Journal of Occupational and Environmental Medicine, Publish Ahead of Print
DOI: 10.1097/JOM.0000000000003010

Physiological responses and performance of simulated high-rise firefighting

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Funding: This study was funded by the London Fire Brigade.

Conflict of interest:

Richard Daniel Mark Stevenson - None declared.

Joseph Warwick - None declared.

James Lee John Bilzon - None declared.

Acknowledgements: We would like to thank the London Fire Brigade and their firefighters for the support in conducting in this study. EQUATER Network Reporting Guidelines (STROBE).

Author contributions: JB: conceptualisation, funding acquisition, supervision, methodology, data collection, writing – review and editing. RS: data collection, formal analysis, writing – original draft preparation. JW: data collection, writing – review and editing.

Ethical considerations and disclosures: This study was approved by the University of Bath's Research Ethics Approval Committee for Health (REACH) (ref: EP 19/20 098).

Abstract

Objectives: To determine the physiological effects of breathing apparatus (BA) and ascent strategies during a simulated 120-m vertical high-rise firefighting ascent. **Methods:** Twenty-eight firefighters completed four high-rise firefighting trials wearing standard- or extended-duration BA with continuous ascent (SDBA-C/EDBA-C) or with breaks (SDBA-B/EDBA-B). Task time (TT), heart rate (HR), ratings of perceived exertion (RPE), core body temperature (CT) and thermal comfort (TC) were recorded at predetermined elevations. **Results:** TT took significantly longer during the EDBA-C compared to SDBA-C trial. HR (at 40, 80 and 100-m) was significantly lower in trials following breaks compared to the continuous trials. CT rose by 0.11ºC every 10-m of ascent. During the SDBA trials, 89-96% of firefighters activated their low air alarm compared with only 7% in EDBA. **Conclusions:** Firefighters should wear EDBA beyond 80-m of ascent and are encouraged to take regular breaks.

Keywords: Firefighters, high-rise, breathing apparatus, physical exertion, core body temperature, heart rate.

Learning objectives

After reading this article, the learner will be better able to:

- Describe the physiological and equipment considerations during high-rise firefighting.
- Identify the differences in physiological and performance responses when using various breathing apparatus equipment and ascent strategies.
- Evaluate the most appropriate breathing apparatus equipment and ascent strategy for performing high-rise firefighting tasks.
- Understand the thermal and cardiovascular responses and limitations during high-rise firefighting operations.

Introduction

Firefighters undertake a range of operational tasks to ensure the safety of the public. In urban areas, high-rise firefighting remains a critical element of the role (1, 2) and has been shown to be one of the most physically demanding tasks (3-6). There have been several recent high-rise incidents where UK firefighters have had to respond in extreme operational circumstances (e.g., Grenfell Tower (24 floors), London, 2017, Downtown Hotel (63 floors), Dubai, 2015, Lacrosse Building (21 floors), Melbourne, 2014). During such incidents that involve fire and/or smoke, the amount of work that a firefighter can undertake is in part limited to the air available within their self-contained breathing apparatus (SCBA). Typically, SCBA provide around 30-33 minutes of air when consuming 40-50 l/min for a standard duration breathing apparatus (SDBA) (7, 8). However, ventilation rates exceeding these values have been reported in studies investigating the demands of simulated emergency operations, particularly in those that include stair climbing (4, 5, 9, 10).

At times, firefighters are also required to undertake their work in hot environmental conditions whilst wearing impermeable personal protective equipment (PPE), often resulting in uncompensable heat stress and a subsequent continuous rise in core body temperature (CT) to unsafe (> 39.0°C) limits (11-14). The relationship between CT and firefighting task intensity and duration have been previously reported (15, 16), with increases nearing 1°C during short duration (< 20 mins) simulated firefighting tasks (17-20). Even greater increases in CT have been observed during more protracted events, which in some cases have exceeded safe working limits (8, 10, 15, 21).

In extreme circumstances, where a building's mechanical lifts are unusable, firefighters may be required to ascend numerous flights of stairs prior to carrying out their

duties, placing even greater demands on these workers and their equipment. This scenario was investigated during a simulated 10-floor high-rise task and found that when using the stairs, task completion took 70% longer, mean peak heart rate (HR) was 34 beats per minute (bpm) higher and mean task HR was 47 bpm higher compared to when firefighters were able to use the lift (22). In another study, firefighters were required to ascend 23 floors (73-m) wearing SDBA whilst carrying an 18-kg high-rise pack to determine the limitations to equipment and personnel. During the climb, participant heart rate averaged 91% of their maximum and such was the physical demand that the majority of firefighters had used 75% or more of their '30 min' air supply within 12 mins, greatly hindering task performance (9). Other work investigating the effect of 32 different iterations of BA type (SDBA & EDBA) along with varying combinations of hose equipment during a high-rise rescue simulation found that of the 32 iterations performed, only 13% were completed successfully, with 38% terminated due to low air supply, 22% ended due to safety concerns of the participants and 28% terminated due to excessive CT ($\geq$ 39.5ºC) (10). Indeed, other studies have also reported CT exceeding recommended safety limits during repeated bouts of firefighting suggesting that CT is also a limiting factor during protracted incidents (23). These studies highlight the significant challenges associated of conducting firefighting in high-rise buildings and the limitations to personnel and equipment. Furthermore, whist some studies have investigated the impact of different stair climbing strategies (albeit not in firefighters) (24), no studies have investigated the impact of taking rest breaks during the ascent phase of a firefighting simulation to assess the impact on task performance and physiological and psychological variables in firefighters.

Despite there being a large number of cities in the world with buildings taller than 100-m (25), there are no published studies investigating the effect of conducting firefighting

operations in these types of buildings. This study therefore sought to investigate the effect of conducting firefighting operations in such buildings. A representative sample of UK firefighters wearing different breathing apparatus (BA) equipment and using various ascent strategies performed a simulated 120-m high-rise firefighting task whilst measuring selected performance and physiological variables. We hypothesised that performance time and physiological strain would be greater when wearing EDBA compared to SDBA, but that rest breaks would reduce these responses.

Materials and Methods

Participants

A stratified and representative (age, sex and body mass index) sample of UK firefighters were recruited via internal advertisement. Twenty-eight firefighters (17 male, 11 female) with a mean ± SD: age 37 ± 9 years; stature 175 ± 8 cm; body mass 80 ± 16 kg; body mass index 25.8 ± 3.6 $kg \cdot m^2$; body fat 24.0 ± 4.9 % and maximal oxygen uptake ($\dot{V}O_2max$) 43.9 ± 5.6 $ml \cdot kg^{-1} \cdot min^{-1}$ volunteered to participate in this randomised crossover trial. All participants were considered fit for operational duties and provided informed written consent. The study was approved by the University of Bath's Research Ethics Approval Committee for Health (REACH EP 19/20 098). This study was conducted in accordance with the EQUATER Network Reporting Guidelines (STROBE) (see checklist) (Supplemental Digital Content, http://links.lww.com/JOM/B449). (26)

Experimental design

The main trials were conducted at a 62-floor (278-m) building in central London in January 2021. Preliminary assessments were conducted at a nearby fire station. These included stature (cm), body mass (kg), estimated body fat percentage using skinfold callipers

(Seca, Germany) and the 4-site method (27), and a test to volitional exhaustion to determine $\dot{V}O_2$ max (Cosmed K5, Italy). Each floor of the 62-floor building had 24 steps and a vertical elevation of 4-m. The stairwell temperature was maintained at ~20ºC. Participants were randomly assigned to complete four trials under different experimental conditions in a repeated measures crossover trial. When on the 2 continuous trials (wearing SDBA-C & EDBA-C), experimental measures were recorded immediately prior to starting the ascent (0-m) and then immediately after arriving at the 40, 80, 100, 120-m and finish (0-m) points. When on the 2 discontinuous trials (wearing SDBA-B & EDBA-B), participants took a timed 1-min break at the 40, 80, 100 and 120-m points with experimental measures being recorded immediately prior to starting the ascent (0-m) and immediately following the 1-min rest break at the 40, 80, 100-m points and then immediately on arriving at the 120-m and finish (0-m) points.

Each participant completed two trials per day, with at least 2 hours recovery between trials by resting in a seated area whilst consuming a packed lunch and room temperature bottled water until HR and CT had returned to normal. Each trial consisted of a 30-floor (120-m) ascent and subsequent descent of a continuous stairwell. During all trials, participants wore full structural firefighting PPE, consisting of standard issue workwear, tunic, leggings, flash hood, gloves, helmet, boots and torch weighing 10.6 kg in addition to either a standard issue (1 cylinder) SDBA (weight 14.0 kg) or (2 cylinder) EDBA (weight 23.0 kg). All BA cylinders were charged to 270 bars prior to use. Participants completed all trials with their face masks on and ‘under air’. Each was fitted with a standard low air alarm (LAA), which sounded at 70 (±5) bars.

Participants also carried a standardised door enforcer tool (Sigma Security Devices, UK) weighing 14.1 kg during the ascent phase only. The enforcer was agreed to be a representative item of equipment that a firefighter may be required to transport during such an operational scenario. Participants were asked to complete each trial as fast as possible, i.e., as if it were an emergency, whilst adhering to standard operating procedures. A safety officer walked behind each participant throughout the trials with a research assistant situated at various elevation points to document the experimental measures of participants.

Experimental conditions

Participants completed the following trials:

1. SDBA-C – continuous ascent wearing SDBA
2. SDBA-B – discontinuous ascent (i.e., with breaks) wearing SDBA
3. EDBA-C –continuous ascent wearing EDBA
4. EDBA-B – discontinuous ascent (i.e., with breaks) wearing EDBA

Experimental measures

Two hours prior to the trials starting, participants were asked to swallow a coded telemetry pill (CorTemp, HQ Inc., US) with room temperature water, noting that 30-60 minutes has been recommended as the minimum period of time to establish baseline CT and mitigate the effect of any cold water consumption (28) prior to arrival at the test centre. Participants were also instructed not to consume any further fluids until after their first trial or within one hour of their second trial. This was to prevent any short-term effects of ingested beverage temperature on sensor measurements (28). The CorTemp logger was placed in a standard issue fire service radio pouch, which was set to record CT at 20 s (second) intervals throughout each trial. Participants with a recorded CT of $\geq$ 39.5ºC were stopped from

continuing the trial immediately and a cooling strategy (tunic and helmet removal, water consumption and radial forearm cooling) was initiated until CT had reduced to safe limits (i.e., < 38.5ºC). Each participant was also fitted with a HR chest strap (Polar Electro Oy, Finland). HR was recorded at 20 s intervals. Both the CorTemp logger and Polar wristwatch were fitted to the outside of the tunic in order that both CT and HR could be observed easily and recorded at designated points. These points were at the start of the trial (start, 0-m), at 40, 80, 100 and 120-m of vertical elevation and then following a full descent of the stairs to the start point (finish, 0-m). Maximum HR (MaxHR) was determined as the maximum value recorded during either the preliminary V̇O2max test or the highest value recorded during the trials. Participants were also asked to report their rating of perceived exertion (RPE) using the 6-20 Borg scale (29) and perception of thermal comfort (TC) on a 9-point Likert scale from 'very cold' to 'very hot' (30). Finally, task time (TT) in min:sec to 40, 80, 100 and 120-m of vertical elevation and to the finish point (0-m) was recorded using a stopwatch monitored by the safety officers. Following completion of the trials, participants were asked to give subjective binary feedback (yes/no) to a series of questions relating to their performance during the trials and based on their operational experience. These questions were developed in collaboration between the research team and fire service managers which has proven beneficial in previous studies when interpreting quantitative data (3). The questions asked were as follows:

- Do you feel this activity of climbing 30 floors in breathing apparatus is something you may be reasonably expected to perform as part of your operational role?
- From your experience in taking part in these trials, do you think you would have been physically able to engage in a firefighting task after ascending 30 floors wearing standard/extended duration breathing apparatus?

- Do you think you would be more able to engage in a firefighting task after ascending 30 floors after taking one minute breaks on certain floors?

Statistical analysis

All statistical analyses were completed using IBM SPSS version 20 (IBM, New York, USA). Descriptive data were calculated for all variables, at each elevation point, for each trial and are presented as mean ± standard deviation (SD), unless otherwise stated. A two-way repeated measures ANOVA was used to analyse the interaction and main effects of elevation time points and BA equipment during continuous ascent, ascent strategy whilst wearing SDBA or ascent strategy whilst wearing EDBA. Where the assumption of sphericity was violated, a Greenhouse-Geisser correction was applied. A dependent sample t-test (with a Bonferroni correction to adjust for family-wise error rate) was used to identify interaction effect differences between BA equipment and ascent strategies where interaction effects were observed. Cohen's *d* was used to calculate the standardised effect sizes in the analysis of simple main effects where an effect size of 0.2 is considered small, 0.5 moderate and 0.8 or above large (31).

To further understand the impact of CT on firefighter safety limits, a one-way ANOVA was used to identify any differences in overall changes in CT between the trials (during ascent, descent and during the entire trial). Partial eta-squared (η_p^2) was used to calculate the standardised effect size of the interaction effect between independent variables where appropriate. In this regard, an effect size of 0.01 is considered small, 0.06 moderate and 0.14 or above large (31). A long-run error rate of 5% (alpha = 0.05) was set *a priori* such that $p < 0.05$ was deemed statistically significant. Exact *p*-values are given unless $p < .001$.

Results

Physical and perceived physical strain

Mean HR during the trials was 162 (± 12) bpm in the SDBA-B trial, 162 (± 13) bpm in the EDBA-B trial and 174 (± 10) bpm in the SDBA-C and EDBA-C trials (87 and 93% of MaxHR in the continuous and discontinuous trials respectively) with mean peak HR values of 180-181 bpm (97% MaxHR). Mean RPE was 16.7 (± 2.0) (SDBA-B) and 16.9 (± 1.9) (EDBA-B) during the discontinuous ascent trials and 17.0 (± 1.7) (SDBA-C) and 17.3 (± 1.5) (EDBA-C) during the continuous trials with mean peak values for RPE ranging between of 18.7-19.0.

Effect of BA equipment

There was a significant interaction between BA equipment (SDBA-C vs EDBA-C) and elevation on TT, (F (1.43, 38.6) = 13.58, p = < .001, η_p^2 = 0.34). Simple main effects analysis showed that the effects of BA equipment had a statistically significant effect on TT (figure 1). Mean TT for participants in the EDBA-C trial were 00:22 (± 00:39) min:sec slower to 40-m, t(27) = -2.94, p = .033, d = 0.56, 00:57 (± 01:17) min:sec slower to 80-m, t(27) = -3.90, p = .003, d = 0.74, 01:27 (± 01:38) min: sec slower to 100-m, t(27) = -4.72, p = < .001, d = 0.89, 01:44 (± 01:55) min:sec slower to 120-m, t(27) = -4.80, p = < .001, d = 0.91 and 02:22 (± 03:10) min:sec slower to the finish (0-m) point, t(27) = -3.96, p = .002, d = 0.75 when compared with the SDBA-C trial.

There was no interaction effect between BA equipment and elevation on HR, RPE, CT or TC. Main effects for BA equipment did not show statistically significant differences between trials with mean differences for HR, (F(1,27) = 0.59, p = .488, d = 0.02, RPE

($F(1,27) = 3.83$, $p = .061$, $d = 0.12$), CT, ($F(1,27) = 2.33$, $p = .139$, $d = 0.08$) or TC, ($F(1,27) = 0.330$, $p = .571$, $d = 0.01$).

Ability to perform firefighting duties

When asked if participants felt they would be unable to perform firefighting duties at the top of the ascent (120-m point), 29% felt that they would not after ascending continuously in the SDBA set (SDBA-C) and a similar proportion (32%) felt that they would not in the EDBA set (EDBA-C).

Effect of ascent strategy (SDBA)

There was a significant interaction between ascent strategy (SDBA-C vs SDBA-B) and elevation on HR, $F(1, 27) = 49.4$, $p = < .001$, $\eta_p^2 = 0.65$, RPE, $F(2.95, 79.7) = 5.18$, $p = .003$, $\eta_p^2 = 0.16$ and TT, $F(2.13, 57.4) = 14.1$, $p = < .001$, $\eta_p^2 = 0.34$.

Simple main effect analysis showed that ascent strategy in SDBA had a statistically significant effect on HR. For the SDBA-B trial mean HR was 19 (± 9) bpm lower at 40-m, $t(27) = 11.1$, $p = < .001$, $d = 2.09$, 19 (± 9) bpm lower at the 80-m, $t(27) = 11.5$, p = < .001, $d = 2.17$ and 19 (± 10) bpm lower at 100-m, $t(27) = 10.6$, $p = < .001$, $d = 2.00$ when compared with the SDBA-C trial. However, mean HR was not statistically different between trials at the other elevation points with mean differences of 0 (± 7) bpm at 120-m, $t(27) = .218$, $p = .999$, $d = 0.04$ and 2 (± 11) bpm at the finish (0-m) point, $t(27) = -.683$, $p = .999$, $d = -0.13$ (figure 2).

Simple main effect analysis also showed that ascent strategy in SDBA had a statistically significant effect on RPE. For the SDBA-B trial, mean RPE was 0.9 (± 1.2) lower

at 80-m $t(27) = 3.75$, $p = .004$, $d = 1.21$, and 0.9 (± 1.4) lower at 100-m $t(27) = 3.55$, $p = .007$, $d = 0.67$ when compared with the SDBA-C trial. However, mean RPE was not statistically different between trials at the other elevation points with mean differences of 0.4 (± 1.4) at 40-m $t(27) = 1.38$, $p = 0.89$, $d = .26$, 0.1(± 0.7) at 120-m, $t(27) = -.528$, $p = .999$, $d = -0.10$ and 0.3 (± 2.2) at the finish (0-m) point $t(27) = .679$, $p = .999$, $d = 0.12$.

Simple main effect analysis also showed that ascent strategy in SDBA had a statistically significant effect on TT. For the SDBA-B trial, mean TT was 00:53 (± 00:26) min:sec slower to 40-m, $t(27) = 10.53$, $p = < .001$, $d = 1.99$, 01:25 (± 00:42) min:sec slower to 80-m, $t(27) = 6.33$, $p = < .001$, $d = 1.20$, 02:04 (± 00:50) min:sec slower to 100-m, $t(27) = 7.45$, $p = . < .001$, $d = 1.41$, 01:49 (± 00:59) min:sec slower to 120-m, $t(27) = 5.05$, $p = < .001$, $d = 0.96$ and 01:59 (± 01:03) min:sec slower to the finish (0-m) point, $t(27) = 3.86$, $p = .003$, $d = 0.73$ when compared with the SDBA-C trial.

There was no interaction effect between ascent strategy and elevation point on CT or TC. However, the main effect for ascent strategy showed a statistically significant difference in TC between trials with a mean difference of 0.2, $F(1,27) = 15.1$ $p = < .001$, $d = 0.36$. The main effects for ascent strategy did not show statistically significant difference between trials for CT, $F(1,27) = .002$, $p = .964$, $d = < 0.01$.

Effect of ascent strategy (EDBA)

There was a significant interaction between ascent strategy (EDBA-C vs EDBA-B) and elevation on HR, $F(1, 27) = 30.14$, $p = < .001$, $\eta_p^2 = 0.53$, RPE, $F(3.49, 94.3) = 3.20$, $p = .021$, $\eta_p^2 = 0.19$ and TT, $F(1.70, 46.1) = 23.06$, $p = < .001$, $\eta_p^2 = 0.46$.

Simple main effect analysis also showed that ascent strategy in EDBA had a statistically significant effect on HR. For the EDBA-B trial mean HR was 17 (± 12) bpm lower at 40-m, $t(27) = 7.65$, $p = < .001$, $d = 1.45$, 18 (± 10) bpm lower at the 80-m, $t(27) = 9.13$, p = < .001, $d = 1.73$ and 21 (± 10) bpm lower at 100-m, $t(27) = 10.1$, $p = < .001$, $d = 1.91$ when compared with the EDBA-C trial. However, mean HR was not statistically different between trials at the other elevation points with mean differences of 2 (± 8) bpm at 120-m, $t(27) = .944$, $p = .999$, $d = 0.18$ and 0 (± 8) bpm at the finish (0-m) point, $t(27) = -.073$, $p = .999$, $d = -0.01$ (figure 2).

Simple main effect analysis also showed that ascent strategy in EDBA had a statistically significant effect on TT. For the EDBA-B trial, mean TT was 00:55 (± 00:26) min:sec slower to 40-m $t(27) = 11.26$, $p = < .001$, $d = 2.13$, 01:39 (± 00:48) min:sec slower to 80-m, $t(27) = 7.50$, $p = < .001$, $d = 1.42$, 02:14 (± 01:10) min:sec slower to 100-m, $t(27) = 7.75$, $p = < .001$, $d = 1.46$, 02:06 (± 01:25) min:sec slower to 120-m, $t(27) = 5.76$, $p = < .001$, $d = 1.09$ and 02:35 (± 01:45) min:sec slower to the finish (0-m) point, $t(27) = 5.74$, $p = < .001$, $d = 1.07$ when compared with the EDBA-C trial.

However, simple main effect analysis also showed that ascent strategy in EDBA did not have a statistically significant effect on RPE. For the EDBA-B trial mean RPE was 0.3 (± 1.5) lower at 40-m, $t(27) = .878$, $p = .999$, $d = 0.17$, 0.7 (± 1.5) lower at 80-m, $t(27) = 2.46$, $p = .103$, $d = 0.47$, 0.8 (± 1.6) lower at 100-m, $t(27) = 2.44$, $p = .107$, $d = 0.47$, 0.2 (± 0.9) at 120-m, $t(27) = 1.24$, $p = .999$, $d = -0.23$ and 0.3 (± 1.5) at the finish (0-m) point, $t(27) = .70$, $p = .999$, $d = 0.19$ when compared with the EDBA-C trial.

There was no interaction effect between ascent strategy and elevation on CT or TC. The main effects for ascent strategy did not show any statistically significant differences between trials for TC, $F(1,27) = .618$ $p = .439$, $d = 0.02$ or CT, $F(1,27) = .539$, $p = .469$, $d = 0.02$.

Ability to perform firefighting duties

When asked if participants felt they would be more able to perform firefighting duties at the top of the ascent (120-m point) after taking 1-min breaks during the ascent, 82% felt that they would and 18% felt they would not.

Core body temperature change

Mean CT for all trials increased over time from the start (37.2 ± 0.4ºC) to the top of the ascent (38.1 ± 0.5ºC) and then continued to rise to 38.5 ± 0.5ºC during the descent to the finish point. The mean rate rise in CT was 0.11ºC (± 0.06) (range 0-0.2ºC) for every 10 m of vertical ascent and 0.03ºC (± 0.02) (range 0-0.2ºC) for every 10 m of vertical descent. There were no significant differences in starting CT between trial conditions. Figure 3 shows the mean CT change in °C for the ascent and descent phases along with the total change for each of the trials. There were no statistically significant differences in CT during the ascent ($F(1,27)$, = 1.17, $p = .110$, $\eta_p^2 = .042$) descent ($F(2.15,58.1) = .969$, $p = .391$, $\eta_p^2 = .035$) or in the total change ($F(1,27) = 1.45$, $p = .235$, $\eta_p^2 = .051$) between the trials.

Core body temperature limits

Two participants reached or exceeded the CT limit of 39.5ºC on the descent phases of the EDBA trials (1 during each of the EDBA trials). However, this was determined at the finish (0-m) point and as such the participants had completed the trial and no data was lost or

needed to be removed. Eight participants (3 male, 5 female) exceeded a CT of 39.0ºC during at least 1 of the 4 trials (4 participants during the SDBA-C, 4 during the SDBA-B, 6 during the EDBA-C during the 6 for EDBA-B). One male participant exceeded this limit on all 4 trials.

In order to contextualise the potential physiological limitations associated with thermal strain during the trials we applied a theoretical safe upper limit of 39.0ºC based on guidance relating the management of heat stress during firefighter training (14). For each elevation we then modelled how many participants would need to begin their descent to exit the building to remain within a 'safe' CT limit (i.e., not exceeding 39.0ºC) by adding their CT at each elevation with the CT change during the descent phase. Figure 4 shows the cumulative number of participants that would be required to turn around and abandon the task at each data collection point to remain within these safe limits. There were no clear differences between BA or between trials when performed continuously or with rest breaks.

Air supply

Figure 5 shows the cumulative number of participants activating the LAA during each of the trials. There were considerable differences in the available air supply between the SDBA and EDBA trails. Between 89-96% of participants triggered their LAA during the SDBA trials, compared to only 7% of participants during the EDBA trials. Additionally, all those that activated their LAA while wearing EDBA, did so during the descent only, whereas during the SDBA trials 25-29% of participants activated their alarm during the ascent.

Discussion

The purpose of the present study was to investigate the effects of different BA equipment and ascent strategies on physiological responses and performance of a simulated 120-m high-rise firefighting task. As anticipated, irrespective of BA configuration, this task was extremely physically demanding for this group of firefighters with near maximal peak values for HR and RPE in all trials, and significant thermal strain, which is similar to other studies investigating the demands of high-rise firefighting (4, 6, 9, 22).

Whilst BA is critical for firefighters at certain incidents, both SDBA and EDBA place substantial demands on firefighters (8, 10, 15, 32). Although EDBA with its increased air supply has been shown to permit extended work durations, the additional weight and associated increase in relative work rate has been reported to negate its benefits with increased core temperatures (10) and decreased work output and greater heart rate responses (8). In this study, we determined that there were no differences in HR or CT between SDBA and EDBA when on the continuous ascent trials. This may be explained by the fact that firefighters were asked to complete the task as fast as possible (but safely and within standard operating procedures) and this may have been different if firefighters had been given no specific instructions. However, a noticeable increase in TT was observed whilst wearing EDBA when compared to SDBA on the continuous ascent. Interestingly, the average performance decrement was only 01:44 min:sec longer to reach the 120-m ascent point and just over 2 mins longer to complete the entire task lasting ~23-25 min. Whilst these differences were found to be both statistically and meaningfully significant, fire service incident commanders may see this time decrement as an acceptable trade off when considering the additional air capacity afforded by the EDBA. Furthermore, only 3% more firefighters (1 participant) felt that they would be unable to perform firefighting duties after

ascending in the EDBA when compared with the SDBA, suggesting that the use of EDBA in these situations may not have such large detrimental effects on firefighting performance as previously thought. These results may help to further the ongoing discussions about the benefits/risks of using larger SCBA air supply in other countries such as in North America.

Core body temperature change

During the ascent phase of the trials, mean CT increases were between 0.88-1.03°C across all trials, although there were large inter-individual differences in these responses (range 0.5-1.8°C). Additionally, the mean rate of increase in CT was very close for all trials ranging from 0.053-0.055°C per min. Considering the mean time taken to ascend to the 120-m point was less than 20 mins for all trials (15:55-19:30 min:sec), the findings in this study report some of the highest absolute changes and rates of change in CT during short-term (< 20 mins) firefighting simulations in ambient conditions (17, 18). Furthermore, these values also exceed the rates of change observed in some live fire simulations (15, 19, 20). This may be explained by the almost maximal nature of this task, with firefighters carrying between 38.7-47.7 kg of equipment (including PPE, BA and firefighting equipment), resulting in high rates of metabolic heat production.

Whilst the maximal CT limits for firefighting work are not clearly defined in the UK, the only published guidelines recommend that during firefighter training activities a CT should not plan to exceed 39ºC (14). During the trials no firefighters would have exceeded a core temperature 39.0ºC had they turned around at the 40-m point and descended. However, by the 80-m point our modelling indicated that 4% of firefighters during the SDBA-C and 4% in both EDBA trials would be required to turn back to remain within theoretically safe CT limits ($\leq$ 39.0ºC). At the 100-m point, this increased to 7% of firefighters in the SDBA-B

trial, 11% in the SDBA-C and 11% in both EDBA trials. At the 120-m point, 32% of firefighters in the SDBA-C and EDBA-C trials, 29% in the EDBA-B trial and 21% in the SDBA-B trial would be unable to engage in further firefighting duties and would need to immediately descend and exit the building to remain within these theoretically safe CT limits ($\leq$ 39.0ºC). Considering the time taken to complete the entire task (full ascent and descent) took between 23-27 mins, irrespective of whether firefighters had enough air supply (i.e., using EDBA), CT is likely a limiting factor in such extreme circumstances which is not dissimilar to other findings (15).

In relation to air supply, during the SDBA trials, approximately one quarter of participants activated their LAA during the ascent phase of the task suggesting that these participants would have had to turn back and been unable to reach the 120-m point in a real live fire situation. Furthermore, almost all the remaining participants wearing SDBA activated their LAA during the descent meaning that in total between 89-96% would have been unable to exit the building without utilising their reserve air supplies. Therefore, the reduced air availability in SDBA may make it unreasonable and unsafe to routinely send firefighters beyond 80-m of elevation. In comparison, none of the firefighters wearing EDBA activated their LAA during the ascent and only 7% activating the alarm during the descent the continuous and breaks trials. Considering the negligible weight impact on CT limits, perceived ability to conduct firefighting activities, EDBA appears to be the more appropriate BA equipment when working beyond 80-m of elevation.

Given that stair climbing with equipment is recognised as being one of the most physically demanding tasks encountered by firefighters (3, 6, 9), there is little research investigating the effect of ascent strategies in firefighters. One study has investigated the

effect of a single step (SS) versus a double step (DS) stair climb (albeit not specifically in firefighters) during a vertical 27-m ascent of a residential building and reported that ventilation, oxygen uptake and HR were all significantly higher in the SS method when compared with the DS method which warrants further investigation in firefighters (24). In this study we found that forced 1-min rest breaks at least every 10 floors (40-m) resulted in both statistically significant and meaningfully large reductions in HR responses on the floors where breaks were taken. These forced rest periods resulted in the vast majority (82%) of firefighters reporting that they would be more able to perform firefighting duties at the 120-m point when compared to having ascended continuously. Further to this, whilst a total of 3 mins of breaks were taken during the ascent (at 40,80 and 100-m), TT to the top of the ascent (120-m) was only 01:26 min:sec slower during the SDBA-B and 01:51 min:sec slower during the EDBA-B trials, indicating that the recovery during the breaks allowed the participants to ascend at a faster rate overall when compared with the continual ascent trials.

Strengths and limitations

One of the broader strengths of this study is that it adds to the paucity of evidence on the physical demands and equipment limitations to extreme high-rise firefighting scenarios. To make these findings more usable to policy makers, we reported elevation in metres rather than in floors ascended allowing the findings of this study to be applied more broadly to any high-rise building. This has not routinely been done in previous studies. More specifically, this study has also shown that EDBA could be considered a viable option for such high-rise operations, where previously this equipment would only have been used for search and rescue type activities (10). We believe this is also the first study to investigate the effect of taking planned rest breaks during high-rise accents, again providing useful quantitative and qualitative data on the impact of such a strategy. Finally, a significant strength of this study

was the range and diversity (i.e., sex, age, body mass and cardiorespiratory fitness) of the purposefully recruited study sample, ensuring that the findings are applicable to the wider fire and rescue service population.

A potential limitation of this study, common to many studies of this kind was that the firefighting tasks were not conducted under live fire conditions, however this was not feasible in this instance. It is possible that the absence of factors such as the psychological stress associated with emergency response as well as the heat and smoke of a live fire situation may alter the performances and physiological responses during these tasks. However, the combination of extreme physical workload and wearing of impermeable PPE are likely to be more important determinants of these responses.

Conclusions

Cardiovascular strain and perceived exertion were near maximal during these simulated high-rise firefighting operations. The rates of rise in core body temperature (CT) are among the highest reported in the literature, indicative of the high rates of metabolic heat production and limited capacity for heat dissipation. Taking short rest breaks at regular intervals reduced cardiovascular strain and improved perceptions of readiness to perform firefighting tasks after ascending the building. Wearing the heavier EDBA had a limited effect on performance time and no effect on thermal or cardiovascular strain. Based on these findings, it is therefore recommended that firefighters wear EDBA if they are likely to ascend beyond 80-m and are encouraged to take regular breaks during the ascent phase.

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Figure Legends

Figure 1. Mean (± SD) task time for the SBBA-C and EDBA-C trials.

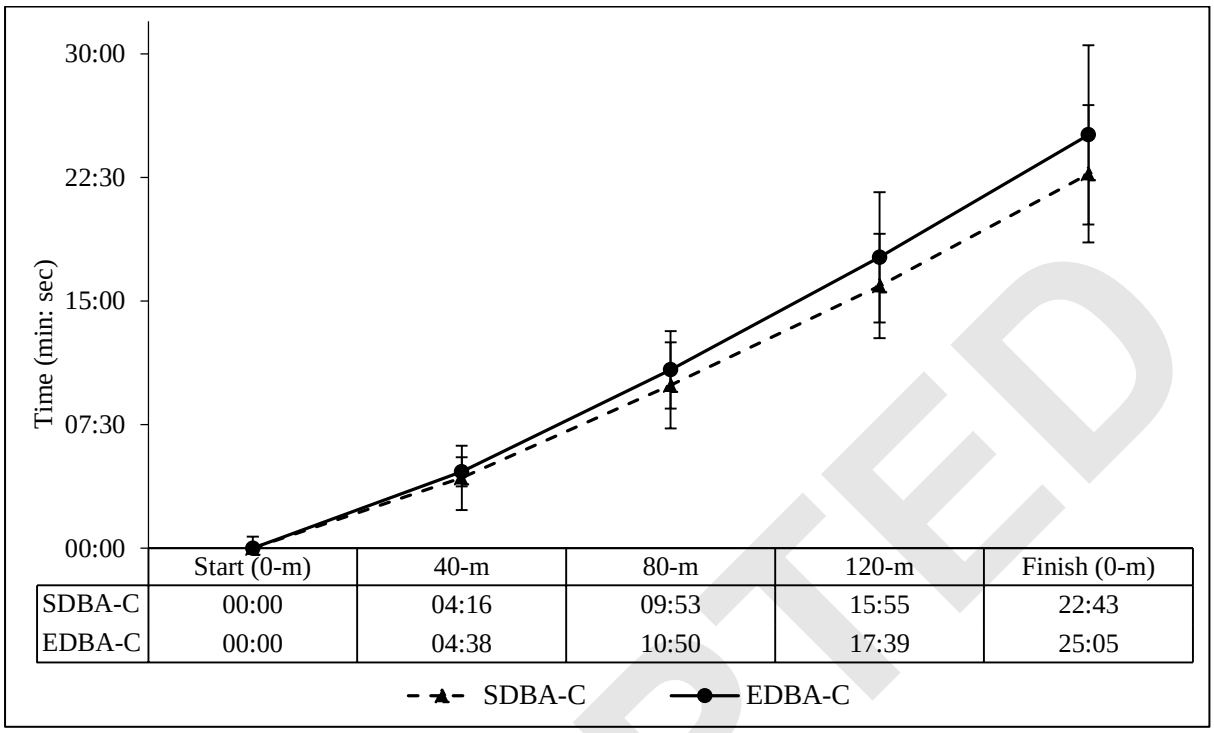
Figure 2. Mean (± SD) heart rate responses across the experimental trials.

Figure 3. Mean (± SD) core temperature changes across the experimental trials.

Figure 4. Cumulative number of participants that would have to turn around at respective elevations to avoid exceeding a CT of 39.0ºC.

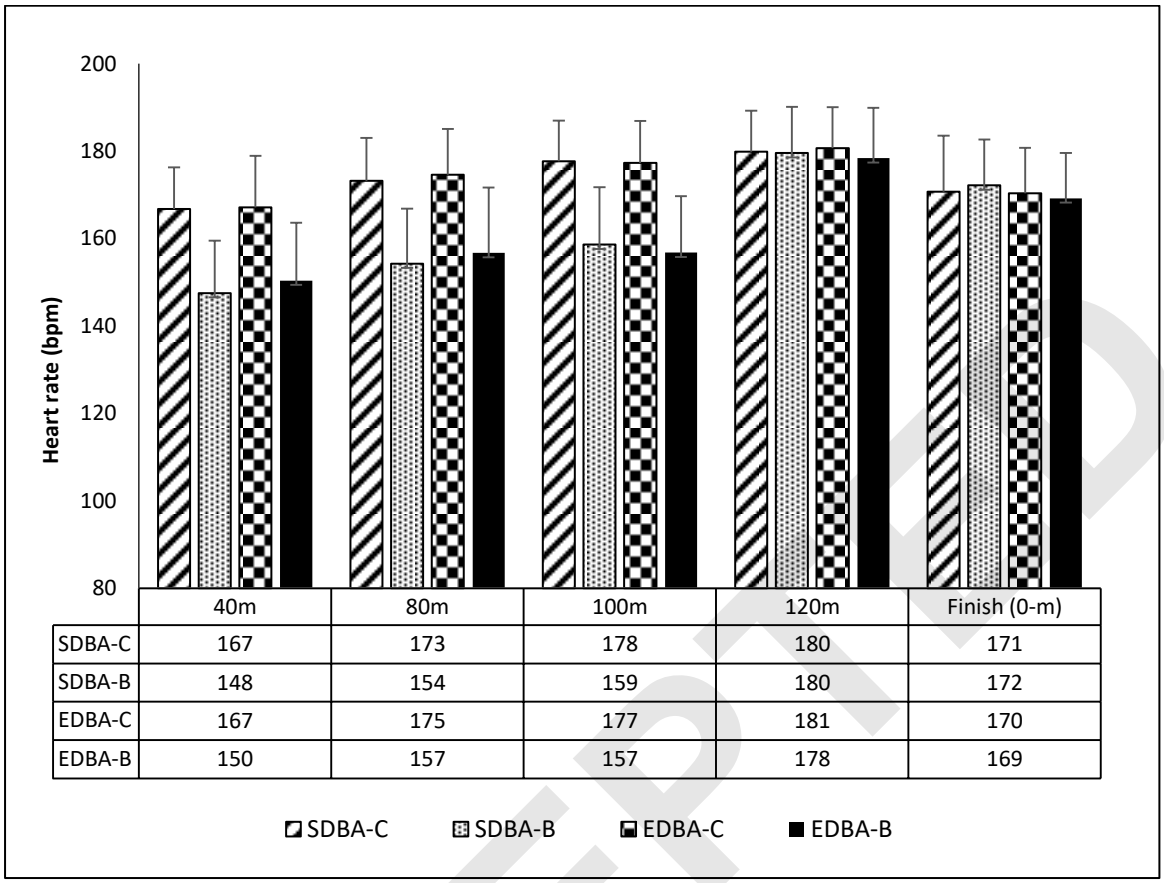
Figure 5. Cumulative number of participants triggering the low warning whistle during the trials.

Figure 1



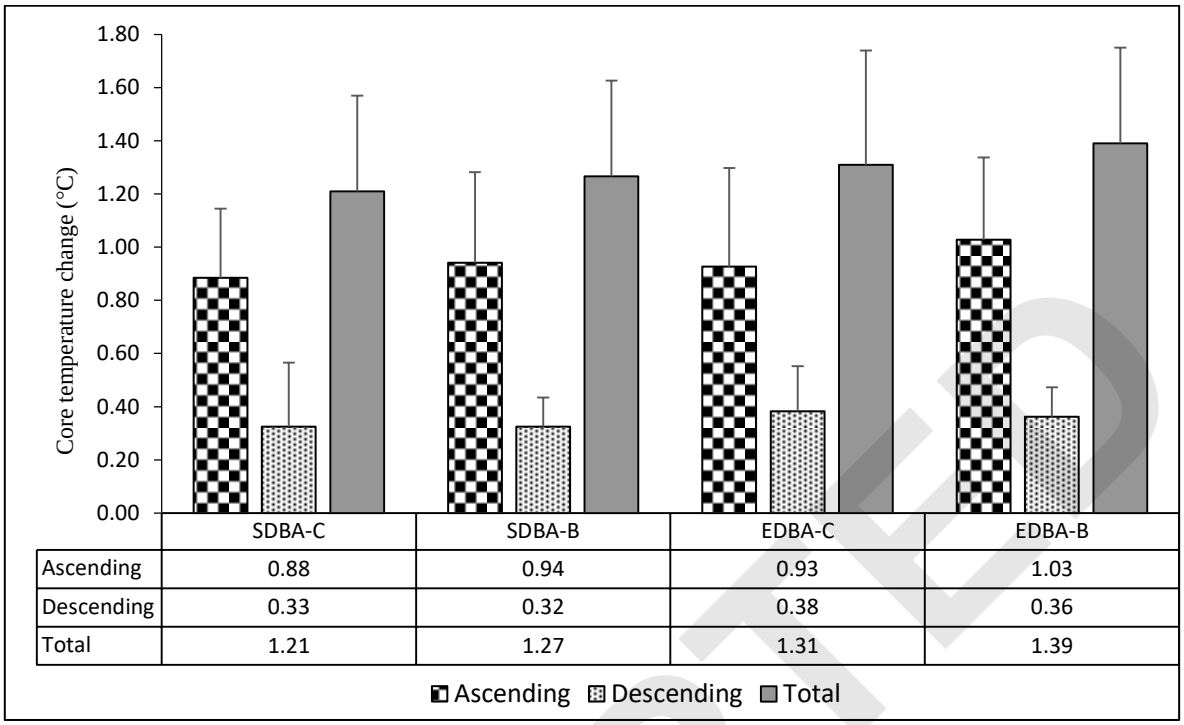
	Start (0-m)	40-m	80-m	120-m	Finish (0-m)
SDBA-C	00:00	04:16	09:53	15:55	22:43
EDBA-C	00:00	04:38	10:50	17:39	25:05

Figure 2



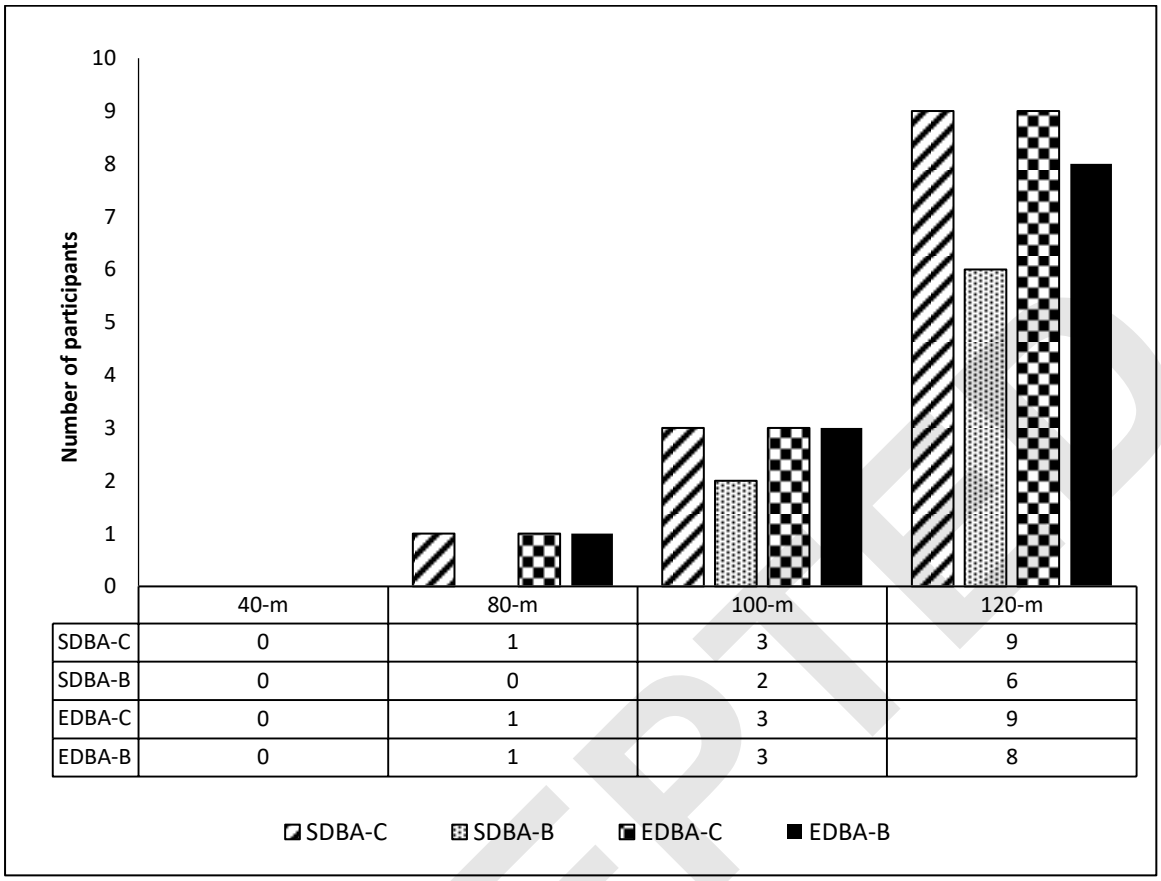
	40m	80m	100m	120m	Finish (0-m)
SDBA-C	167	173	178	180	171
SDBA-B	148	154	159	180	172
EDBA-C	167	175	177	181	170
EDBA-B	150	157	157	178	169

Figure 3



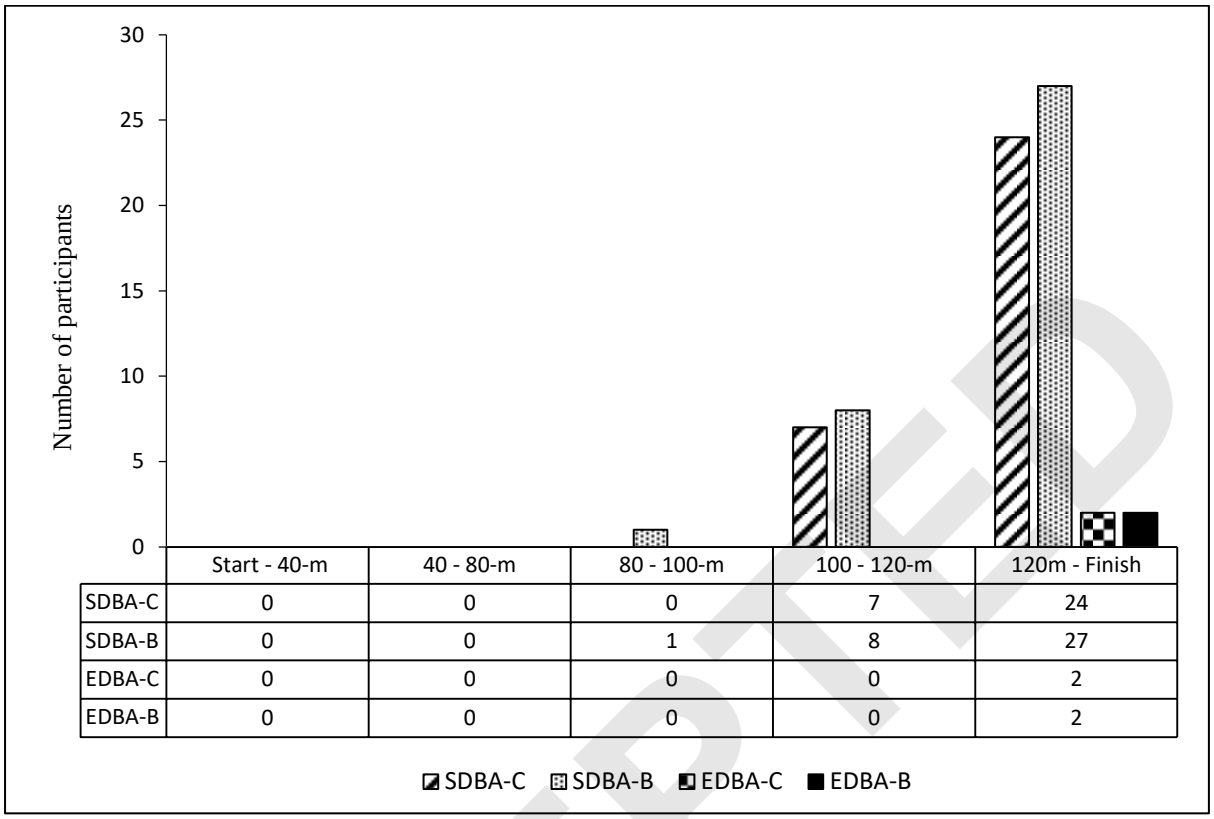
	SDBA-C	SDBA-B	EDBA-C	EDBA-B
Ascending	0.88	0.94	0.93	1.03
Descending	0.33	0.32	0.38	0.36
Total	1.21	1.27	1.31	1.39

Figure 4



	40-m	80-m	100-m	120-m
SDBA-C	0	1	3	9
SDBA-B	0	0	2	6
EDBA-C	0	1	3	9
EDBA-B	0	1	3	8

Figure 5



	Start - 40-m	40 - 80-m	80 - 100-m	100 - 120-m	120m - Finish
SDBA-C	0	0	0	7	24
SDBA-B	0	0	1	8	27
EDBA-C	0	0	0	0	2
EDBA-B	0	0	0	0	2

STROBE Statement—checklist of items that should be included in reports of observational studies

	Item No	Recommendation	Page No
Title and abstract	1	(*a*) Indicate the study's design with a commonly used term in the title or the abstract	1
		(*b*) Provide in the abstract an informative and balanced summary of what was done and what was found	2
Introduction			
Background/rationale	2	Explain the scientific background and rationale for the investigation being reported	3-5
Objectives	3	State specific objectives, including any prespecified hypotheses	5
Methods			
Study design	4	Present key elements of study design early in the paper	6
Setting	5	Describe the setting, locations, and relevant dates, including periods of recruitment, exposure, follow-up, and data collection	6-9
Participants	6	(*a*) *Cohort study*—Give the eligibility criteria, and the sources and methods of selection of participants. Describe methods of follow-up *Case-control study*—Give the eligibility criteria, and the sources and methods of case ascertainment and control selection. Give the rationale for the choice of cases and controls *Cross-sectional study*—Give the eligibility criteria, and the sources and methods of selection of participants	5
		(*b*) *Cohort study*—For matched studies, give matching criteria and number of exposed and unexposed *Case-control study*—For matched studies, give matching criteria and the number of controls per case	NA
Variables	7	Clearly define all outcomes, exposures, predictors, potential confounders, and effect modifiers. Give diagnostic criteria, if applicable	7-10
Data sources/ measurement	8*	For each variable of interest, give sources of data and details of methods of assessment (measurement). Describe comparability of assessment methods if there is more than one group	7-10
Bias	9	Describe any efforts to address potential sources of bias	7-10
Study size	10	Explain how the study size was arrived at	5
Quantitative variables	11	Explain how quantitative variables were handled in the analyses. If applicable, describe which groupings were chosen and why	9-10

Statistical methods	12	(*a*) Describe all statistical methods, including those used to control for confounding	9-10
		(*b*) Describe any methods used to examine subgroups and interactions	NA
		(*c*) Explain how missing data were addressed	NA
		(*d*) *Cohort study*—If applicable, explain how loss to follow-up was addressed *Case-control study*—If applicable, explain how matching of cases and controls was addressed *Cross-sectional study*—If applicable, describe analytical methods taking account of sampling strategy	NA
		(*e*) Describe any sensitivity analyses	NA
Results			
Participants	13*	(a) Report numbers of individuals at each stage of study—eg numbers potentially eligible, examined for eligibility, confirmed eligible, included in the study, completing follow-up, and analysed	5-6
		(b) Give reasons for non-participation at each stage	NA
		(c) Consider use of a flow diagram	NA
Descriptive data	14*	(a) Give characteristics of study participants (eg demographic, clinical, social) and information on exposures and potential confounders	5-6
		(b) Indicate number of participants with missing data for each variable of interest	NA
		(c) *Cohort study*—Summarise follow-up time (eg, average and total amount)	NA
Outcome data	15*	*Cohort study*—Report numbers of outcome events or summary measures over time	NA
		Case-control study—Report numbers in each exposure category, or summary measures of exposure	NA
		Cross-sectional study—Report numbers of outcome events or summary measures	NA
Main results	16	(*a*) Give unadjusted estimates and, if applicable, confounder-adjusted estimates and their precision (eg, 95% confidence interval). Make clear which confounders were adjusted for and why they were included	NA
		(*b*) Report category boundaries when continuous variables were categorized	NA
		(*c*) If relevant, consider translating estimates of relative risk into absolute risk for a meaningful time period	NA

Other analyses	17	Report other analyses done—eg analyses of subgroups and interactions, and sensitivity analyses	NA
Discussion			
Key results	18	Summarise key results with reference to study objectives	10, 16-19
Limitations	19	Discuss limitations of the study, taking into account sources of potential bias or imprecision. Discuss both direction and magnitude of any potential bias	20
Interpretation	20	Give a cautious overall interpretation of results considering objectives, limitations, multiplicity of analyses, results from similar studies, and other relevant evidence	20
Generalisability	21	Discuss the generalisability (external validity) of the study results	20
Other information			
Funding	22	Give the source of funding and the role of the funders for the present study and, if applicable, for the original study on which the present article is based	Title page

*Give information separately for cases and controls in case-control studies and, if applicable, for exposed and unexposed groups in cohort and cross-sectional studies.

Note: An Explanation and Elaboration article discusses each checklist item and gives methodological background and published examples of transparent reporting. The STROBE checklist is best used in conjunction with this article (freely available on the Web sites of PLoS Medicine at http://www.plosmedicine.org/, Annals of Internal Medicine at http://www.annals.org/, and Epidemiology at http://www.epidem.com/). Information on the STROBE Initiative is available at www.strobe-statement.org.