The trapped human experiment

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The trapped human experiment

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Abstract

This experiment observed the evolution of metabolite plumes from a human trapped in a simulation of a collapsed building. Ten participants took it in turns over five days to lie in a simulation of a collapsed building and eight of them completed the 6 h protocol while their breath, sweat and skin metabolites were passed through a simulation of a collapsed glass-clad reinforced-concrete building. Safety, welfare and environmental parameters were monitored continuously, and active adsorbent sampling for thermal desorption GC-MS, on-line and embedded CO, CO\(_2\) and O\(_2\) monitoring, aspirating ion mobility spectrometry with integrated semiconductor gas sensors, direct injection GC-ion mobility spectrometry, active sampling thermal desorption GC-differential mobility spectrometry and a prototype remote early detection system for survivor location were used to monitor the evolution of the metabolite plumes that were generated. Oxygen levels within the void simulator were allowed to fall no lower than 19.1% (v). Concurrent levels of carbon dioxide built up to an average level of 1.6% (v) in the breathing zone of the participants. Temperature, humidity, carbon dioxide levels and the physiological measurements were consistent with a reproducible methodology that enabled the metabolite plumes to be sampled and characterized from the different parts of the experiment. Welfare and safety data were satisfactory with pulse rates, blood pressures and oxygenation, all within levels consistent with healthy adults. Up to 12 in-test welfare assessments per participant and a six-week follow-up Stanford Acute Stress Response Questionnaire indicated that the researchers and participants did not experience any adverse effects from their involvement in the study. Preliminary observations confirmed that CO\(_2\), NH\(_3\) and acetone were effective markers for trapped humans, although interactions with water absorbed in building debris needed further study. An unexpected observation from the NH\(_3\) channel was the suppression of NH\(_3\) during those periods when the participants slept, and this will be the subject of further study, as will be the detailed analysis of the casualty detection data obtained from the seven instruments used.

(Some figures in this article are in colour only in the electronic version)

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1. Introduction

Disaster strikes, buildings collapse and people become trapped on a regular basis. An uninjured healthy adult with a supply of fresh air has a high probability of survival, if they are recovered within 72 h of becoming trapped. Most (80%) of those who are recovered alive are rescued within 48 h of becoming trapped [1, 2]. After 72 h survival rates reduce rapidly and without access to water most casualties are highly unlikely to survive longer than 120 h. Most rescues are undertaken by the survivors at the scene [2] and the larger the scale of the collapse, the longer it will take to escalate the support for the search-and-rescue effort from local to regional, to national and ultimately to international responses. However, whatever the scale, the most important factor in reducing mortality is the rapid location of survivors within collapsed structures.

The casualties trapped within a void inside a collapsed building release volatile metabolites through their skin, any urine they release and their breath [3]. (Interviews conducted as part of the preparation of this study with search-and-rescue specialists suggest that defecation is unusual in recovered survivors, although voiding of the bowels does sometimes occur at, or near to, the point of death.) Injured casualties may also release volatile organic compounds (VOCs) associated with blood and visceras. If the air within the void is not replenished, then carbon dioxide levels will increase and oxygen levels will fall. This leads to asphyxiation and death [4]. If the air is replenished and the void is ventilated, then volatile metabolites from the casualty will form a plume that will travel through the building debris. As the plume of volatile metabolites moves through the collapsed building, complicated interactions between the disrupted building materials and the plume occur. Furthermore, the interactions are dynamic, changing with environmental conditions such as humidity, solar heating, as well as wind strength and wind direction. It is in this context that the European funded project Second Generator Locator for Urban Search and Rescue (SGL for USaR) [5] is developing sensor systems to identify the physical and chemical signatures that trapped casualties generate.

At the moment, the location of entrapped people is undertaken at great personal risk on the part of the rescuers, who are sometimes assisted by dog search-and-rescue teams. Images of search-and-rescue teams at work are iconic in the way they exemplify the highest notions of valour and selfless courage; however, they fail utterly to convey the limitations of the current state of the art. A trained and rested search-and-rescue dog will search the upper surface of a collapsed building rapidly, with a high probability of locating survivors close to the surface. Note though that dogs tire after about 20 min and then they must rest for hours. Search-and-rescue teams also use sensors to help them detect signs of life and for the most part these are cameras, microphones and carbon dioxide sensors [6]. Rescuers are normally only able to assess each location at a search site briefly, and continuous monitoring of large collapsed structures does not normally occur. The plume containing life’s signatures of carbon dioxide, NH₃, acetone, isoprene and many other biogenic volatiles may not be present in the samples taken from the monitoring site at the precise time when monitoring takes place.

Setting up and running field tests to generate ‘ground-truth’ data from collapsed buildings are so problematic that no scientifically validated data are available to inform sensor specifications, and enable validated operating protocols to be developed. Furthermore, there are no methods for realistically testing the operational capabilities of sensors, and/or evaluating potential search-and-rescue protocols in a rigorous and reproducible way. The aim of this research was to address this and study the evolution of chemical plumes produced by humans trapped inside collapsed buildings. Finally, the effects of humidity and temperature on biogenic chemical plumes within building debris were factors that needed to be included within the experimental design. The data from the experiment were intended to be used to evaluate and inform decisions about the sensor specifications included in a second generator locator for search-and-rescue operations.

A simulator of a collapsed building with an entrapped casualty was designed and built to enable controlled and reproducible sampling and monitoring of chemical plumes within the simulated collapsed structure. The provision of safe and ethical experimental conditions for volunteer participants, and research staff, was the most important element of this study and there was necessarily a tension between providing a complete and accurate simulation of a trapped casualty within a collapsed building and ensuring the welfare of volunteer participants. The operating specifications were chosen to reflect the conditions most likely to support life for trapped but uninjured casualties for up to 72 h, and these were derived from detailed search-and-rescue briefings (December 2008, SDIS 84, Vaulcuse (Avignon) provided by search-and-rescue specialists.)

This study, termed ‘trapped human experiment’, is described in this paper along with some of the preliminary findings that are helpful in the evaluation of its implementation. The detailed analysis of the substantial and wide ranging data sets that were collected will be the subject of future journal articles.

2. Description of concept

A safe and reproducible simulator of a person trapped inside a collapsed building was designed, built and tested, see figure 1. The experiment enabled the gases and VOCs released from an entrapped human to be studied as they travelled through the materials associated with structural collapse. Furthermore, the experiment was specified so that a range of environmental conditions to simulate building collapses in different climates and seasons could be generated. Three sub-systems were used: an environmental chamber, a void simulator and a collapsed building simulator. The environmental chamber provided a buffer reservoir of purified air at a specified humidity that was supplied to the void simulator. The void simulator was large enough for an above-average size adult (120 kg and 2 m) to lie in. Air was passed through the void simulator from the environmental chamber and into the collapsed building simulator. The collapsed building simulator presented the
Figure 1. A schematic diagram of the trapped human experiment, showing the environmental chamber, (bottom), feeding air to the void simulator and hence to the collapsed building simulator. A—air supply; H—humidifier; E—in-line Environics air quality air monitoring; T—in-line temperature and humidity monitoring; P—thermoelectric heat pump; G—CO$_2$, CO and O$_2$ gas monitoring; S—sampling point; V—vital signs monitoring; and F—flow control. 1a–4b: sampling point locations within the collapsed building simulator. Airflow through the experiment is indicated by arrows.

The collapsed building simulator was fitted with multiple sampling points that enabled a range of analytical and sensor systems to be interfaced into the experiment. The analytical instrumentation was chosen to span a range of operational specifications. Robust temporal responses in a timescale of seconds were sought from aspirating ion mobility spectrometers, significantly greater fidelity on a timescale of minutes was delivered by GC-IMS and GC-DMS and gold-standard GC-MS data for trace analysis were based on an adsorbent sampling thermal desorption approach.

3. Experimental details

3.1. Details of the design

3.1.1. Environmental chamber and air supply. The environmental chamber was a gas-tight glass-lined tank with an internal volume of approximately 500 dm$^3$ (2010 mm × 510 mm × 505 mm); this provided an air residence time of about 25 min at an air-supply flow of 20 dm$^3$ min$^{-1}$. The humidity of the air supplied to the environmental chamber was maintained at a specified level by pumping distilled water (peristaltic pump) into a heated air-supply inlet. The humidified air passed through the environmental chamber where O$_2$, CO and CO$_2$ concentrations were monitored continuously. Temperature and humidity were also recorded, and an ion mobility spectrometer combined with a semiconductor gas sensor array was used to test, continuously, for the presence of potentially harmful contaminants in the air supply. The residence time of the air was long enough to ensure that in the event of a failure in the monitoring systems, or a loss of control in air quality, the volunteer participants would be removed before they were subjected to risk of injury or harm. The outlet from the environmental chamber was split into three 6.35 mm (1/4”) PTFE tubes. See figure 1 for a schematic diagram that summarizes the experiment and table 1 for a detailed overview of the instrument and sensor systems.

3.1.2. Void simulator. The three PTFE tubes from the environmental chamber were connected around the participant’s head to direct conditioned air directly onto the participant’s face. The void simulator was large enough (2 m long, 72 cm wide and 51 cm high) to allow the participant to move and maintain some level of comfort. The intention was to avoid inflicting discomfort on the participant and so a pillow and a closed-cell foam mattress with a ‘strong’ cotton covering were placed inside the void simulator for the participant to lie on. The cotton sheet was strong enough and arranged in such a way so that the participants could be lifted as a ‘dead-weight’ from within the void simulator in the event that they...
Table 1. Summary of the sensors and instruments used in the trapped human experiment.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Instrumentation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Welfare</td>
<td></td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>Dräger X-am 500 electrochemical gas detector, with sampling probes.</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td></td>
</tr>
<tr>
<td>O₂ (%)</td>
<td></td>
</tr>
<tr>
<td>$T_{\text{body}}$ °C</td>
<td>GE Healthcare Datex Ohmeda S/5™ Compact critical care monitor</td>
</tr>
<tr>
<td>Pulse rate (bpm)</td>
<td></td>
</tr>
<tr>
<td>Oxygen saturation (%)</td>
<td></td>
</tr>
<tr>
<td>Blood pressure (mm Hg)$^{-1}$</td>
<td></td>
</tr>
<tr>
<td>VOC au</td>
<td>Environics Vampii transverse ion mobility spectrometer with MOS sensing array.</td>
</tr>
<tr>
<td>Experimental control</td>
<td></td>
</tr>
<tr>
<td>Airflow dm$^{-3}$</td>
<td>Platon NG/X Rotameters</td>
</tr>
<tr>
<td>$T_{\text{chamber}}$ °C$^{-1}$</td>
<td>Digitron 2080R temperature and relative humidity probe</td>
</tr>
<tr>
<td>%RH (%)</td>
<td></td>
</tr>
<tr>
<td>Metabolite and chemical profile monitoring</td>
<td>Environics Escort Elf pump to markes international adsorbent tube (Tenax/Carbotrap).</td>
</tr>
<tr>
<td>VOC au</td>
<td>Fisons Trio 1/1 Quadrupole mass spectrometer</td>
</tr>
<tr>
<td>CO₂ (%)</td>
<td>Varian GC-MS Saturn 4000 Ion trap mass spectrometer</td>
</tr>
<tr>
<td>VOC au</td>
<td>MSA escort Elf pump to markes international adsorbent tube (Tenax/Carbotrap).</td>
</tr>
<tr>
<td>Ammonia (ppm)</td>
<td>Markes International thermal desorption.</td>
</tr>
<tr>
<td></td>
<td>ISAS, research gas chromatograph ion mobility spectrometer</td>
</tr>
<tr>
<td></td>
<td>Sionex suitcase integrated thermal desorption gas chromatograph ion mobility spectrometer</td>
</tr>
<tr>
<td></td>
<td>ISAS, research gas chromatograph ion mobility spectrometer</td>
</tr>
<tr>
<td></td>
<td>Sionex suitcase integrated thermal desorption gas chromatograph ion mobility spectrometer</td>
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<tr>
<td></td>
<td>Environics Vampii transverse ion mobility spectrometer with MOS sensing array.</td>
</tr>
<tr>
<td></td>
<td>Sionex suitcase integrated thermal desorption gas chromatograph ion mobility spectrometer</td>
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<tr>
<td></td>
<td>Varian GC-MS Saturn 4000 Ion trap mass spectrometer</td>
</tr>
<tr>
<td></td>
<td>Varian GC-MS Saturn 4000 Ion trap mass spectrometer</td>
</tr>
</tbody>
</table>

were unable to help themselves out. The void simulator was sealed with a lightweight polycarbonate lid (2 m long, 72 cm wide). The lid was light enough so that a firm push from the participants was enough to release themselves should they need to. External handles were fitted so that the researchers could remove the lid quickly should they need to. A window in the lid enabled the participants to be observed and the readings on their personal air monitors to be recorded. The air exhaust from the void simulator was split into two streams. One stream was directed to a pump that ensured that the flow through the void simulator was maintained at the specified level and the other stream ensured that the flow was directed into the collapsed building simulation, figure 1 and table 1.

3.1.3. Collapsed building simulation. The collapsed building simulator, figure 2, was a glass column (1.5 m long, 15 cm ID; QVC process tubing with gas tight fittings and end caps). The column was packed with four sets of cylindrical discs of building materials. Each set of building materials was composed from three discs of concrete, two discs of plasterboard, a layer of medium-density fibreboard, a layer of polystyrene insulation and a layer of ceiling board. The discs were held in place on three stainless steel threaded rods (10 mm) and a 22 mm OD copper pipe was passed through the whole assembly to house the sampling lines. Every other layer of the building material was drilled out in the middle (22 mm) and fitted with a gasket made from a silicone seal and PVC to form a gas tight seal. The four sets of building materials were coupled together using compression unions on the copper pipe. This arrangement forced the air to flow through the packed column in a serpentine way, and so enabled a significant burial depth to be ‘folded’ into the column. Each set of discs was equivalent to a burial depth of approximately 70 cm and equivalent to a channel through a ‘pancake’ collapse that compresses a single story of a multi-story building into a densely packed set of layers of compressed building material. Two sampling points were placed in between each of the four sets, as well as at both ends of the column, giving a total of ten 3.18 mm (1/8”) PTFE tube sampling lines that were fed through the copper pipe. Each sampling point represented a different burial depth and enabled the plume dynamics to be studied. The airflow through the collapsed building simulation was specified to be maintained at approximately 5 dm$^3$ min$^{-1}$.

3.2. Method

3.2.1. Safety. The void simulator was a confined space and the experiment protocols were designed to comply with the UK Health and Safety Executive’s Confined Spaces Regulations 1997 [7]. The experiment contained four levels of safety within it: engineered safety, redundant and multiple monitoring of safety critical parameters, safe operational procedures and participant monitoring.
The void simulator was lined with toughened shatterproof glass and sealed with polycarbonate to provide an electrically insulated barrier between the participant and the laboratory; the maximum voltage allowed in the experiment was 12 V dc. The void simulator was encased in aluminium and the lid was subjected to a strength drop test to ensure that it could withstand the accidental impact of a person or piece of equipment falling onto it. The glass lining also ensured effective disinfection and cleaning between tests, as well as a reproducible and non-reactive surface that was free from carry-over artefacts between participants and tests. The volume of air within the void simulator was sufficient to prevent injury or ill effects for no less than 30 min in the event of a failure in the air supply. Modelling and safety checks were undertaken to verify these important design criteria.

The flow of air to the experiment was provided by a scroll pump and continuously monitored. Supply pressure and airflow readings at the inlet, exhaust and pumps were verified every 15 min. Three $O_2$, $CO_2$, and CO gas monitors were used to continuously monitor the air in the experiment (Draeger X-am 5000 $CO_2$, $CO_2$, $O_2$ gas detector). One monitor was placed in the void simulator with the participant, one on the air inlet to the void simulator and the third was used to monitor the exhaust from the void simulator. Temperature measurements were made from the walls of the void simulator as well as air temperature and the temperature readings from the participants. The air in the environmental chamber was monitored continuously with a VAMPI chemical detection system (Environetics). The VAMPI chemical detection system contained an aspirating ion mobility spectrometer, and a sensor array of three metal oxide semiconductor sensors and a field effect transistor sensor. Humidity and temperature sensors were also present.

The safe operation of the experiment was maintained by a welfare team of three researchers comprising an experiment director who assessed the monitoring systems and all activity on the experiment, and two welfare scientists who independently monitored and recorded the safety system’s parameters continuously throughout the experiment. Positive reporting protocols were followed and the experiment would have been stopped with the immediate recovery of the participant in the event of any of the following conditions: the absence of more than one of the three welfare scientists, any request to stop from the participant, a gas safety alarm (set at $> 3\% CO_2$, $< 19\% O_2$ and $> 30$ ppm CO), any vital-signs-monitoring alarm, any external building alarm, the loss of the chemical-detection-monitoring system for more than 15 min, loss of monitoring of airflow or air pressure for more than 15 min, loss of more than one gas detector; the loss of the chemical-detection-monitoring system for more than 15 min, a change in the ion mobility or sensor responses in the chemical detection system, and a breach of the air inlet exclusion zone (an exclusion zone was set up around the air inlet to the air compressor of 20 m. No vehicle, internal combustion engine, or activity with a risk of vapour release was allowed within the exclusion zone during the experiments, and unauthorized personnel were excluded from this zone during the experiments). Every 30 min, the experiment director reviewed the data and operation of all the aspects of the experiment, and provided all the systems were within operating parameters and the participant was well and content (see below), the experiment was allowed to proceed into the next 30 min period.

The participant was monitored continuously using the systems and procedures described above. Every 30 min, the participants were asked a series of questions related to physical comfort, anxiety, hunger and thirst and bladder and bowel comfort. It is important to note that apart from boredom, the experiment was not intended to place the participants under physical or psychological stress. Some of the participants
fell asleep during the experiment. When this happened blood pressure measurements and welfare questionnaires were suspended until they woke up. If the participants obscured their gas monitor while they were asleep, they were woken up to enable the gas monitor readings to be recorded (through the window in the lid).

Prior to the experiment, a series of training and practice exercises were undertaken to test and validate the welfare procedures. These preparatory tests started at 30 min duration and increased to 2 h. Five 2 h welfare tests were run before the experiment. An important part of the welfare preparations were exercises undertaken to ensure that in the event of a medical emergency the participant could be safely recovered and provided with life support. The research team received special training in emergency resuscitation and psychological first aid as part of their preparations for the experiment and a medical emergency exercise was run to ensure that an appropriate response could be mounted if the need arose.

3.2.2. Ethics and participant preparation. This study was conducted in accordance with the ethical principles of Good Clinical Practice and the Declaration of Helsinki. The local ethics advisory committee (Loughborough University, Leicestershire LE11 3TU UK Reference: R10-P49) approved the protocol before commencement of the study. All the participants gave written informed consent and all data about them were kept anonymous.

Four female and six male volunteers participated in the experiment, and each of them completed a welfare questionnaire before and after their test period, see Table 2. Meta-data were collected from the participants about age, body mass index, gender, diet, personal care, recent urination and bowel movements. Information from the female participants about their contraception and menstrual cycles were also recorded. The participants then changed into a clean cotton tracksuit, and breath, skin and saliva samples were taken. At the start of each experiment the participant was monitored continuously throughout the experiment while they were in the void simulator. During this familiarization each participant demonstrated that they were able to open the void simulator from the inside, unaided, and that they could operate the alarm and use the two-way communication radio. Permission was then sought from each participant to fit cardiac- and respiratory-monitoring electrodes to their abdomen and torso, a thermometer to their axilla and a blood-pressure-monitoring cuff to their right arm. Finally a blood oxygen monitor was placed on their right index finger. These critical-sign sensors were connected to a vital-signs monitor (Datex-Ohmeda S/5 vital-signs monitor) via an umbilical bundle of cables fitted through a gas-tight connection in the wall of the void simulator. The critical-signs monitoring was then tested along with the gas-monitoring systems. At the end of these preparations, the participant was asked if the void simulator could be sealed, if the participant agreed to this the lid was placed onto the void simulator and the participant sealed inside.

The participant was monitored continuously throughout the experiment and every 30 min the critical-signs monitor, gas monitors, direct observations and welfare questionnaires were assessed. A further member of the research team (the participant’s personal assistant) was designated to care for the participant and assume responsibility for ensuring that the participant was kept informed about all aspects of the experiment while they were in the void simulator.

At the end of each 6 h test, the participants were helped out of the void simulator and accompanied to the sampling/changing room. Saliva, breath and skin samples were taken before they changed back into their own clothes. The participants were then provided with a light snack and a drink, and asked to complete a welfare questionnaire. The participants were also given an information sheet and contact details of a ‘person of trust’ along with information on continuing welfare support. After six weeks, the participants were contacted again and invited to complete a Stanford Acute Stress Response Questionnaire [10].

3.2.3. Sampling schedule. At the start of each experiment blank measurements were obtained for all the sampling systems and on-line instrumentation before commencing a series of twelve 30 min cycles. During each cycle the welfare observations described above were recorded by the three welfare scientists. Other researchers recorded the experimental parameters needed to analyse the data once the experiment was completed. These data included airflow in the various parts of the experiment, temperatures and humidity. CO₂, CO and O₂ data were recorded every 15 min at different sampling points within the collapsed building simulation.

<table>
<thead>
<tr>
<th>Reference</th>
<th>Gender</th>
<th>Age yr⁻¹</th>
<th>Mass kg⁻¹</th>
<th>Height cm⁻¹</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>F</td>
<td>24</td>
<td>62</td>
<td>160</td>
<td>Experiment ran overnight</td>
</tr>
<tr>
<td>2</td>
<td>F</td>
<td>31</td>
<td>50</td>
<td>160</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>M</td>
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<td>4</td>
<td>M</td>
<td>33</td>
<td>78</td>
<td>175</td>
<td>Experiment ran overnight</td>
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<tr>
<td>5</td>
<td>M</td>
<td>31</td>
<td>106</td>
<td>173</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>M</td>
<td>27</td>
<td>70</td>
<td>178</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>M</td>
<td>43</td>
<td>108</td>
<td>192</td>
<td>Experiment ran overnight</td>
</tr>
<tr>
<td>8</td>
<td>F</td>
<td>31</td>
<td>69</td>
<td>170</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>F</td>
<td>26</td>
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<td>170</td>
<td>Left experiment prematurely</td>
</tr>
<tr>
<td>10</td>
<td>M</td>
<td>48</td>
<td>83</td>
<td>170</td>
<td>Experiment ran overnight</td>
</tr>
</tbody>
</table>
Air samples were collected from the void simulator and at different sampling points within the collapsed building simulator starting during the fifth 30 min cycle, after 2 h had elapsed. Twelve 500 cm³ samples were collected onto mixed bed (Tenax TA/Carbotrap) adsorbent traps (C2-AAXX-5032, Markes International) at a flow rate of 50 cm³ min⁻¹ using air-sampling pumps. The sample lines were primed by drawing 50 cm³ of sample through the sample line before the sample was taken. (The maximum internal volume of the sample line was 5 cm³.) Air samples were collected sequentially from different sampling points for the rest of the test. The sampling and measurement schedule followed during each experiment was summarized in figure 3.

3.2.4. On-line measurements. CO₂, O₂ and CO levels in the void simulator and at different sampling points in the collapsed building simulator were monitored and recorded continuously as described above. Temperature and humidity were also monitored and recorded. In addition to these physical measurements, seven chemical-monitoring systems were connected to various places within the experimental system.

Three chemical detection systems containing an aspirating ion mobility spectrometer with integrated chemical sensors (VAMPPI; a modified Chempro 100i aspirating ion mobility spectrometer Environics Oy Mikkeli, Finland) were connected on recalculating sampling loops to sampling points 5a and 5b (labelled E in figure 1), the environmental chamber and the void simulator, see figure 1 and table 1.

A thermal desorption gas chromatograph differential mobility spectrometer was connected to sample point 4 (Sionex suitcase integrated thermal desorption gas chromatograph ion mobility spectrometer, USA). Air was sampled at 100 cm³ min⁻¹ for 30 s through a Tenax trap, which was then thermally desorbed to 300 °C. The column was 10 m long with a diameter of 0.25 mm and a stationary phase thickness of 0.25 μm with an intermediate polar stationary phase (VF-1701MS; a VARIAN stationary phase from the FactorFour family, with ultra-low bleed, 14% cyanopropyl/phenyl + 86% PDMS). Temperature programme for the capillary GC column was ramped from 40 to 120 °C over 350 s with an air carrier gas flow of approximately 1 cm³ min⁻¹.

Two separate GC-IMS systems were connected to the collapsed building simulator. The first (GAS) was connected to a sample point 1b and sampled air at a rate of 250 ml min⁻¹ using an internal pump to a six-port valve with a 5 cm³ sample loop maintained at 40 °C. Sampled air was injected directly into a multi-capillary column (OV-1701) 20 cm long with 1200 channels and a film thickness of 0.2 μm. The column was maintained at 40 °C and GC-IMS data were collected over a run time of 6 min every 10 min. The second GC-IMS (ISAS) was connected to sampling point 1a and sampled air at a rate of 150 cm³ min⁻¹ to a six-port 8 cm³ sample loop maintained at 40 °C. Sampled air was injected directly into a (OV-5) multi-capillary column (MULTICHROM, Novosibirsk, Russia) 20 cm long with approx 1000 channels. The column was maintained at 40 °C and data were collected over a run time of 10 min.

The final on-line system was the sensor bundle for a prototype remote early detection system for locating trapped casualties (REDS) that sampled air directly from the void. The REDS gas sensor system contained NH₃, CO₂, hydrocarbon vapour, O₂, CO as well as vibration sensors and sampled air at 300 cm³ min⁻¹. A detailed description and evaluation of this system will be the subject of a more detailed account and will be presented in a follow-on study.

4. Results and discussion

4.1. Participant welfare

Figure 4 summarizes the welfare measurements for all the participants. The data show the mean levels of the respective measurements against time for all the participants. Furthermore, the lower and upper quartiles are indicated with solid lines, while the emboldened dashes show the maximum and minimum values observed from the ten studies.

The void temperature data show that experiments started mostly in the range 19–21 °C (min = 18 °C and...
observed values (dashes). Ten participants (lines) are shown with maximum and minimum grouped average data (circles) with upper and lower quartiles for all the experiment; if the oxygen level approached to within 0.1%–oxygen were managed and maintained above 19% throughout or symptoms associated with oxygen depletion; the levels of mild chilling with some discomfort. was that some of the participants felt damp, and two reported RH after 6 h. The consequence of these high-humidity levels albeit more slowly after this, increasing to approximately 90% RH. Humidity levels continued to increase increased significantly and rapidly over the first two hours to the range 57% RH to 71% RH. The humidity levels then increased around a well-established build-up to a stable level. Humidities at the start of the studies fell in the void. Humidities tended to be higher with these participants exhaled more water and occupied a larger volume of respiration rates of the individuals concerned; heavier body mass; however, we need to recognize that the quality of the air was managed and safety margins were maintained by increasing the ventilation. To enable data to be more easily compared, the carbon dioxide concentrations are plotted against the volume of air passed through the void as opposed to time. These carbon dioxide data reveal a range of variability around a well-established build-up to a stable level.

Occasionally, carbon monoxide was detected at levels below 50 ppm(v) for a few seconds in the experiment. Carbon monoxide is associated with methanogenesis [11] and these transient carbon monoxide ‘spikes’ were attributed to the participants’ flatulence, and the frequency of these observations, randomly distributed at approximately 0.5 h−1, was in line with normal digestive processes in healthy adults. The alternative source of carbon monoxide from exhaust plumes from engines entering the air intake to the compressors used in this experiment was ruled out as unlikely; the nearest traffic was 200 m away and ingress from this source would have resulted in diffused transients. Such challenges followed by mixing within the environmental chamber would have resulted in a broad transient followed by an exponential decay. The transients observed did not have such dynamics. Average blood pressures, heart rates and oxygen saturation all fell within ‘normal’ limits. Average values for blood pressure fluctuated at or around 120/80 mm Hg. At the start of the experiment, on entry to the void simulator, blood pressures were elevated and these reduced over 30 min. As participants became familiar with the surroundings of the experiment, it was quiet with a faint hissing sound from the pumps and air supplies with bed coverings and a pillow with a comfortable light level, they relaxed enough to sleep. Some slept for a while after about an hour and many fell asleep between 3.5 and 5.5 h and this behaviour is reflected in the blood pressure data. Towards the end of the 6 h some increase in blood pressures and heart rates was observed. Although none of the participants reported adverse signs or symptoms, it seems plausible to accept that the onset of feelings of restlessness may have been the underlying cause for these observations. Two participants elected to leave the study early so that they could urinate. None of the remaining participants elected to leave nor did they urinate into their clothing during their time in the void simulator. It seems reasonable to accept that after 6 h entrapment, some or many of the participants would have experienced some discomfort from over-full bladders.

One participant [7] recorded an average systolic pressure of 142 mm Hg, with an average diastolic value of 82 mm Hg, perhaps indicative of hypertension stage 1 [8]. This

Figure 4. Participant welfare data for relative humidity and temperature (top), (CO2) (middle) and blood pressure (bottom). Grouped average data (circles) with upper and lower quartiles for all ten participants (lines) are shown with maximum and minimum observed values (dashes).

max = 21.4 °C). The void temperature then increased by approximately 3 °C over a period of 2 h. After this period, the temperature tended to stabilize around an average level of approximately 23 °C. The temperature data indicated a set of reproducible and controlled studies.

Humidity levels were more variable and reflected the range of respiration rates of the individuals concerned; heavier participants exhaled more water and occupied a larger volume in the void. Humidities tended to be higher with these individuals. Humidities at the start of the studies fell in the range 57% RH to 71% RH. The humidity levels then increased significantly and rapidly over the first two hours to approximately 85% RH. Humidity levels continued to increase albeit more slowly after this, increasing to approximately 90% RH after 6 h. The consequence of these high-humidity levels was that some of the participants felt damp, and two reported mild chilling with some discomfort.

None of the participants reported or showed any signs or symptoms associated with oxygen depletion; the levels of oxygen were managed and maintained above 19% throughout the experiment; if the oxygen level approached to within 0.1%–19% in the void chamber the supply airflow was increased to ensure that the level did not fall below 19%.

None of the participants reported or showed any signs or symptoms associated with elevated levels of carbon dioxide and the maximum carbon dioxide concentration observed was 2.1% (V), figure 4. The average carbon dioxide concentration increased rapidly from the outset of the experiment to achieve a steady concentration of approximately 1.5% (V) with the upper and lower quartiles spanning the range 1.4–1.9% (V). The level of carbon dioxide in the void tended to increase with body mass; however, we need to recognize that the quality of the air was managed and safety margins were maintained by increasing the ventilation. To enable data to be more easily compared, the carbon dioxide concentrations are plotted against the volume of air passed through the void as opposed to time. These carbon dioxide data reveal a range of variability around a well-established build-up to a stable level.

Carbon monoxide is associated with methanogenesis [11] and these transient carbon monoxide ‘spikes’ were attributed to the participants’ flatulence, and the frequency of these observations, randomly distributed at approximately 0.5 h−1, was in line with normal digestive processes in healthy adults. The alternative source of carbon monoxide from exhaust plumes from engines entering the air intake to the compressors used in this experiment was ruled out as unlikely; the nearest traffic was 200 m away and ingress from this source would have resulted in diffused transients. Such challenges followed by mixing within the environmental chamber would have resulted in a broad transient followed by an exponential decay. The transients observed did not have such dynamics. Average blood pressures, heart rates and oxygen saturation all fell within ‘normal’ limits. Average values for blood pressure fluctuated at or around 120/80 mm Hg. At the start of the experiment, on entry to the void simulator, blood pressures were elevated and these reduced over 30 min. As participants became familiar with the surroundings of the experiment, it was quiet with a faint hissing sound from the pumps and air supplies with bed coverings and a pillow with a comfortable light level, they relaxed enough to sleep. Some slept for a while after about an hour and many fell asleep between 3.5 and 5.5 h and this behaviour is reflected in the blood pressure data. Towards the end of the 6 h some increase in blood pressures and heart rates was observed. Although none of the participants reported adverse signs or symptoms, it seems plausible to accept that the onset of feelings of restlessness may have been the underlying cause for these observations. Two participants elected to leave the study early so that they could urinate. None of the remaining participants elected to leave nor did they urinate into their clothing during their time in the void simulator. It seems reasonable to accept that after 6 h entrapment, some or many of the participants would have experienced some discomfort from over-full bladders.

One participant [7] recorded an average systolic pressure of 142 mm Hg, with an average diastolic value of 82 mm Hg, perhaps indicative of hypertension stage 1 [8]. This
participant did not report any feelings of anxiety or discomfort and fell asleep during the fourth hour of the study. The elevated blood pressures have been attributed to 108 kg weight of the participant. Blood pressures are summarized in figure 4. After the experiment, the participants completed a welfare questionnaire and six weeks later they were invited to complete a Stanford Acute Stress Response Questionnaire. No adverse stress responses were reported or disclosed in these follow-up checks. It seems reasonable to conclude that risks were maintained within acceptable safety margins. Participant monitoring was effective and that welfare checks and protocol were sufficient to ensure that the participants felt safe and in control of the experiment. No failures in the systems occurred that resulted in a loss of control of the air quality, or a negative effect on the emotional and physical welfare of the participants and researchers.

4.2. Reproducibility

Temperature and relative humidity data provide indication that the ten studies were run reproducibly. Levels of these factors tracked body mass and metabolism (sleep). No significant differences in temperature between male and female participants were observed, although the relative humidity levels were higher with the male participants and this was attributed to their larger masses. The reproducibility of the gas flows through the experiment was also influenced by the sizes of the participants and their respiration rate. Figure 5 reviews the two critical airflows in the experiment: the flow through the void simulator and the flow through the collapsed building simulation. The variability of the flow through the void simulator is evident as the air supply was managed to maintain the oxygen level above 19% (V); what is also evident was how the flow was increased incrementally throughout the experiment. In other words, the flow was maintained at the lowest value needed to ensure that the O2 concentration did not fall between below 19% (V), the minimum value. The flow through the collapsed building simulation was maintained with significantly less variation. The earlier studies were more variable than those towards the end of the experiment; however, the overall average of 5 dm3 min⁻¹ was precisely maintained.

The last set of variables, the chemical background from the materials in the collapsed building simulator, will be described in greater detail in a subsequent paper describing and evaluating the results from the GC-MS analyses performed on the samples collected in the adsorbent tubes. The preparation of the 320 discs of precisely cut and drilled building materials with gas seals and gaskets took approximately 16 weeks. Some of the materials were stored for a longer time than others. The preparation of the sets of discs and their allocation to the ten studies were randomized; nevertheless, in the low-concentration region of the volatile profile the materials used in the collapsed building simulator were expected to have variable levels of trace VOC.

4.3. Preliminary results

4.3.1. Carbon dioxide. In figure 6, the levels of CO2 observed at different points in the experiment are summarized. These data show averaged readings obtained for the different sampling points, equivalent to different burial depths within the experiment. The underlying movement of CO2 through the collapsed building may be compared in a straightforward manner. However, it is helpful to note that the ‘raw’, unprocessed, data show significant scatter around these trends and figure 7 illustrates this point. It seems to be highly unlikely that the variability of the observed levels of CO2 was caused by the instruments. (Three CO2 monitors were used in this work and the monitors were switched between sampling points throughout the experiment.) The CO2 monitors were all calibrated by the supplier and their readings cross-checked. Note also that the CO2 levels in the void simulator, figure 4, did not show appreciable scatter.

The ventilation rate of the void simulator was set to be enough to replenish the air breathed, and no more, and so the CO2 levels ‘downstream,’ of the participant were expected to approach 3% (V)–4% (V). If there was no interaction between

Figure 5. Reproducibility of the ten studies. Flow through the void simulator (top) showing the average (circles) upper and lower quartile flows (solid lines) across all ten studies with maximum and minimum values (dotted lines). Flow through the column with the collapsed building simulation (bottom) with the same symbols and key.

Figure 6. Average levels of carbon dioxide at different ‘burial depths’ of the experiment with increasing volume of air through the collapsed building simulator. Note that the level of carbon dioxide was observed to initially increase to higher levels than those observed in the respiratory zone of the participants. The subsequent slight reduction in the level has been attributed to dissolution phenomena as water levels increased with the increasing entrapment time.
the expired CO₂ and the materials in the collapsed building simulator, then the discs of building material would promote mixing within the volume leading to an exponential increase in concentration to a steady state level after approximately 200 dm³ of air from the void simulator has been passed through the collapsed building simulator, see figure 7. Furthermore, the air in the void simulator was sampled from the respiratory zone of the participant, which was ventilated continuously with fresh air, and the level of CO₂ in this region reflected partial mixing with the spent air in the void simulator. However, for the most part the spent air was swept into the exhaust line or the collapsed building simulator, and as a consequence the CO₂ levels in the collapsed building simulator were higher than those in the void simulator, figures 6 and 7. The dotted line in figure 7 indicates a theoretical level of CO₂ that would be observed if there was no mixing within the void simulator and no interaction between the CO₂ and the materials in the collapsed building simulation.

The movement of CO₂ through the layers of collapsed building simulator appeared to be influenced by the levels of water in the void simulator. Water vapour was absorbed into the different building materials and once these materials became equilibrated with the water level in the spent air, condensation formed within the experiment. As the experiment progressed, CO₂ levels tended to decrease slightly, suggesting dissolution into the condensate, and this phenomenon was most marked with the void-simulator exhaust, where some condensate pooled in the connecting tubing.

CO₂ travelled rapidly through the collapsed building debris. The exact nature of the concentration profile appears to be influenced in part by the hydroscopic nature of the debris that the plume travels through along with the levels of water within the collapsed structure. It is clear that some interactions occurred and that breakthrough was retarded somewhat. Nevertheless, elevated levels of CO₂ (> 0.1%(v)) were detected at a burial depth of 1.4 m by the time 50 dm³ of air had been passed through the collapsed building simulator, < 10 min from the start. The observation that water appears to have an effect on the breakthrough behaviour of CO₂ is not controversial, and while CO₂ is a sensitive marker of life, the specification of monitoring protocols needs to reflect the extent and levels of water within collapsed building debris, and this is an aspect of search-and-rescue detection that would benefit from further investigation.

4.3.2. Ammonia. The levels of NH₃ increased rapidly in the experiment and were observed with the REDs prototype sensor bundle and in the GC-IMS, GC-DMS and transverse IMS systems. (A detailed analysis of the NH₃ dynamics in this experiment will be the subject of a later study.) That ammonia was detected rapidly and with high sensitivity was an encouraging finding, and the combination of different metabolites with markedly different pKa values enables the specification of a potential sensor system that will have resilience to changes in the pH of the media the plume passes through. A marked response, and an unexpected observation,
The tests performed in this study were limited to 6 h, by a human trapped within a void inside a collapsed building. The trapped human experiment sought to provide a reproducible representation of the metabolic profile generated as breath [3], figure 8.

The levels in ammonia were significantly higher than those reported previously in breath, suggesting that sources for this compound included skin and sweat emanations as well as breath [3], figure 8.

4.3.3. Volatile organic compounds. Unsurprisingly, large numbers of VOC were detected across all the instrument platforms used in this study. Acetone and isoprene were isolated rapidly and the development of algorithms for NH$_3$, acetone and isoprene detection within GC-IMS is a logical development of this research, figure 9. Preliminary evaluation of the results of the air monitoring across the network of sampling points within the experiment reveals a range of endogenous VOC behaviours. Some VOCs were observed to rapidly accumulate within the experiment before declining, while others tracked CO$_2$ and NH$_3$ behaviours. Others were present at significant levels for a single participant while absent for the rest. The study of this range of behaviours and relationships continues and the results of chemometric analysis of these data will be described in due course.

5. Conclusions

The trapped human experiment sought to provide a reproducible representation of the metabolic profile generated by a human trapped within a void inside a collapsed building. The tests performed in this study were limited to 6 h, and sought to identify, demonstrate and validate a range of analytes best suited as markers for the signs of life within collapsed buildings. The methods developed enabled a range of detection devices and instruments to be evaluated in a controlled environment. The collected data is currently being processed to develop detection algorithms which will be described in future studies and papers. The use of human participants enabled the interaction of breath, skin and sweat to be integrated into the study and the NH$_3$ observations indicate that skin-based metabolite releases may be significant factors in specifying survivor detection systems.

Safety and ethical considerations were the most important features of this research, and therein resides a tension and contradiction. This simulation was free of choking dust, it was ventilated and the participants were not physically or psychologically stressed, and all of these factors may be viewed as detracting from the validity of the design. It is important, therefore, to avoid the temptation to over analyse the data, and acknowledge that the underlying metabolic processes were consistent with a trapped human and focus on the candidate analytes. The duration of the experiment (6 h) was determined by ethical considerations, and although the NH$_3$ and carbon dioxide levels appeared to stabilize, the water levels did not. So, the interaction between the condensate and the metabolite plume needs to be better understood.

Another important feature that will need to be studied in future is the release of urine. None of the participants were prepared to, or needed to, urinate inside the void simulator. Including urination in this experiment will impose significant challenges on the participants and longer experiments with coached volunteers are a logical next step in this research.

The preliminary findings confirmed that NH$_3$, acetone and CO$_2$ are reliable indicators of active metabolism and that these compounds travel rapidly with a metabolite plume through building debris. The on-line sensing and analytical systems all worked, and data were observed that confirmed that fieldable systems based on ion mobility approaches were likely to be effective. Water was identified as an important external and metabolic factor and further studies on the effect of water on casualty location will be needed in the future. For the absorption of metabolites into damp building materials is likely to occur and whether or not this is a major factor of concern is difficult to state with confidence at this stage. On balance the CO$_2$ observations indicate that levels of this compound will be higher in dry conditions.

The trapped human experiment enabled analytical approaches for search and rescue to be evaluated and developed under reproducible conditions with human participants for the first time. Traceable, safe and ethical procedures were developed that enabled instrument and protocol development to be undertaken in a simulation that was close enough to reality to enable the underlying hypothesis that an IMS approach with a sensor bundle could detect humans reliably in collapsed buildings to be tested. The extension of this approach to different climates, levels of water, durations and building materials will be research themes to be developed in future studies.
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