurations: compression layer (CO; tight-fit underwear), base layers (BL; provided t-shirt and athletic shorts), and turnout suit (TS; coat and pants) using a Size Stream SS20 three-dimensional body scanner. A fourth scan was performed with participants wearing the TS and donning an SCBA. In a matter of 15 seconds or less, more than 240 body measurements were collected for each participant when wearing each ensemble. Three replicate scans were taken in each ensemble and averaged. Individual upper body measurements (across chest, front waist, stomach circumference, and waist circumference) were taken by the scanner and used to study air gap formation. From these measurements, garment ease and air gaps were calculated in specific front torso areas (McQuerry, et al., 2018) and are reported in centimeters.

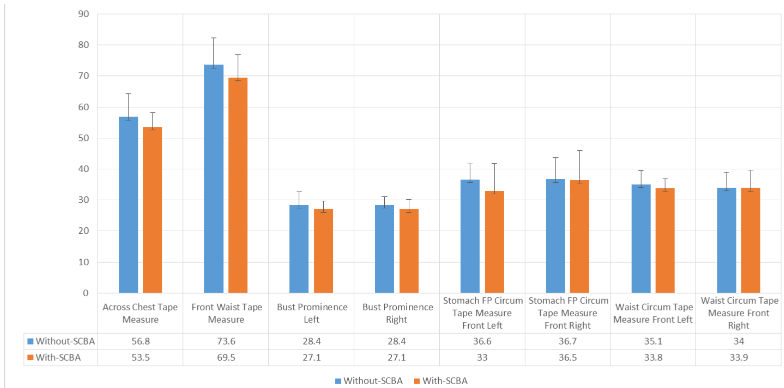

Figure 2. Average front torso measurements (cm) with and without the SCBA.

Results: With the addition of the SCBA donned overtop of the turnout suit, most of the body measurements included in this study decreased across the front torso. The largest reduction in front body measurements were found to be in the front waist, across chest, and the front left circumference of the stomach with an average reduction greater than three centimeters. This decrease in garment ease and air gaps indicates the potential for improved heat loss through the system (Tian et al., 2024), however, it also illustrates potential points of restriction in the fit of the turnout suit which correlates to previous studies that have reported reduced mobility when wearing an SCBA (Hooper, et al., 2001; McQuerry, 2020; White, et al., 1989). For the across axilla chest and front shoulder width, however, an increase in garment ease was detected when donning the SCBA compared to the TS. These findings may correlate to the presence of the SCBA straps in these locations, however, more research is needed to draw definitive conclusions. It is also possible that the synching of the SCBA straps leads to reduced air gaps in some areas and forces excess air volume in others, creating a balloon like effect within the clothing microclimate. Further research on this unique finding is necessary.

Discussion: Although the SCBA is essential for respiratory protection, it is crucial that it does not detrimentally interfere with the fit of the PPC such that it compromises heat loss and protection. The SCBA's weight, bulk, and subsequent impact on the fit and thermal comfort of structural firefighters has not been specifically studied. Air gaps have previously been quantified for various turnout suit materials and designs (Deng, et al., 2018; McQuerry, et al., 2018; Phelps, et al., 2019; Psikuta, et al., 2012), but the effect of donning the SCBA on top of the turnout coat has not been considered. This study aimed to quantify the garment ease and air gaps between firefighting ensembles and the addition of the SCBA. On average, across all participants, most front torso cross contour measurements decreased when wearing the SCBA. This suggests potential improvements in heat loss in these specific areas, however, it also points to significant potential fit restrictions in the upper body. Future research should quantify and correlate the impact of the SCBA on air gaps with garment level total heat loss (THL) and range of motion (ROM) as reduced mobility can indirectly lead to quicker onset of heat stress.

Conclusions: This study only begins to quantify the realized impact of SCBA fit on firefighter performance. Correlational analysis with heat loss and ergonomic mobility measures would better inform the design of both the SCBA and the turnout suit. Reduced air gaps may also significantly decrease thermal protection in some areas; therefore, flash fire manikin testing should be performed to ensure minimum thermal protective performance maintained. Limitations of this study include the small sample size, consideration of front torso measurements only, and the inability to determine the exact decrease in torso volume and circumference due to scanning technology constraints. This study lays the foundation for much more work that is needed on the full systems ensemble level to better understand how fit impact thermal comfort, mobility, and protection of firefighters.

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