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Potential of volatile organic compounds as markers of entrapped humans for use in urban search-and-rescue operations

Paweł Mochalski [a,*], Karl Unterkofler [a,b], Gerald Teschl [c], Anton Amann [a,d]

[a] Breath Research Institute of the University of Innsbruck, Rathausplatz 4, Dornbirn A-6850, Austria
[b] Vorarlberg University of Applied Sciences, Hochschulstr. 1, Dornbirn A-6850, Austria
[c] Faculty of Mathematics, University of Vienna, Oskar-Morgenstern-Platz 1, Wien 1090, Austria
[d] Univ.-Clinic for Anesthesia and Intensive Care, Innsbruck Medical University, Anichstr., 35, Innsbruck A-6020, Austria

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ABSTRACT

Volatile organic compounds (VOCs) emitted by a human body form a chemical signature capable of providing invaluable information on the physiological status of an individual and, thereby, serving as signs of life for detecting victims after natural or man-made disasters. For this review, we created a database of potential biomarkers of human presence based on literature reports on VOCs in human breath, skin emanations, blood and urine. We estimated approximate fluxes of these VOCs from the human body, and used them to predict concentrations in the vicinity of victims. We classified proposed markers in groups by potential for victim detection. The major classification discriminants were the capability of detection by portable, real-time analytical instruments and background levels of VOCs in the urban environment. We intend data summarized in this review to assist studies on the detection of humans via chemical analysis and to accelerate investigations in this area of knowledge.

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Contents

1. Introduction

Earthquakes belong to the most frequent and most catastrophic natural disasters affecting mankind. In the past century, earthquakes occurred with an annual worldwide incidence of one million events (two earthquakes per minute) [1] causing more than 1.5 million deaths and affecting another 2 billion people [2]. Bearing in mind the increase of global urbanization and that the most populous cities are located in seismic zones, it is reasonable to assume that these numbers will rise considerably in the near future [3]. In contrast to many other disasters, earthquakes cause not only many deaths, but also many traumatic injuries and massive entrapment of survivors in collapsed buildings [1,3,4]. While about half the survivors are found and rescued quickly by bystanders or other civilians [5,6], the remaining survivors are subjected to prolonged entrapment under complex debris. Their extrication frequently requires

* Corresponding author. Tel.: +43 512 504 24636; Fax: +43 512 504 6724636.
E-mail address: pawel.mochalski@uibk.ac.at (P. Mochalski).

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trained, specially equipped rescuers. Since the survivability of victims directly relates to the entrapment time [1], the early location of entrapped victims is of the utmost importance for urban search and rescue (USaR) operations.

Until now, a number of technical tools have been employed to reduce the duration of entrapment (e.g., fiber-optic cameras (borescopes), acoustic probes aiming at voices, or heartbeats, thermal cameras, and sonars) [5]. Nevertheless, SaR dogs remain indispensable for rescue teams and are commonly recognized as gold standard in this context [7]. Search dogs exhibit excellent scenting skills, are able to search relatively large areas in a short period of time and can work in areas that are deemed unsafe or inaccessible to human rescuers. However, dogs exhibit a number of limitations. Their working time is relatively short and restricted to approximately 30 min (with a subsequent break of 2 h) and their training is time consuming and expensive. Moreover, they respond poorly to being stressed or frustrated and can easily be injured in highly toxic, harsh disaster environments [8]. All these constraints create a huge demand for novel detecting tools, which could complement, or even replace, search dogs during USaR operations.

The fact that SaR dogs can detect survivors in highly contaminated disaster sites implies that there is a human-specific chemical signature in void spaces of collapsed buildings and that analysis of this signature could be a valuable detection tool. Unexpectedly, this approach has received little attention and was limited to carbon-dioxide sensing [9]. This is surprising as small-molecule volatile species are often the final products of vital metabolic pathways occurring in human organisms and could therefore serve as signs of life in the context of rescue operations [10–12]. Indeed, there is growing evidence suggesting that some constituents of the human scent could be employed for this purpose and thereby considerably improve the effectiveness of rescue teams [13–16]. Apart from detecting victims, chemical analysis could provide the rescuers with the capability to recognize exposures to potentially toxic agents that can be present at disaster sites [17,18]. Consequently, toxicological hazards and risks for humans and animals could be considerably minimized during rescue operations. Thus, in the context of USaR operations, chemical analysis towards volatiles can be considered a very promising field, which is, however, still in its infancy.

The primary goal of this review is creation of a database containing constituents of the human scent having potential to serve as signs of life during USaR operations. The database is built on the basis of existing literature reports on volatiles in breath, blood, urine and skin emanations. We stress that only quantitative data are taken into consideration. In particular, by this, we intend to provide a list of preliminary markers of human presence to be verified and complemented during future field studies. An effort is also made to estimate the approximate emission rates of these compounds from the human body as paramount factors determining their levels in the vicinity of survivors. Secondary goals are to predict tentative levels of the preselected markers in void spaces of collapsed buildings and to assess the capabilities of their detection by selected portable field analytical instruments against the urban environmental background.

2. Sources of human scent during entrapment

Volatile species forming human scent during entrapment can stem from different biological fluids (breath, urine, blood, sweat) and organs (skin, lungs, bowels). Generally, sources of human-related volatiles can be classified into continuous and temporal. The former group embracing breath and skin emanations is particularly important in the context of victim detection, as it offers a long-lasting emission of potential markers of human presence. Moreover, breath holds here a distinguished status, since the breath-borne volatile species can help to differentiate between living and dead victims.

Temporal sources, such as blood or urine, have a more transient contribution to human scent; nevertheless, this impulse-type contribution cannot be neglected. The occurrence of this impulse of volatiles is difficult to predict; however, it is reasonable to assume that emission of blood-borne species should appear at the early stage of entrapment as a result of injuries induced by the disaster. Furthermore, urine- and blood-borne compounds are expected to strengthen the location signal provided by breath markers of human presence due to the physiological dependencies between these fluids. However, blood and urine should be considered as limited reservoirs of species tending to dry out and/or clot.

The emission rates of volatiles from these sources depend on the physiological and medical status of the victim (e.g., injuries, dehydration, shock, diet, history of environmental exposure, and drug intake), conditions in the entrapment scene (e.g., confined space volume, type of collapse, temperature, humidity, and oxygen content), and the time of entrapment. In particular, the disaster event and the entrapment induce a number of neuroendocrine, metabolic and physical responses [19], which can comprise, e.g., intense emotional stress, physical shock, hypermetabolism (manifested by hyperglycemia, hyperlactatemia, and protein catabolism), immunological responses, and up-regulation of hormone secretion. All these factors inevitably influence the production and the emission of volatiles by a human organism. Unfortunately, this impact is poorly understood because of the limited quantitative data on the emission rates of volatile organic compounds (VOCs) from the human body, limited knowledge of human physiology during entrapment, and ethical and methodological problems related to the simulation of entrapment under laboratory conditions. As a consequence, the emission of volatiles from entrapped individuals and their propagation during entrapment are very difficult to estimate. In this context, emission rates of volatile species from healthy volunteers at normal conditions seem to be the only reasonable surrogate for these parameters. Moreover, understanding the production and the initial composition of the human-specific chemical signature is particularly important for modeling the behavior of potential markers of human presence in the surroundings of the entrapped person and determines the selection of on-site, real-time, and hand-held analytical instruments, which could be used for the field detection of entrapped victims.

One of the main goals of this work is to pre-select potential markers of human presence and to estimate their emission rates from the human body on the basis on existing literature data on volatile organic and inorganic compounds in breath, urine, blood, and skin emanations. Several prerequisites have been assumed to achieve this goal. First, only emissions via breath and skin are used to calculate the total fluxes of volatiles from the human body, because the occurrence and the intensity of urine- or blood-borne VOCs is much more variable and difficult to predict. Second, only omnipresent and reliably identified compounds are used to construct the set of potential markers of human presence. Here, a compound is recognized as omnipresent when it is reported to have an incidence of at least 80%. The threshold of 80% was arbitrarily chosen. Reliable identification is defined as identification based on several methods, thereby providing unequivocal results. For example, in gas chromatography mass spectrometry (GC-MS) studies, compounds identified exclusively on the basis of a spectral library match (e.g., NIST) without taking into account the retention time (or retention index) are excluded, as only tentatively identified. Finally, only species having clearly higher levels in breath than in room air are recognized as produced by the human body and thereby contributing to the formation of human scent. We also stress that compounds are not pre-selected with respect to their origin as it still has not been

elucidated in sufficient depth and, in many cases, is a matter in dispute. Table 1 lists volatile organic and inorganic compounds, which fulfil these requirements. We tried to provide for each compound data from different literature sources and obtained by different analytical techniques to improve the reliability of calculated fluxes.

2.1. Breath

Exhaled breath contains a wide range of volatile compounds capable of providing invaluable information on normal and disease processes occurring in an individual, environmental exposure to pollutants/toxins, or microorganism activity in the body [10–12]. Its attractiveness in biomedical applications stems from it being readily and non-invasively obtainable and may be sampled as often as desirable without discomfort for a subject. Moreover, concentration levels of breath compounds can respond rapidly to changes in human physiology and thereby provide near real-time information on processes occurring in the body [57,92–94]. In the context of USaR operations, breath volatiles play a fundamental role, as breathing can be considered a sign of life and the breath-specific species can help to distinguish the living from the dead. For these reasons, breath volatiles received enormous attention in the literature. Moreover, most published clinical studies also provide data obtained for control populations (e.g., healthy volunteers, and hospital personnel), which could be useful for this work. Unfortunately, a considerable fraction of the existing sources suffers from disadvantages, such as reporting only qualitative or semi-qualitative data (e.g., peak areas, and relative abundances), absence of detection frequencies of observed species, or absence of data on room air (inhaled air). Consequently, their value for this work is limited. Moreover, literature sources were constrained to those providing data for the end-tidal exhalation phase and mean concentrations of species under scrutiny. This approach aimed to reduce the variability of results induced by different sampling protocols.

Table 1 lists 34 breath volatiles selected using these criteria together with their literature levels in the end-tidal exhalation segment. These concentration data were used to calculate the breath fluxes of compounds of interest. First, for each compound, a weighted arithmetic mean of means was calculated using all literature sources considered. The weight factor was the population involved in the particular study. Next, these means were converted into nmol × L^{-1}. Finally, the emission rates expressed in nmol × min^{-1} × $person^{-1}$ were calculated, assuming alveolar ventilation of 3.3 L × min^{-1}, which is typical for sleep [95], because entrapped victims are frequently unconscious, or drift between sleep and consciousness over the course of entrapment [5]. Since the real values of alveolar ventilation during entrapment are difficult to predict and can be considerably affected by the conditions in the entrapment environment, sleep seems to be a good (although simplified) surrogate model. Table 1 and Fig. 1 show the calculated breath fluxes of compounds of interest. With the exception of CO_2, the estimated emission rates are 0.03–524 nmol × min^{-1} × $person^{-1}$. Within this group, the highest values were for CO (524 nmol × min^{-1} × $person^{-1}$), ammonia (91 nmol × min^{-1} × $person^{-1}$), acetone (60 nmol × min^{-1} × $person^{-1}$), and methanol (45 nmol × min^{-1} × $person^{-1}$). The majority of compounds (56%) exhibited breath fluxes below 1 nmol × min^{-1} × $person^{-1}$ (considering means).

2.2. Skin

Skin, next to breath, is a principal source of human-scent constituents, as it offers a long-lasting emission of VOCs from a relatively large area. The composition of skin emanations in humans has received considerable attention and numerous reports dealing with this issue can be found in the literature [20,51,96–98]. Although these studies reported a large number of species, the majority of them yield only qualitative data (i.e., names of identified compounds and possibly their occurrence in skin emanations). Moreover, the GC-MS-based studies provide mainly tentative identification of these species based on peak spectra that were checked against commercial mass spectral libraries (e.g., NIST). Quantitative data (emission rates) are relatively sparse [25,32,33,43,51–53] and usually determined for peripheral skin (hand, arm, or leg). Such a sampling protocol is obviously convenient for human subjects; however, the

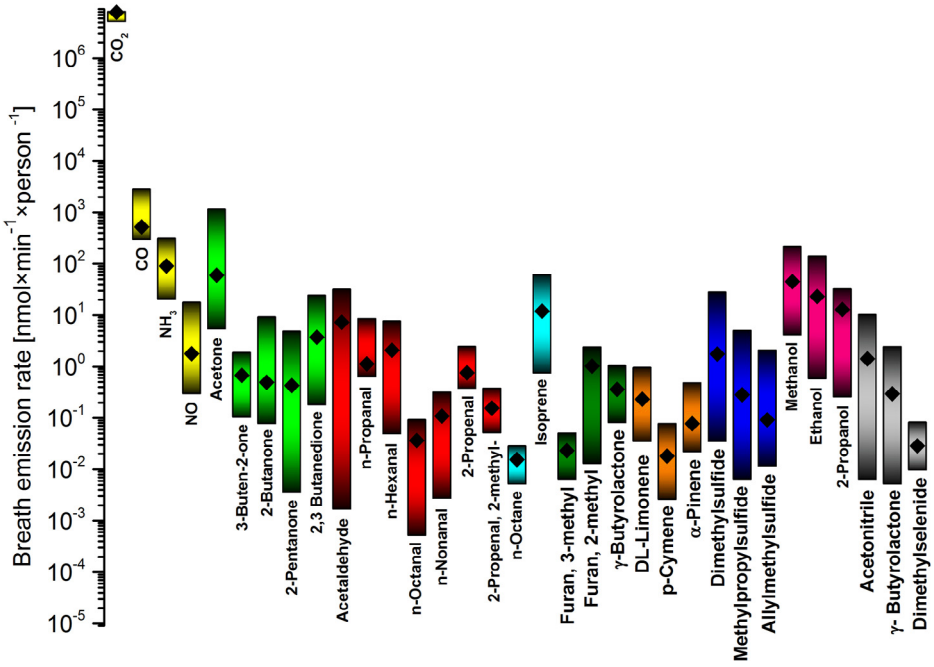

Fig. 1. Ranges and means of emission rates of potential breath markers of human presence from the human body. Different colors correspond to the different chemical classes of compounds. Ranges calculated on the basis of reports indicated in column B of Table 1.

Table 1
Breath concentrations, skin emissions, tentative origins and whole body fluxes of potential volatile markers of human presence. Urine and blood omnipresent species taken from [16,20–22]

A	B	C	D	E	F	G	H	I
Compound CAS	Breath levels mean (population) [ppb]	Skin emission mean (population)	Urine	Blood	Tentative origin in humans	$Flux_{breath}$ [nmol/min]	$Flux_{skin}$ [nmol/min]	$Flux_{total}$ [nmol/min]
CO_2 124-38-9	(a) 4.9 % (19) [23] (b) 6.1 % (6) [24]	(a) 3.4×10^{-5} ml × cm^{-2} × min^{-1} (63) arm/hand [25]		●	(a) Cellular respiration	66.8×10^5	26.5×10^3	67.1×10^5
NO 10102-43-9	(c) 7.8 (294) [26] (d) 7.2 (20) [27] (e) 8.2 (10) [28] (f) 27.6 (106) [29] (g) 18.9 (26) [30] (h) 17.5 (89) [31]	(b) 12.8 fmol × cm^{-2} × min^{-1} (14) hand [32] (c) 79.5 fmol × cm^{-2} × min^{-1} (14) hand/arm [33]	●		(a) Enzymatic oxidation of L-arginine (iNOS) [34]	1.8	0.8	2.6
CO 630-08-0	(a) 3.2 ppm (20) [27] (b) 2.9 ppm (37) [35] (c) 4.3 ppm (239) [36] (d) 3.6 ppm (55) [37] (e) 4.1 ppm (857) [38]			●	(a) Hemoprotein turnover [39]	524.5		524.5
Ammonia 7664-41-7	(a) 1015 (5) [40] (b) 854 (17) [41] (c) 589 (48) [42] (d) 775 (20) [43] (e) 480 (30) [44]	(a) 0.5 ng × cm^{-2} × min^{-1} (30) hand [43]	●	●	(a) Bacterial metabolism of proteins in gut [45] (b) Bacterial metabolism of proteins in oral cavity [21,46]	90.9	513.8	604.7
Acetone 67-64-1	(a) 487 (5) [40] (b) 477 (30) [44] (c) 456 (17) [41] (d) 226 (143) [47] (e) 255 (31) [48] (f) 217 (40) [49] (g) 950 (28) [22] (h) 628 (215) [50]	(a) 1370 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 44.8 nmol × $person^{-1}$ × min^{-1} (10) body [52] (c) 4.3 ng × cm^{-2} × h^{-1} (60) hand [53]	●	●	(a) Endogenous decarboxylation of acetyl–CoA [50] (b) Oxidation of squalene [54] (c) 2-propanol metabolism [55] (d) Diet	59.8	25	84.8
2-Butanone 78–93-3	(a) 5.1 (143) [47] (b) 0.24 (40) [49] (c) 2.6 (28) [22]	(a) 7.2 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 4.3 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●	●	(a) Diet [56]	0.5	1.15	1.65
2-Pentanone 107-87-9	(a) 4.8 (143) [47] (b) 0.36 (40) [49] (c) 0.62 (28) [22] (d) 0.22 (7) [57]	(a) 2.47 fmol × cm^{-2} × min^{-1} (31) hand [51]	●	●	(a) Diet [56] (b) 2-pentanol metabolism [58]	0.43	0.05	0.47
5-Hepten-2-one, 6-methyl- 110-93-0		(a) 212.9 fmol × cm^{-2} × min^{-1} (31)hand [51] (b) 0.98 nmol × $person^{-1}$ × min^{-1} (10) body [52]			(a) Cutaneous oxidation of squalene [54]		3.08	3.08
3-Buten-2-one 78–94-4	(a) 3.8 (28) [22] (b) 5.5 (143) [47]	(a) 9.2 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 6.8 nmol × $person^{-1}$ × min^{-1} (10) body [52]			(a) Oxidation of isoprene [59]	0.67	1.78	2.45
2,3 Butanedione 431-03-8	(a) 29 (28) [22]				(a) Diet (butter) [56]	3.74		3.74
Acetaldehyde 75-07-0	(a) 67.4 (143) [47] (b) 5.5 (12) [60] (c) 24 (30) [61]	(a) 466 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 3.8 ng × cm^{-2} × h^{-1} (60) hand [53]	●	●	(a) Ethanol metabolism [62] (b) Cutaneous oxidative degradation of linoleic acid [63]	7.3	15.4	22.7
n-Propanal 123-38-6	(a) 18.3 (28) [22] (b) 6.9 (143) [47]	(a) 18.4 fmol × cm^{-2} × min^{-1} (31)hand [51] (b) 6.6 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●		(a) Cutaneous of linoleic acid and oleic acid [63] (b) 1-propanol metabolism (c) Diet [56]	1.13	1.85	2.98

(*continued on next page*)

Table 1 (*continued*)

A	B	C	D	E	F	G	H	I
Compound CAS	Breath levels mean (population) [ppb]	Skin emission mean (population)	Urine	Blood	Tentative origin in humans	$Flux_{breath}$ [nmol/min]	$Flux_{skin}$ [nmol/min]	$Flux_{total}$ [nmol/min]
2-Propenal 107-02-8	(a) 5.9 (28) [22]	(a) 21 fmol × cm^{-2} × min^{-1} (31) hand [51]			(a) Smoking [64]	0.76	0.37	1.13
2-Propenal, 2-methyl 78–85-3	(a) 1.2 (28) [22]	(a) 20.5 fmol × cm^{-2} × min^{-1} (31)hand [51] (b) 0.54 nmol × $person^{-1}$ × min^{-1} (10) body [52]			(a) Oxidation of isoprene [59]	0.15	0.42	0.57
Propanal, 2-methyl- 78–84-2		(a) 11.6 fmol × cm^{-2} × min^{-1} (31)hand [51]	●		(a) Diet [65]		0.21	0.21
Butanal, 2-methyl- 96-17-3		(a) 13.9 fmol × cm^{-2} × min^{-1} (31) hand [51]	●		(a) Diet [65]		0.25	0.25
Butanal, 3-methyl- 590-86-3		(a) 15.1 fmol × cm^{-2} × min^{-1} (31)hand [51]	●		(a) Diet [65]		0.28	0.28
n-Hexanal 66-25-1	(a) 15.4 (31) [48]	(a) 56.2 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 2.46 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●		(a) Cutaneous degradation of linoleic, palmitoleic and vaccenic acids [66]	2.1	1.36	3.44
n-Heptanal 111-71-7	(a) 0.07 (12) [60]	(a) 29.8 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 1.85 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●		(a) Cutaneous oxidative degradation of palmitoleic acid, vaccenic acid [66]	<0.001	0.84	0.84
n-Octanal 124-13-0	(a) 0.27 (12) [60]	(a) 42.7 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 1.3 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●		(a) Oxidative degradation of oleic acid [63]	0.04	0.88	0.92
n-Nonanal 124-19-6	(a) 0.8 [60]	(a) 60.2 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 2.16 nmol × $person^{-1}$ × min^{-1} (10) [52]	●		(a) Oxidative degradation of oleic acid [66]	0.11	1.33	1.44
Isoprene 78–79-5	(a) 89 (5) [40] (b) 118 (30) [67] (c) 99.3 (205) [68] (d) 71 (143) [47] (e) 131 (28) [22]	(a) 4.6 fmol × cm^{-2} × min^{-1} (31) hand [51]	●	●	(a) Endogenous cholesterol synthesis [68] (b) Peroxidation of squalene [69] (c) Cutaneous synthesis of squalene [70]	12.0	0.09	12.1
1,3-Pentadiene, 2-methyl-, Z- 2787-45-3		(a) 2.54 fmol × cm^{-2} × min^{-1} (31) hand [51]					0.05	0.05
1,3-Pentadiene, 2-methyl-, E- 926-54-5		(a) 1.7 fmol × cm^{-2} × min^{-1} (31) hand [51]					0.03	0.03
2-Pentene, 2-methyl- 625-27-4		(a) 12.7 fmol × cm^{-2} × min^{-1} (31)hand [51] (b) 0.32 nmol × $person^{-1}$ × min^{-1} (10) body [52]			(a) Peroxidation of squalene [69]		0.25	0.25
1-Heptene 592-76-7		(a) 1.73 fmol × cm^{-2} × min^{-1} (31)hand [51]					0.003	0.003
n-Heptane 142-82-5		(a) 3.3 fmol × cm^{-2} × min^{-1} (31)hand [51]			(a) Cutaneous degradation of oleic acid [63]		0.06	0.06
1-Octene 111-66-0		(a) 3.25 fmol × cm^{-2} × min^{-1} (31)hand [51]					0.06	0.06
n-Octane 111-65-9	(a) 0.12 (28) [22]	(a) 8.3 fmol × cm^{-2} × min^{-1} (31) hand [51]		●	(a) Oxidative degradation of oleic acid [63]	0.02	0.15	0.17
1-Nonene 124-11-8		(a) 3.7 fmol × cm^{-2} × min^{-1} (31)hand [51]					0.06	0.06
n-Nonane 111-84-2		(a) 14.3 fmol × cm^{-2} × min^{-1} (31)hand [51]					0.26	0.26
Methanol 67-56-1	(a) 450 (30) [71] (b) 272 (20) [72] (c) 202 (10) [73]	(a) Emitted (no quantitative data) [74,75]	●	●	(a) Bacterial metabolism of carbohydrates in gut [76] (b) Diet	45.1	*	45.1

(*continued on next page*)

Table 1 (*continued*)

A	B	C	D	E	F	G	H	I
Compound CAS	Breath levels mean (population) [ppb]	Skin emission mean (population)	Urine	Blood	Tentative origin in humans	$Flux_{breath}$ [nmol/min]	$Flux_{skin}$ [nmol/min]	$Flux_{total}$ [nmol/min]
Ethanol 64-17-5	(a) 86 (5) [40] (b) 189 (143) [47] (c) 196 (30) [61] (d) 233 (15) [77] (e) 165 (20) [72] (f) 46 (15) [78]	(a) Emitted (no quantitative data) [74]	●	●	(a) Gut bacterial metabolism [79] (b) Diet	23.1	*	23.1
2-Propanol 67-63-0	(a) 22 (30) [44] (b) 150 (46) [80]	(a) Emitted (no quantitative data) [74]			(a) Diet [56] (b) Acetone metabolism [81]	12.84	*	12.84
Dimethyl sulfide 75-18-3	(a) 9.3 (143) [47] (b) 35 (50) [82] (c) 7.3 (31) [48] (d) 13.9 (40) [49] (e) 5 (28) [22] (f) 7.6 (20) [72]	(a) 2.52 fmol × cm^{-2} × min^{-1} (31) hand [51]	●	●	(a) Endogenous metabolism of sulfur-containing amino acids [83] (b) Bacterial decomposition of sulfur-containing amino acids [83]	1.77	0.05	1.81
Allyl methyl sulfide 10152-76-8	(a) 0.1 (40) [49] (b) 1.6 (28) [22]				(a) Diet (garlic) [84]	0.09		0.09
Methyl propyl sulfide 3877-15-4	(a) 2.6 (28) [22]			●	(a) Diet (onion) [85]	0.29		0.29
p-Cymene 99-87-6	(a) 0.14 (28) [22]	(a) 4.9 fmol × cm^{-2} × min^{-1} (31) hand [51]		●	(a) Diet [56]	0.018	0.075	0.094
DL-Limonene 138-86-3	(a) 1.46 (28) [22] (b) 2.3 (20) [72]	(a) 25.6 fmol × cm^{-2} × min^{-1} (31) hand [51] (b) 0.89 nmol × $person^{-1}$ × min^{-1} (10) body [52]	●	●	(a) Diet [56]	0.23	0.54	0.77
α-Pinene 80-56-8	(a) 0.6 (28) [22]				(a) Perfumes, cosmetics	0.08		0.08
Furan, 2-methyl- 534-22-5	(a) 0.55 (28) [22] (b) 9.5 (143) [47]	(a) 1.9 fmol × cm^{-2} × min^{-1} (31) hand [51]	●		(a) Smoking [64]	1.03	0.03	1.06
Furan, 3-methyl- 930-27-8	(a) 0.18 (28) [22]	(a) 1.2 fmol × cm^{-2} × min^{-1} (31) hand [51]	●	●	(a) Oxidation of isoprene [59] (b) Skin microbiota metabolism [86]	0.023	0.023	0.045
Furan, 2-pentyl- 3777-69-3		(a) 2.3 fmol × cm^{-2} × min^{-1} (31)hand [51]	●		(a) Cutaneous oxidation of linoleic acid [87] (b) Skin microbiota metabolism [88]		0.04	0.04
Acetonitrile 75-05-8	(a) 31.5 (28) [22] (b) 2.0 (19) [89] (c) 5.7 (77) [90]	(a) 26.8 fmol × cm^{-2} × min^{-1} (31) hand [51]	●	●	(a) Smoking [64]	1.41	0.56	1.98
γ-Butyrolactone 96-48-0	(a) 2.8 (28) [22]	(a) 34.4 fmol × cm^{-2} × min^{-1} (31)hand [51]			(a) Skin microbiota metabolism [91] (b) Diet [56]	0.36	0.59	0.95
Methyl acetate 79-20-9	(a) 2.6 (28) [22] (b) 0.98 (7) [57]		●	●		0.29		0.29
Dimethyl selenide 593-79-3	(a) 0.35 (28) [22] (b) 0.13 (40) [49]			●	(a) Selenomethionine and selenocysteine metabolism	0.029		0.029

* No quantitative data.

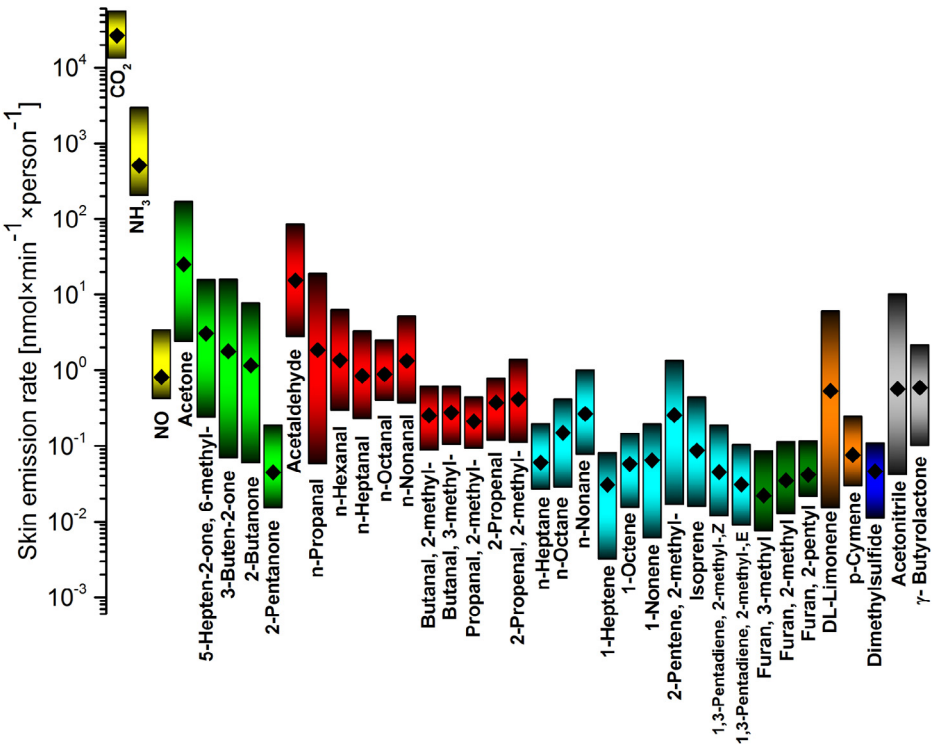

Fig. 2. Ranges and means of emission rates of potential skin-borne markers of human presence from the human body. The colors correspond to the different chemical classes of compounds. Ranges have been calculated on the basis of reports indicated in column C of Table 1.

results obtained are not necessarily representative for the remaining parts of the skin, because, due to the differences in the distribution of sebaceous glands, the composition and the thickness of human sebum vary between different parts of the body [20,99] and the emission of volatiles can reflect these variations. Whole-body emission data are even sparser, although the most valuable for this review [52], so assessment of the contribution of skin-borne species to the formation of a human-specific chemical fingerprint may suffer from shortage of reliable data.

The skin fluxes of compounds of interest from the whole human body were estimated in several steps. First, the emission rates reported for a certain skin area (e.g., cm^2) were rescaled to the total skin area of the volunteer. This was done using the skin area of the volunteer estimated by the formula given by Mosteller [100], or (in the case of the unavailability of the volunteer data) by taking the average area of the human skin of 1.7 m^2. Next, the emission rates were converted into $nmol \times L^{-1} \times person^{-1}$ and the weighed arithmetic mean of the means of all literature data considered was calculated. The weight factor was the population of the particular study. We stress that the use of peripheral skin data for these purposes implies underestimation of the calculated whole body fluxes. Table 1 and Fig. 2 show the emission rates of potential markers of human presence obtained from skin. Their values vary from 26.5 $\mu mol \times min^{-1} \times person^{-1}$ to 0.02 $nmol \times min^{-1} \times person^{-1}$ for CO_2 and 3-methylfuran, respectively. Of 38 species, only five (CO_2, ammonia, acetone, acetaldehyde, and 6-methyl-5-hepten-2-one) exhibit fluxes exceeding 2 $nmol \times min^{-1} \times person^{-1}$.

2.3. Urine

Urine is an important reservoir of human-scent constituents. Until now, more than 230 VOCs belonging to different chemical classes (e.g., aldehydes, ketones, furans, pyrroles, terpenes, sulfur-containing compounds) have been identified in human urine [16,79,101–103]. This high abundance of species results from the pre-concentration capabilities of the kidneys, so, in a certain sense, urine offers an insight into the composition of blood volatile compounds. Nevertheless, in the context of USaR operations, this source of markers suffers from several disadvantages, such as unpredictable and temporal occurrence, or limited capacity. Its contribution to the total flux of volatiles from human body during entrapment is also difficult to estimate. It is reasonable to assume that the fluxes of some species (e.g., ketones) can be temporarily strengthened [14,16] after the urinating event, but this increase of emission will depend on their physicochemical properties. For example, compounds well soluble in urine will be released for much longer than poorly soluble ones [14]. Moreover, the entrapment conditions, such as temperature, humidity, or dehydration, can considerably affect the urination cycles and quantities. For these reasons, the contribution of urine-borne species to the total flux of VOCs has not been assessed quantitatively within this review. Instead, we report only their omnipresence to indicate that this source can raise the total signal.

2.4. Blood

Apart from many deaths, earthquakes typically result in many traumatic injuries. These injuries are highly mechanical and often multiple. The musculoskeletal injuries typically embrace lacerations, fractures, crush injuries, soft-tissue contusions, or chest trauma [1]. Consequently, the probability of victims bleeding after the disaster event is relatively high. Although, the levels of volatiles in blood are generally lower than in urine (acetone is here an exception worth mentioning), the emission of blood species is much more predictable and should occur at the early stage of entrapment. However, blood, as a source of volatiles, shares the limitations of urine. It is temporal, of limited capacity, and its contribution to the chemical signature is variable and depends on the medical status

of the victim. Thus, as in the case of urine, Table 1 shows only the omnipresence of blood species to stress its possible contribution.

3. Potential markers of human presence

Altogether, 47 compounds were selected as potential markers of buried victims (see Table 1) on the basis of data on skin and breath VOCs. Their total mean emission rates from the human body are given in Table 1 (column I) and shown in Fig. 3. The tentative origins of these species in human organisms have been listed in Table 1 (column F). Within this set of species, the most numerous chemical classes are aldehydes (23%) and hydrocarbons (21%). Other well-represented families are ketones (13%) and inorganic compounds (9%).

We stress that this list should be considered an initial library to be complemented and verified under field conditions rather than a closed, complete set of potential markers. In particular, a number of omnipresent breath species were excluded due to the shortage of quantitative data, or contradictory information on their origin. The chemical pattern depicted in Fig. 3 demonstrates that both permanent sources of volatiles in humans contribute considerably to the formation of a human-specific chemical fingerprint and numerous species stem from both breath and skin. This is not surprising, as endogenously produced compounds can be distributed actively (vascular system) or passively (diffusion) among tissues and organs and finally released via breath, skin, or urine.

Four inorganic compounds (CO_2, CO, NO, and ammonia) have been preselected within this work. With the exception of NO, they exhibit very high emission rates from the human body, and thereby offer an enhanced possibility for the detection of victims in voids of collapsed buildings. They are predominantly released via breath. Only ammonia has a considerable skin-emission component.

Carbon dioxide appears to be the most natural candidate as a sign of life. It is produced endogenously in huge amounts and released almost exclusively via breath. Its total flux is approximately four orders of magnitude higher than the flux of the second most abundant compound – ammonia. Moreover, it is relatively inert and rapidly transportable by air currents; however, its levels can be influenced by high humidity and water absorption on debris materials [15], or fires in the voids of collapsed buildings. Indeed, CO_2 has already been employed by shipping companies for detection of stowaways in, e.g., harbor or airport locations [9]. Despite these advantages CO_2 poses some hazards for an entrapped victim. In the absence of air currents within the void spaces, its levels will rise and the levels of oxygen will decrease, leading to asphyxiation and death of victims.

Conversely, ammonia – another abundant inorganic compound – seems to be released mainly through skin emanations. More

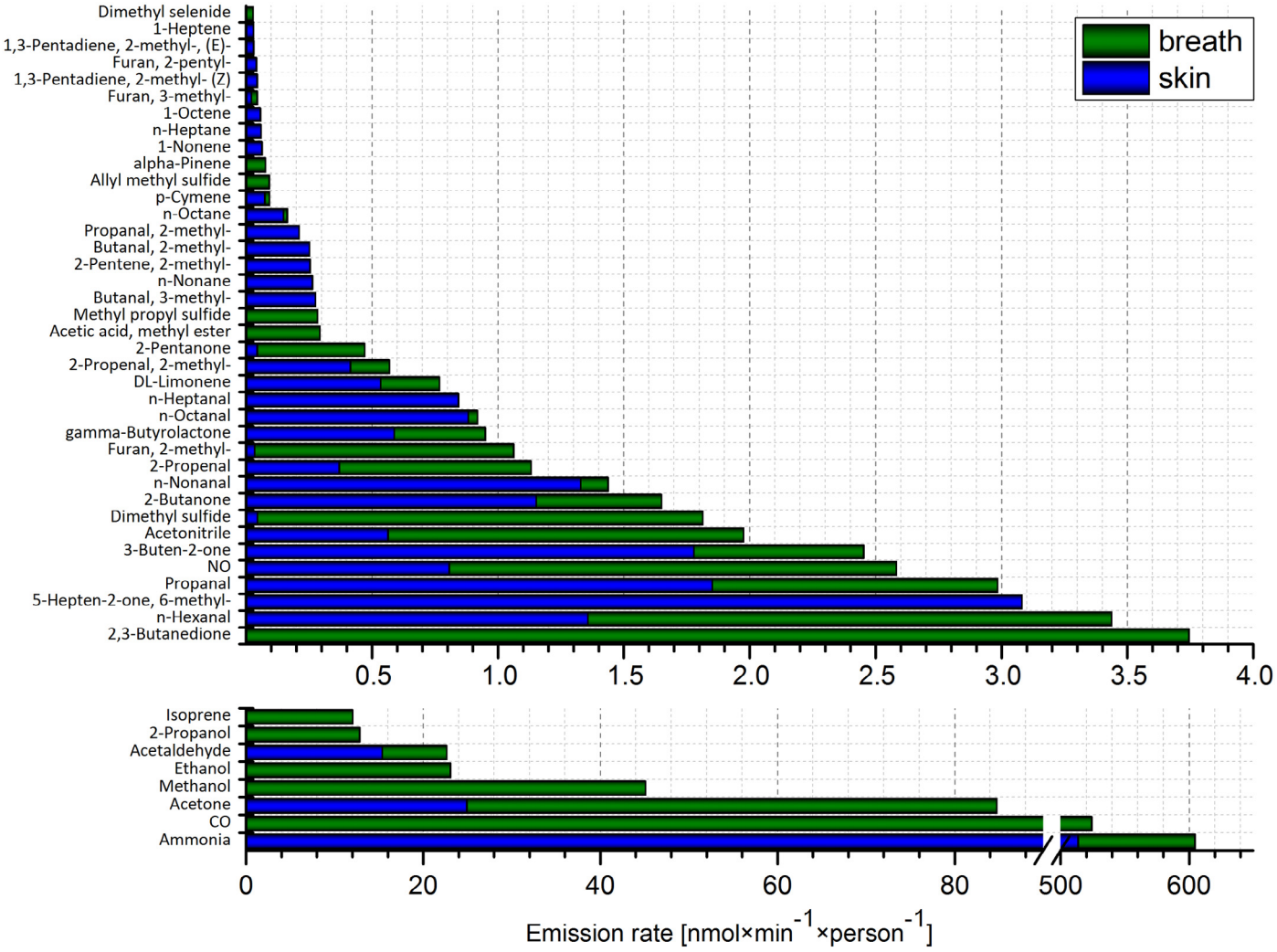

Fig. 3. Total emission rates (considering means) of potential volatile markers of human presence from the human body. CO_2 was excluded for reasons of clarity.

than 85% of its total flux stems from this source. In healthy individuals, ammonia is produced in the gut during bacterial breakdown of proteins [45]. However, analogous protein breakdown in the oral cavity or on the surface of the skin may also contribute to the flux of ammonia [21]. It is unclear why ammonia exhibits such a considerable skin component. Perhaps skin emission is promoted by the rapid diffusion of NH_3 via tissues resulting from the low molecular mass of this volatile. The usefulness of ammonia as an indicator of human presence was suggested by several authors [13,15]. Interestingly, its flux seems to differ between sleep and consciousness [15]. Since other species can share this phenomenon, studies on breath VOCs during sleep are of particular importance for USaR operations [24]. The production of CO in humans is ascribed to the endogenous metabolism of heme [39]. Relatively high levels in breath (at low-ppm concentration) render CO one of the most abundant volatiles amongst species released by humans.

A total of six ketones were found to be omnipresent in human breath and/or skin emanations and thereby valuable for the detection of humans – acetone, 2-butanone, 2-pentanone, 3-buten-2-one, 2,3-butanedione, and 6-methyl-5-hepten-2-one. Acetone is the major ketone produced in the human organism, exhibiting high abundances in breath [22,44,50], blood [104] and urine [16,101]. Several sources of acetone in humans can be indicated:

(i) endogenous decarboxylation of acetyl–CoA [50,105];
(ii) oxidative degradation of squalene on human skin [54];
(iii) 2-propanol metabolism [55]; and,
(iv) diet.

However, the latter two are of minor importance. The high emission rate of 85 nmol × min^{-1} × $person^{-1}$, endogenous production and high volatility render acetone a very promising marker of buried victims. Indeed, early experiments aiming at the identification of markers of human presence indicated acetone as a compound having great potential [13,15]. The remaining ketones were characterized by much lower emission rates of 0.47–3.7 nmol × min^{-1} × $person^{-1}$. The origin of these species remains ambiguous, so it is difficult to assess their usefulness during USaR operations. For example, 2,3 butanedione appears to originate from butter consumption; whereas 3-buten-2-one may be a product of isoprene degradation. 6-methyl-5-hepten-2-one is an interesting ketone released from human skin in considerable amounts. It stems from the oxidative degradation of squalene – a major component of human sebum. Squalene is a particularly interesting component of sebum, as its levels are very low in other organs but particularly high in human skin and in the range 12–20% of total skin-surface lipids [106]. This high abundance is also unique to human skin, when compared to other animals. Squalene is believed to be a natural antioxidant capable of neutralizing reactive oxygen species (ROS) [99,107]. While exposed to ROS, it degrades, producing a wide range of semi-volatile and volatile products [69,99,108]. Some of these compounds can thus be human specific and thereby very valuable for USaR operations. 6-methyl-5-hepten-2-one could be a prototypic representative of this group. Although it was found to be emitted by some plants [54], in urban environments, it could be a biomarker of human presence.

Aldehydes with 11 representatives were the most numerous chemical family amongst the compounds of interest. Interestingly, they predominantly originate from skin. With the exception of acetaldehyde, 2-propenal, n-hexanal, and n-propanal, their breath fluxes are very small, frequently negligible, compared to the skin fluxes. This ample presence of aldehydes in skin emanations mirrors the oxidative stress-inducing peroxidation of unsaturated fatty acids on skin. Apart from squalene, sebum contains numerous long-chain fatty acids (up to 26 carbon atoms), linear or branched, predominantly saturated or mono-unsaturated [99,109]. Strikingly, the fatty-acids fraction embraces unique components (e.g., branched-chain species) or lipids with unique patterns of unsaturation [109,110]. For example, two predominant sebum lipids, sapienic and sebaleic acid, have not been identified in other human tissues or the sebaceous gland secretions of other animals [106]. Oxidative stress on the skin surface causes peroxidation of these fatty acids with subsequent formation of numerous volatile products (aldehydes, ketones, hydrocarbons, alcohols, or esters) [63,66,111,112]. They are generated via β-scission of alkoxy radicals formed by the homolytic cleavage of fatty-acid hydroperoxides. For example, oxidation of oleic acid leads to the release of n-octanal, n-nonanal, n-decanal, n-heptane, and n-octane [63,66,111,112]. Interestingly, some aldehydes are more abundant in skin emanations of older subjects {e.g., n-nonanal [20], or 2-nonenal [66]}, indicating some age-related changes in the fraction of fatty acids in skin. Bearing in mind the multitude and diversity of fatty acids building the human sebum, it is not surprising that skin emanations contain numerous members of this chemical family. However, oxidation of fatty acids is not the only source of aldehydes in the human organism. They can also be products of the endogenous oxidation of primary alcohols catalyzed by alcohol dehydrogenases (ADHs) [62], or stem from dietary sources. Thus, breath acetaldehyde can mirror ethanol metabolism, whereas n-propanal may reflect exposure to 1-propanol.

Regarding hydrocarbons, 10 species were preselected. Amongst them, there are four alkenes, three alkanes, and three diens. Although hydrocarbons emitted by the human body have received special attention as non-invasive markers of numerous diseases or metabolic disorders [10–12], their sources in humans have not been elucidated in sufficient depth. Nevertheless, several metabolic pathways leading to the formation of hydrocarbons of interest can be indicated. A wide range of hydrocarbons (both saturated and unsaturated) is generated during cutaneous oxidation of the sebum components, such as fatty acids and squalene. This mechanism is identical to that responsible for the formation of aldehydes and proceeds as described above. Thus, n-octane was found to be the product of the oleic-acid degradation [63], whereas, 2-methyl-2-pentene was reported to stem from decomposition of squalene [69]. Isoprene is an unsaturated hydrocarbon produced in humans in large quantities [68]. According to the current theory, it is formed from isopentenyl pyrophosphate (IPP) and its isomer dimethylallyl pyrophosphate (DMAPP) in the mevalonic acid (MVA) pathway [68]. In animals and humans, it has been suggested to be produced non-enzymatically by acid-catalyzed formation from DMAPP occurring in the cytosol of hepatocytes. Nevertheless, there is growing evidence provided by a number of recent studies suggesting that other endogenous metabolic sources may contribute to isoprene formation in humans [113,114].

All preselected alcohols (ethanol, methanol, and 2-propanol) exhibit high abundances in human scent. Their total emission rates range from 12.8 nmol × min^{-1} × $person^{-1}$ for 2-propanol to 45.1 nmol × min^{-1} × $person^{-1}$ for methanol. It is worth mentioning that these species are also emitted via skin emanations in considerable amounts [74]. However, due to the shortage of quantitative data, it is difficult to assess their skin-borne component in the total flux. Several sources of these compounds can be listed in humans. First, they can stem from dietary sources (e.g., fruit consumption) [56]. Methanol and ethanol can be produced by the bacterial flora in gut and/or oral cavity [76,115] and 2-propanol can be the product of acetone metabolism catalyzed by ADHs [81,116,117].

Amongst sulfur-containing compounds, there were two diet-related species (allyl methyl sulfide and methyl propyl sulfide) and dimethyl sulfide (DMS). The presence of allyl methyl sulfide in human tissues and fluids is attributed to the garlic consumption [84]; whereas, methyl propyl sulfide was shown to appear in human breath after onion intake [85]. DMS is a volatile reported to be omnipresent in human breath and blood [22]. Its production is ascribed

to the metabolization of sulfur-containing amino acids methionine and cysteine in the transamination pathway [83]. Thus, in liver, thiol S-methyl transferase forms DMS via the methylation of methyl mercaptane [83,118].

Of terpenes, DL-limonene exhibits the highest emission rate of 0.77 nmol × min^{-1} × $person^{-1}$. The fluxes of the remaining species from this chemical family (p-cymene and α-pinene) are notably lower and do not exceed 0.1 nmol × min^{-1} × $person^{-1}$. Despite their omnipresence, the origin of these species in humans remains ambiguous. Nevertheless, diet seems to be the most probable reason for their occurrence [56,119].

Amongst the remaining compounds are three furans (2-methylfuran, 3-methylfuran, and 2-pentylfuran), acetonitrile, γ-butyrolactone, methyl acetate, and dimethyl selenide. Several compounds from this set can stem from the metabolism of microbiota inhabiting the surface of human skin. For example, fungi of the genus *Malassezia* naturally found on the human skin were found to produce an odor exhibiting high abundance of a homologous series of γ-lactones (C8-C12) in the presence of oleic acid or human sebum [91]. Although γ-butyrolactone could not be measured in the above study [119], due to some analytical limitations, it appears plausible that also this compound could be a marker of fungi from this genus. Moreover, 2-pentylfuran was demonstrated to be produced by *Fusarium sp.* and *Aspergillus flavus* [88]; whereas, 3-methylfuran was found to be released by *Penicillium sp.* and *Aspergillus flavus* [86]. All these species of fungi inhabit human skin [120]. Alternatively, 3-methylfuran might also be produced endogenously during the alkoxy radical-induced degradation of isoprene, as was established in atmospheric studies [59,121]. If so, isoprene could be considered as a ROS scavenger protecting the skin surface from oxidative stress-induced damage. Nevertheless, additional experiments are necessary to pinpoint the role of isoprene in human physiology. Interestingly, acetonitrile, a compound commonly being attributed to smoking habits [64], also appears in the scent of non-smokers [89,90]. Perhaps additional endogenous sources contribute to its presence in humans.

4. Changes in emission rates of VOCs during entrapment

Entrapment conditions and disaster-related injuries notably affect the physiology and the biochemistry of humans [19]. Earthquakes typically cause highly mechanical and often multiple injuries. Amongst them musculoskeletal injuries, such as lacerations, fractures, crush injuries, or spinal trauma are the most common [1]. These traumas induce numerous systemic complications and a number of neuroendocrine, metabolic, and physical responses. The latter can comprise, e.g., intense emotional stress, physical shock, hypermetabolism (manifest by hyperglycemia, hyperlactatemia, and protein catabolism), immunological responses, or up-regulation of hormones secretion [19]. Moreover, prolonged entrapment introduces additional complications (e.g. dehydration, starvation, or asphyxiation). Although the epidemiology of disaster-related injuries and complications has received considerable attention [1], little is known about how these conditions affect the production and the emission of volatiles from the human body in general and markers of human presence in particular. This lack of knowledge is due to the limited quantitative information on the emission rates of VOCs from the human body, limited knowledge of their origin and fate, and ethical and methodological problems related to the simulation of entrapment in a laboratory environment. Nevertheless, despite these constraints, several possible responses of the human-specific chemical fingerprint to the entrapment can be indicated.

Starvation, stress, and hypermetabolism (hyperglycemia) induce the production of ketones in the body, which should manifest increased emission rates of acetone [19]. Abnormally high concentrations of acetone (ketoacidosis), in turn, foster its biotransformation into 2-propanol catalyzed by ADHs and thereby increase the levels of 2-propanol in the human organism [81,116,117].

Crush injuries are usually associated with traumatic rhabdomyolysis and release of products of muscle degradation. These compounds may include myoglobin, uric acid, potassium, lactic acid, or creatine kinase [1]. In excess, these species have toxic effects on distant organs. In particular, high levels of myoglobin accompanied by acidosis and hypovolemia obstruct the tubular flow of kidneys and induce acute kidney injury. Impaired kidneys fail to eliminate urea and precipitate the rise of ammonia levels in tissues and fluids (hyperammonemia) [19].

The entrapped victim is inherently cut off from the predominant factors inducing oxidative stress on the skin surface, such as UV radiation or O_3, so we can expect that the skin production of oxidative stress-related species will be reduced shortly after entrapment. In particular, this reduction can affect emission rates of numerous aldehydes and hydrocarbons (see Table 2). Consequently, the applicability of compounds from this group may be limited to the initial period of rescue operations.

Diet contributes enormously to the pool of VOCs in the human organism. Myriads of volatile compounds are consumed as flavor constituents of food or beverages [56]. Some of them are of natural origin, whereas others stem from human or bacterial food metabolism. These volatiles are next distributed amongst tissues and excreted via breath, skin, or urine. A number of compounds being potential markers of human presence can at least partly originate from this source, as shown in Table 2. Prolonged starvation will reduce the abundance of diet-related compounds in the specific chemical pattern of a human. Thus, they can have limited applicability during longer rescue operations. In particular, this problem can concern some abundant species, such as methanol, ethanol, or ammonia (produced mainly by bacteria in gut and/or oral cavity). Thus, knowledge of the origin and the metabolic fate of potential markers of human presence is of utmost importance for their verification.

5. Human-specific chemical signature at the entrapment site

Once emitted, volatiles forming the human scent are spread by air currents throughout the void spaces of collapsed buildings, interact with debris materials, and mix with environmental and disaster-related contaminants and/or toxic agents. All these factors can considerably distort the original human-specific chemical fingerprint. The type of the building construction and construction materials are considered critical factors in mortality and epidemiology of earthquake-related injuries. Survivors are frequently found in confined spaces of collapsed building structures. The retention of these voids depends on the collapse mechanism {e.g., pancake, lean-to, V-shaped [5]} and is much more likely in well-constructed, reinforced concrete, steel-frame buildings than in masonry, brick, or adobe constructions [6].

The presence of void spaces and the type of debris materials also affect the dispersion and the air levels of potential volatile markers of human presence. Here, a very important parameter is the debris surface area-to-volume ratio (SA:V), as it governs the surface chemistry. High values of SA:V favor the adsorption of volatile species on building materials and decrease their concentrations in void spaces. Moreover, these losses can also be boosted by the presence of dust and powdered building materials covering the rubble and buried victims. In particular, dust can notably suppress the emission of skin-borne species and thereby limit their applicability during USaR operations.

Additional factors affecting the levels of VOCs in void spaces are temperature and especially humidity. Relative humidity over 90% induces condensation and formation of water films and thereby triggers wet chemistry. Thus, knowledge of the surface chemistry of

Table 2
Predicted levels in void spaces (see text for detailed conditions), exemplary urban levels, possibilities of detection by portable instruments and classification of potential volatile markers of human presence. The classification criteria are defined in Section 6

A	B	C	D	E	F
Compound CAS	Predicted level at 3 m distance [ppb]	Exemplary urban air levels	Main urban sources	Detection possibilities LOD, technique	Class of marker
CO_2 124-38-9	30×10^6	(b) 408 ppm (Dallas) [122] (c) 390 ppm (Phenix) [123] (d) 469 ppm (Wrocław) [124] (e) 403–408 ppm (Portland) [125]	Vehicle emissions,	(a) 0.25% optical sensor [126] (b) 0.23% Solvatochromic probe [127]	A
NO 10102-43-9	7.7	(a) 24.5 ppb (Hong Kong) [128] (b) 11.7 ppb (A Coruna) [129] (c) 127/35 ppb (Seoul) [130]	Vehicle exhaust	(a) 6 ppb chemiresistor (PEDOT:PSS/TiO_2) [131] (b) 5 ppb electrochemical (WO_3/Pt) [132] (c) 18 ppb chemiresistor (WO_3/Cr_2O_3) [133] (d) 3.6 ppb ICOS [134] (e) 0.03 ppb lase QCL [135] (f) 4 ppb electrochemical sensor [136]	C
CO 630-08-0	1350	(a) 1.6 ppm (Karachi) [137] (b) 0.592 ppm (Hong Kong) [128] (c) 1.7 ppm (Rio de Janeiro) [138] (d) 0.53 ppm (London) [139] (e) 1.2 ppm (Seul) [130]	Coal burning Vehicular exhaust Cigarette smoke	(a) 1 ppm chemiresistor (Ca-SnO_2) [140] (b) 1 ppm electrochemical sensor [141] (c) 0.1 ppm controlled potential electrolysis [142] (d) 4 ppb electrochemical sensor [136]	C
Ammonia 7664-41-7	1260	(a) 22 ppb (Santiago, Chile) [143] (b) 24.7 ppb (Rome, Italy) [144] (c) 5.5 ppb (New York, USA) [145] (d) 8.2 ppb (Salzburg, Austria) [146] (e) 9 ppb (Munich, Germany) [146]	Agriculture, vehicular exhaust	(a) 0.014 ppb MCC-IMS [147] (b) 50 ppm AIMS [148] (c) 18 ppb chemiresistor (H_2SO_4 solution) [46] (d) 50 ppb chemiresistor (MoO_3) [149]	A
Acetone 67-64-1	435	(a) 18.6 ppb (Ottawa, Canada) [150] (b) 5.4 ppb (Melbourne, Australia) [151] (c) 1.1 ppb (Sao Paulo, Brazil) [152] (d) 2.4 ppb (Quinzhou, China) [153] (e) 13.5 ppb (average from towns) [154] (f) 7 ppb (Beijing) [155] (g) 1.45 ppb (Zurich, Switzerland) [156]	Solvents, oxidation of NMHCs	(a) 0.02 ppb MCC-IMS [147] (b) 14 ppb AIMS [157] (c) 500 ppb AIMS [148] (d) 20 ppb Si:WO_3 chemiresistor [158] (e) 120 ppb Pt-WO_3 chemiresistor [159] (f) 130 ppb optical spectroscopy [160] (g) 170 ppb CTL (Mn_3O_4) [161]	A
2-Butanone 78–93-3	9.8	(a) 0.9 ppb (Ottawa) [150] (b) 0.76 ppb (Quinzhou) [153] (c) 1.35 ppb (average from towns) [154] (d) 0.2 ppb (Zurich, Switzerland) [156] (e) 0.5 ppb (Niterói City, Brazil) [162]	Industrial solvent	(a) 11 ppb AIMS [157]	B
2-Pentanone 107-87-9	3.2			(a) 8 ppb AIMS [157]	B
5-Hepten-2-one, 6-methyl- 110-93-0	16.6	(a) 0.36 ppb (Rome) [163] (b) 0.65 ppb (Milan) [163]	Plants	(a) 0.7 ppb MCC-IMS [164]	A
3-Buten-2-one 78–94-4	13.2	(a) 0.17 ppb (Hong Kong) [128] (b) 0.43 ppb (Nashville) [165]	Oxidation of isoprene, vehicle exhaust		B
2,3 Butanedione 431-03-8	20		Food, kitchen waste		B
Acetaldehyde 75-07-0	98	(a) 9.4 ppb (Sao Paulo) [152] (b) 2.4–45 ppb (Rio de Janeiro) [138] (c) 8.0 ppb (Quinzhou) [153] (d) 5.7 ppb (Beijing) [155] (e) 3.6 ppb (Niterói City, Brazil) [162]	Ethanol fuel combustion, oxidation of NMHCs	(a) 500 ppb AIMS [148] (b) 110 ppb bio-sniffer [166] (c) 0.15 ppb chemiresistor (ZnO) [167] (d) 500 ppb CTL [168]	A
n-Propanal 123-38-6	15.4	(a) 0.4 ppb (Sao Paulo) [152] (b) 0.35 ppb (Quinzhou) [153] (c) 0.12 ppb (Zurich, Switzerland) [156] (d) 0.83 ppb (Niterói City, Brazil) [162]	Disinfectant, kitchen waste, vehicle exhaust	(a) 25 ppb AIMS [157] (b) 0.15 ppb chemiresistor (ZnO) [167] (c) 250 ppb CTL (ZrO_2) [169]	A
2-Propenal 107-02-8	5.8	(a) 0.6 ppb (Sao Paulo) [152] (b) 0.09 ppb (Zurich, Switzerland) [156]	Vehicle exhaust	(a) 50 ppb AIMS [148]	B

(*continued on next page*)

Table 2 (*continued*)

A	B	C	D	E	F
Compound CAS	Predicted level at 3 m distance [ppb]	Exemplary urban air levels	Main urban sources	Detection possibilities LOD, technique	Class of marker
2-Propenal, 2-methyl 78–85-3	3.2	(a) 0.1 ppb (Hong Kong) [128] (b) 0.24 ppb (Nashville) [165] (c) 0.02 ppb (Zurich, Switzerland) [156]	Oxidation of isoprene, vehicle exhaust		B
Propanal, 2-methyl- 78–84-2	1.3		Kitchen waste, vehicle exhaust		C
Butanal, 2-methyl- 96-17-3	1.5		Kitchen waste		C
Butanal, 3-methyl- 590-86-3	1.7		Kitchen waste		C
n-Hexanal 66-25-1	26	(a) 1.2 ppb (Melbourne) [151] (b) 0.35 ppb (Rome) [163]	Fuel combustion	(a) 24 ppb AIMS [157] (b) 0.3 ppb MCC-IMS [13]	A
n-Heptanal 111-71-7	7.1	(a) 0.4 ppb (Rome) [163]	Fuel combustion, atmospheric photooxidation of HCs, kitchen waste		A
n-Octanal 124-13-0	8.2	(a) 0.48 ppb (Rome) [163]	Fuel combustion, atmospheric photooxidation of HCs, kitchen waste	(a) 28 ppb AIMS [157] (b) 0.1 ppb MCC-IMS [13]	A
n-Nonanal 124-19-6	13.6	(a) 1.4 ppb (Melbourne) [151] (b) 1.2 ppb (average from towns) [154] (c) 0.37 ppb (Rome) [163] (d) 0.14 ppb (Niterói City, Brazil) [162]	Fuel combustion, atmospheric photooxidation of HCs, kitchen waste	(a) 0.3 ppb MCC-IMS [13]	A
Isoprene 78–79-5	36	(a) 0.3 ppb (Seul) [170] (b) 0.8 ppb (Karachi) [137] (c) 0.13 ppb (Lille) [171] (d) 0.34 ppb (Rome) [172] (e) 0.252 ppb (Hong Kong) [128] (f) 0.66 ppb (Guangzhou) [173] (g) 0.41 ppb (Nashville) [165] (h) 0.27 ppb (A Coruna) [129]	Plants, vehicular emissions	(a) 0.003 ppb MCC-IMS [147] (b) 36 ppb MIR [174]	A
1,3-Pentadiene, 2-methyl-, Z- 2787-45-3	0.3				C
1,3-Pentadiene, 2-methyl-, E- 926-54-5	0.2				C
2-Pentene, 2-methyl- 625-27-4	1.7				C
1-Heptene 592-76-7	0.23				C
n-Heptane 142-82-5	0.5	(a) 0.5 ppb (Seul) [170] (b) 3.9 ppb (Karachi) [137] (c) 9 ppb (Rio de Janeiro) [175] (d) 0.05 ppb (Rome) [172] (e) 0.56 ppb (Guangzhou) [173] (f) 0.34 ppb (A Coruna) [129] (f) 0.09 0.53 ppm (London) [139]	Petrol evaporation, vehicle exhaust		C
1-Octene 111-66-0	0.5				C
n-Octane 111-65-9	1.5	(a) 0.3 ppb (Seul) [170] (b) 1.1 ppb (Karachi) [137] (c) 1.2 ppb (Rio de Janeiro) [175] (d) 0.1 ppb (Lille) [171] (e) 0.79 ppb (Guangzhou) [173] (f) 0.3 ppb (A Coruna) [129] (g) 0.04 ppb (London) [139]	Petrol evaporation, vehicle exhaust		C

(*continued on next page*)

Table 2 (*continued*)

A	B	C	D	E	F
Compound CAS	Predicted level at 3 m distance [ppb]	Exemplary urban air levels	Main urban sources	Detection possibilities LOD, technique	Class of marker
1-Nonene 124-11-8	0.57				C
n-Nonane 111-84-2	2.5	(a) 0.6 ppb (Seul) [170] (b) 0.7 ppb (Karachi) [137] (c) 2.1 ppb (Rio de Janeiro) [175] (d) 0.95 ppb (average from towns) [154]	Petrol evaporation, vehicle exhaust		C
Methanol 67-56-1	160	(a) 8 ppb (Barcelona) [176] (b) 22 ppb (average from towns) [154] (c) 14 ppb (Rio de Janeiro, Brazil) [177] (d) 5.8 ppb (Osaka, Japan) [178] (e) 1.8 ppb (Zurich, Switzerland) [156]	Solvents, biofuel evaporation	(a) 100 ppm AIMS [148] (b) 380 ppb CTL (nano-CdS) [179]	B
Ethanol 64-17-5	105	(a) 37 ppb (Melbourne) [151] (b) 64 ppb (average from 50 studies) [154] (c) 66.4 ppb (Rio de Janeiro, Brazil) [177] (d) 8.2 ppb (Osaka, Japan) [178] (e) 176.3 ppb (Sao Paulo, Brazil) [178] (f) 6.6 ppb (Zurich, Switzerland) [156]	Solvents, biofuel evaporation,	(a) 0.525 ppb MCC-IMS [147] (b) 55 ppb AIMS [157] (c) 300 ppb biochemical [180] (d) 700 ppb CTL [181]	C
2-Propanol 67-63-0	69.6	(a) 7.4 ppb (Ottawa, Canada) [150] (b) 7.2 ppb (Osaka, Japan) [178] (c) 44.2 ppb (Sao Paulo, Brazil) [178]	Disinfectants, antifreeze, biofuel evaporation		C
Dimethyl sulfide 75-18-3	9.0	(a) 0.37 ppb (Seul, Korea) [182]			B
Allyl methyl sulfide 10152-76-8	0.5				C
Methyl propyl sulfide 3877-15-4	1.5				C
p-Cymene 99-87-6	0.8		Oxidation of α-pinene		C
DL-Limonene 138-86-3	6.7	(a) 9.4 ppb (Rio de Janeiro) [175] (b) 19.6 ppb (Melbourne) [151] (c) 3.7 ppb (average from towns) [154]	Plants, wood emission, food, kitchen waste	(a) 0.9 MCC-IMS [183]	C
α-Pinene 80-56-8	0.65	(a) 2.4 ppb (Rio de Janeiro) [175] (b) 6.2 ppb (Melbourne) [151] (c) 0.2 ppb (Rome) [163] (d) 0.21 ppb (Milan) [163] (e) 0.19 (A Coruna) [129]	Plants, wood emission, food, kitchen waste	(a) 0.9 MCC-IMS [183]	C
Furan, 2-methyl- 534-22-5	6.8				B
Furan, 3-methyl- 930-27-8	0.3	(a) 0.05 ppb (USA) [184]	Oxidation of isoprene, vehicle exhaust		C
Furan, 2-pentyl- 3777-69-3	0.23				C
Acetonitrile 75-05-8	8.3	(a) 0.12 ppb (Sydney) [185]	Biomass burning		B
γ-Butyrolactone 96-48-0	5.8		Solvents		B
Methyl acetate 79-20-9	1.6	(a) 0.06 ppb (Zurich, Switzerland) [156]	Solvents, oxidation of MTBE and TAME		B
Dimethyl selenide 593-79-3	0.14				C

building materials can determine the applicability of markers of human presence.

The interactions of VOCs forming the human scent with debris materials have already received some attention. Several authors investigated the permeation of urine-borne volatiles through layers of different building materials, such as concrete, brick, or quartz stone [16,186,187]. Volatiles in the urine headspace were found to exhibit a concentration profile with an initial peak related to urinating, which was next washed out by the prevailing air currents. The influence of debris materials on these profiles depended on their fundamental physicochemical properties. Brick was demonstrated to be a much less adsorptive material for urine-borne species than concrete. Although concrete considerably reduced the observed levels of compounds, it prolonged the presence of VOCs in the debris. Some classes of compounds (i.e., furans, and sulfur-containing species) showed weak interactions with the tested materials and were relatively quickly removed from the surroundings of the urine samples. Conversely, more polar analytes (e.g., ketones) were more influenced [14]. Predictably, the increase of molecular mass promoted the interactions with debris and increased the residence times of VOCs in void spaces [14]. Huo et al. [15] monitored species released by healthy volunteers closed in an environmental chamber mimicking void space and permeating through a glass column packed with different discs of building materials. The study involving whole-body emission demonstrated the permeation of CO_2, NH_3, acetone, and isoprene through a collapsed building simulator.

Urban air is typically highly contaminated with numerous VOCs. They predominantly stem from anthropogenic sources, such as vehicle exhausts, solvents and fuel evaporation, fossil fuel combustion, or emissions of liquefied petroleum gas [126,137,170,172]. Their levels may vary over relatively brief periods of time, show diurnal/seasonal cycles, or exhibit spikes related to local temporal emissions. Moreover, the profiles of urban VOCs differ from one country to another due to differences in heating patterns, composition of vehicle fuel, local regulations concerning VOC emissions, or climatic conditions. This highly complex, variable phase becomes even more complicated and harsh after massive collapse of buildings. Damaged building structures, sewage systems, broken gas pipes, fire and smoke produce additional contaminants and/or toxic agents, which mix with air filling the void spaces and human-borne volatiles [17,18]. In particular, released toxic agents might embrace polychlorinated biphenyls, hazardous metals, asbestos, various harmful gases (e.g., hydrogen cyanide, hydrogen sulfide, halogenated gases, and CO), detergents, acids and alkalis, ethylene glycol, propylene glycol, phenol, and alcohols [18,188]. Furthermore, volatiles emitted by rodents, insects or decomposing bodies can also complicate chemical analysis at the disaster site and induce false positives [189]. All these factors and confounders considerably affect the levels of the human-specific volatiles in the voids of collapsed buildings and make their identification and detection a really challenging task.

The complexity and the unpredictability of an entrapment environment, the variety of confounders and interactions, and ethical restrictions also limit laboratory-based studies in this specific field. It is therefore very difficult to model the behavior of the human-specific chemical fingerprint in the surroundings of the entrapped person in reliable way, and predict the levels of its constituents. However, knowledge of even approximate concentrations of potential indicators of human presence would provide invaluable benefits for chemical analysis towards victim location, including:

(i) validation of potential markers against the possibility of their detection in highly polluted air in the disaster environment;
(ii) selection of appropriate analytical instruments, which could be used for the field detection of entombed victims; and,
(iii) optimization of these techniques for the detection of human markers in the disaster environment.

As mentioned above, air filling void spaces in the collapsed buildings is highly contaminated with a complex chemical signature. In particular, it is characterized by variable and unpredictable levels of VOCs, which can interfere with human-specific chemical fingerprints. Thus, debris air constitutes a background, against which markers of human presence have to be identified and detected. Despite these limitations, an effort was made within this work tentatively to verify the preselected markers against their typical urban levels. Such a comparison could help, for example, to exclude markers exhibiting emission rates that are too small to provide air levels able to be reliably distinguished from the background. For this purpose, a simple model of the dispersion of human-borne VOCs in debris has been developed. In this model, an entrapped human is represented by a ball (i.e., a radially symmetric structure with a certain radius R) emitting a constant stream j of VOCs. VOCs are assumed to be inert species, which do not interact with the debris in the disaster environment (no losses/sinks of VOCs). Moreover, the transport of VOCs in the voids of collapsed building is restricted only to diffusion and diffusion coefficients are postulated to be homogeneous and constant. The results of the diffusion calculation are independent of the specifically chosen radius of this ball (assuming, of course, that the distance from the center of the ball is larger than radius R).

Appendix A gives detailed description of the applied model and the calculations of tentative levels of human markers in the vicinity of an entrapped victim. In general, the model predicts a VOC-concentration decrease proportional to the inverse of the distance from the victim. We stress that, although such a model is unrealistic and provides presumably overestimated concentrations of species of interest, it can be used as the first verification tool for the proposed preliminary markers. The exemplary calculations done for the arbitrary chosen conditions: distance of 3 m from the entrapped person and a debris-to-air ratio 3:1 are presented in Table 2 and illustrated in Fig. 4. Hence, we assume that the volume of debris is three times the volume of air, which is a reasonable assumption [and can also easily be adapted, see formula (A.17) in Appendix A]. The realistic estimation of the latter factor poses an additional challenge, as it depends on the collapse pattern, which, in turn, is determined by the type of the building construction and the building code [5,6]. Due to the shortage of information on this parameter, it is futile to indicate its typical or most probable value. However, it is reasonable to assume that it will be smaller for well-constructed, reinforced concrete buildings. The values presented in Table 2 should be treated rather as upper boundaries of possible marker levels. For these particular conditions, the majority of compounds is expected to exhibit low-ppb levels. More specifically, concentrations of 19 species (40%) might be spread around 1 ppb and levels of further 13 (28%) should not exceed 10 ppb. Only seven compounds (CO_2, CO, ammonia, acetone, methanol, ethanol, and acetaldehyde) could produce levels higher than 100 ppb in the vicinity of survivors.

These values can next be compared to the typical urban concentrations of species of interest. For this purpose, an extensive literature search was done. Effort was made to select data reported for cities from different countries and continents to include region/continent dependent differences in concentrations. We stress that, for several compounds, the urban/indoor air data are difficult to obtain, due to their low toxicity, ultra-low levels and, consequently, lack of regulations concerning their emissions. The typical urban air levels of markers under scrutiny have been listed in Table 2 and are shown in Fig. 4.

In general, we believe that valuable information can be extracted from the juxtaposition of these data. First, levels of several tentative indicators can be too low to be distinguished from the background in the void spaces of collapsed buildings. For example, emission of CO from the human body can produce levels comparable to those usual in urban air. Bearing in mind that CO levels

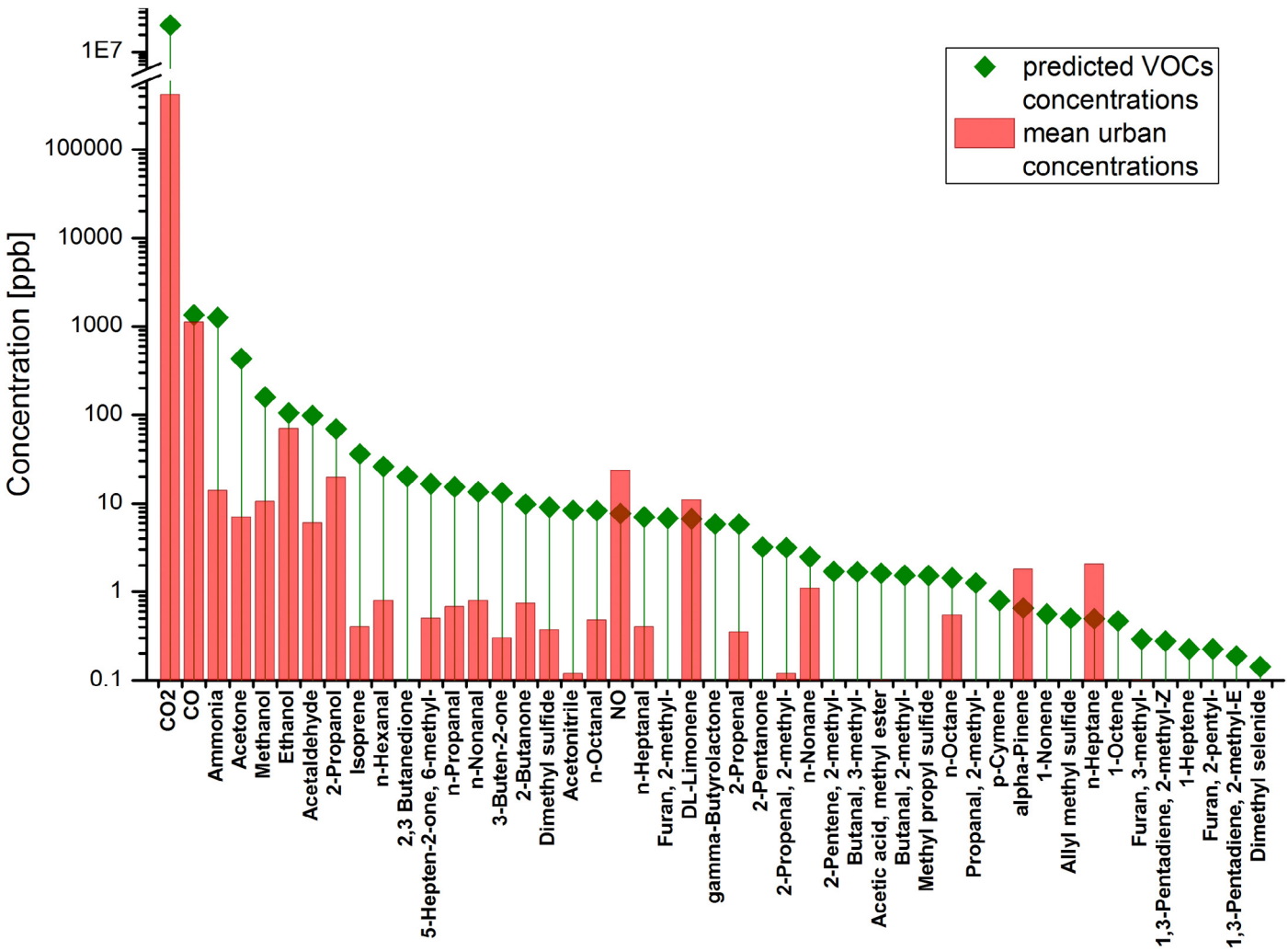

Fig. 4. Exemplary chemical signature of entrapped person predicted for a point located 3 m from a survivor and debris-to-air ratio 3:1. Red bars indicate mean urban air levels of compounds of interest.

exhibit diurnal and seasonal variability, it can be very difficult to separate urban and human-borne components of CO levels during a chemical analysis in the field. Moreover, concentrations of CO can change considerably during the USaR operation as a result of incidental hazards or fires [18,19]. The same holds true for methanol and ethanol. Although both these alcohols show relatively high abundances in the human chemical signature, their urban levels are also high. The high urban background stems from the increasing use of alcohols as alternative energy sources, replacing gasoline and related emission of unburned fuel, or their evaporation from leaking tanks [177]. Overall, the suitability of several constituents from the proposed set can be reduced by high and variable urban air levels.

Bearing in mind all the above problems and confounders, it is difficult to establish a clear criterion, which would exclude markers being too affected by urban air to be applied to detect entrapped victims. Nevertheless, a sufficiently high difference between background levels and human-borne levels in debris air seems to be a reasonable discriminant. Within this review, void concentrations at least 10 times higher than the urban-air background were recognized as a threshold. Several species from the original set failed to fulfill this criterion (e.g., CO, ethanol, 2-propanol, NO, DL-limonene, n-nonane, n-octane, α-pinene, and n-heptane). Interestingly, apart from DL-limonene and α-pinene, species from this group are typical vehicle exhausts, or fuel vapors. This finding makes vehicle-related pollution one of the main confounders hindering application of the human chemical fingerprint during USaR operations.

6. Analytical instrumentation for field detection of VOCs

The laboratory-based analytical instruments commonly used to determine and to track volatile species forming the human-specific chemical pattern are inherently large in size and expensive, demand laborious and time-consuming sample-preparation methods, and require well-trained, experienced operators. These attributes place significant limitations on their routine use in field conditions in general and the disaster environment in particular. Here, simple-in-use ("yes/no" response), rapid, hand-held, low-energy and simultaneously sensitive screening instruments are desirable. A number of technologies could meet these requirements.

Recent rapid progress in electronic sensor technology has stimulated the development of devices known as electronic noses (e-noses) [190], which are arrays of different non-selective sensors capable of detecting and discriminating a wide diversity of chemical species. Strictly speaking, their responses are not correlated to one specific compound, but rather to the whole chemical fingerprint. Thus, e-noses discriminate different VOC profiles using qualitative or semi-quantitative information. The versatile capabilities of e-noses stem from the variety of sensors available for selection for sensor arrays

(i.e., conducting-polymer, metal-oxide, optical, and electrochemical) and the abilities of manufacturers to produce customized, low-cost, multi-use devices for particular applications [190–193]. However, a key prerequisite for the success of e-nose devices in a particular application is knowledge of the chemical pattern of interest, which can only be provided by more sophisticated analytical techniques. If successful, sensor arrays may revolutionize USaR operations, when built into robust and small instruments. Once installed, e.g., on borescopes, they could penetrate the collapsed structures and screen their interiors for volatile chemical signs of life. Despite encouraging facilities, sensor arrays suffer from several disadvantages, such as temperature-dependent stability, or humidity effects.

Another promising technique is ion-mobility spectrometry (IMS) separating volatiles on the basis of differences in their migration speed in an inert buffer gas under the influence of an electric field [194]. Recent rapid advances in IMS resulted in the development of numerous sub-techniques exploiting different strengths and forms of the electric fields [e.g., linear drift tube IMS (DTIMS), travelling wave IMS (TWIMS), aspiration IMS (AIMS), or field-asymmetric IMS (FAIMS)], or combining IMS with other techniques [e.g. GC multi-capillary column IMS (MCC-IMS)]. The IMS instruments can be miniaturized, measure rapidly, have low energy consumption, and are very sensitive. Moreover, these techniques have already been successfully applied for the field detection and identification of chemical warfare agents (CWAs), or toxic industrial chemicals (TICs), and the expertise and know-how gained within these applications could be transferred into the "search and rescue" science, notably accelerating the pace of investigations.

Fast GC, combined with MS detection also exhibits a considerable potential for USaR operations. Short analysis time (several minutes) and progressive miniaturization render this technique a possible tool for locating entrapped victims. Fast GC-MS instruments can be field-portable [195,196] and, in combination with some pre-concentration methods [e.g., solid-phase microextraction (SPME)] could provide the detection of the majority of volatiles under scrutiny. Nevertheless, their weight (10–20 kg) still hinders their applicability in searching large disaster areas.

However, the successful employment of the above techniques for locating entrapped victims is determined by their analytical limitations. Here the limit of detection (LOD) can be regarded as a basic factor influencing the selection of the optimal technique. Table 2 lists exemplary LODs of different sensor-based or IMS-based instruments reported for some of compounds of interest. We stress that some of these analytical tools are still at the early phase of the development and should be considered as prototypes. Several conclusions can be distilled from this comparison. First, the detection of many potential volatile signs of life can pose a challenge due to their ultra-low concentrations and the unsatisfactory capabilities of the available field techniques. Nevertheless, we expect rapid progress in analytical chemistry instrumentation to solve this problem in the future. In this context, an interesting technique is MCC-IMS. Although this technique is strictly speaking not hand-held and real-time, and can impose operational problems for inexperienced users, it offers LODs that are adequate for the detection of many compounds under scrutiny. Indeed, recently MCC-IMS was demonstrated to be capable of detecting some constituents of human scent [13].

7. Classification of potential markers of human presence

An ideal marker of human presence should be omnipresent, volatile, relatively non-reactive, continuously emitted by the human body and present at relatively high concentrations in the proximity of an entrapped victim. In this spirit, we propose the classification of potential indicators of human presence preselected within this review into three subsets:

- Subset A comprises predominantly endogenous species exhibiting high emission rates from the human body, which can produce debris concentrations detectable by currently available, portable field analyzers and are clearly distinguishable from urban background levels. This group represents the most promising markers.
- Subset B contains volatiles of different (frequently unknown) origins with tentatively predicted debris levels being at least 10-fold higher than the expected background levels, but too low to be reliably detected by current portable techniques.
- Subset C incorporates volatiles stemming from sources that can be suppressed during the entrapment, or species with potential debris levels difficult to separate from the urban background.

Table 2 shows the proposed classification of particular species of interest. Following this classification, CO_2, ammonia, acetone, 6-methyl-5-hepten-2-one, isoprene, n-propanal, n-hexanal, n-heptanal, n-octanal, n-nonanal, and acetaldehyde constitute class A, and are thereby the strongest candidates for markers of human presence. The potential of class A species is also supported by some of them having already been indicated as promising human indicators by several early studies [13–15].

8. Conclusions

The main goals of this review were to create a database of human-borne volatiles having high potential as markers of human presence, which could be used for early location of entrapped victims during rescue operations, and to estimate their emission rates from the human body on the basis of existing literature data.

Altogether, 47 compounds were pre-selected using skin emission and quantitative exhaled breath data. They belong to several chemical classes; however, aldehydes and hydrocarbons are the most numerous. We stress that these species may originate from several distinct sources and their production is still far from being completely understood.

Due to the nature of this specific field, and ethical and methodological restrictions, the prediction of fluxes of these species and their concentrations in the voids of collapsed buildings poses considerable challenges and problems. In particular, unpredictable and variable conditions in the entrapment environment, shortage of quantitative data on VOC emissions by the human body, or poorly known interactions of VOCs with debris materials affect efforts towards this goal. In this context, the emission rates that we calculated should be treated as tentative and the predicted concentrations in void spaces as approximate, indicating only the order of magnitude of the expected levels in real situations (e.g., low ppb, ppt).

We believe that valuable information can be distilled from the data we presented. First, optimal field analytical techniques can be selected on the basis of the physicochemical characteristics of markers and their approximate levels in confined spaces. These techniques can be further improved to provide an optimal response at the disaster site (targeted analysis). Moreover, species from the proposed set can be verified by lowering the value of those, which produce a signal too small to be reliably separated from the background.

To sum up, the set of potential markers of the human presence preselected within this review should be considered as an initial database of species to be verified during field studies. Within this context, a major focus lies on the investigations of interactions of volatiles of interest with building materials and other adsorbents in the disaster environment, such as clothing, dust, or soil. Further efforts will need to take into account disaster-related emission of species as well as different conditions such as, e.g., temperature and humidity affecting the surface chemistry. Thus, we expect that the VOC database proposed here will be further complemented and

verified. However, the success of chemical analysis toward the detection of humans will primarily depend on the availability of analytical technologies for the rapid, continuous, field detection of volatiles as signs of life. Although a number of techniques show a huge potential in this context, their applicability has to be verified in harsh, highly contaminated, and toxic disaster environments. In this sense, we recognize that data and considerations included in this review will guide future investigations in this exciting field.

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Appendix A: On decrease of exhaled VOC concentrations

We use the following notation: t time variable, x space coordinates, $C(t,x)$ concentration of a VOC, V volume, S surface of V, ∂V boundary of V, F flux, n normal vector.

For the following, compare Evans (Section 2.3) [197].

The change of mass in a volume V is given by the flux through the surface of V plus the net production in V. Thus the mass balance for a fixed volume V then reads

$$\frac{d}{dt}\int_V C(t,x)dV = -\int_{\partial V} F\cdot n dS + \int_V f(t,x)dV \tag{A.1}$$

where f is the production rate in V. Using Stokes' theorem (Gauss's divergence theorem) which states:

$$\int_{\partial V} F\cdot n dS = \int_V (\nabla\cdot F)dV \tag{A.2}$$

where $\nabla\cdot F = \operatorname{div} F$, and we arrive at:

$$\frac{d}{dt}\int_V C(t,x)dV = -\int_V (\nabla\cdot F)dV + \int_V f(t,x)dV. \tag{A.3}$$

By Fick's law the flux F is proportional (diffusion constant $a>0$) to the gradient of the concentration $\nabla C(t,x)$.

$$F = -a\nabla C(t,x). \tag{A.4}$$

We arrive at

$$C_t(t,x) = \nabla\cdot(a\nabla C(t,x)) + f(t,x). \tag{A.5}$$

Remark: up to this point the derivation is completely general. We make now the following assumptions:

Assumption 1: a is homogeneous and constant

Assumption 2: A human is modeled by a ball with radius R emitting a constant stream of a VOC (e.g., nmol/min) of the form

$$f(t,x) = f(x) = \frac{3\dot{J}}{4\pi R^3}\chi_{B_R(0)}(x), \tag{A.6}$$

where $\chi_{B_R(0)}$ denotes the characteristic function of a ball with radius R at $x=0$ and $\dot{J}$ the emitted stream. Here f is chosen such that there is constant production within the ball which totals to $\dot{J}$. Note that the specific form of f will not affect the concentration outside the ball as long as it is radially symmetric.

Then we have

$$C_t(t,x) = a\Delta C(t,x) + f(x). \tag{A.7}$$

Now we consider stationary solutions

$$0 = a\Delta C(t,x) + f(x). \tag{A.8}$$

A special solution C_s of the non-homogeneous Equation (A.8) is given by

$$C_s(x) = \frac{9\dot{J}}{4\pi R a}\begin{cases}\frac{1}{2}\left(1-\frac{|x|^2}{3R^2}\right), & |x|\le R,\\ \frac{1}{3}\frac{R}{|x|}, & |x|\ge R.\end{cases} \tag{A.9}$$

If we consider an initial concentration

$$C(0,x) = g(x) \tag{A.10}$$

the general solution of Equation (A.7) is then given by

$$C(t,x) = C_s(x) + (\Phi_t * \tilde{g})(x), \quad \tilde{g}(x) = g(x) - C_s(x), \tag{A.11}$$

where

$$\Phi_t(x) = \frac{1}{\left(4\pi\sqrt{at}\right)^{3/2}} e^{-\frac{|x|^2}{4\sqrt{at}}} \tag{A.12}$$

denotes the fundamental solution of the heat equation and * denotes convolution.

Note that the convergence to the equilibrium concentration can be estimated by

$$\|\Phi_t * \tilde{g}\|_\infty \le \frac{1}{\left(4\pi\sqrt{at}\right)^{3/2}}\|\tilde{g}\|_\infty \tag{A.13}$$

and in the special case $g\equiv 0$, that is $\tilde{g} = -C_s$, we have

$$\|\tilde{g}\|_\infty = \|C_s\|_\infty = \frac{3\dot{J}}{4\pi a R}. \tag{A.14}$$

Summary

The stationary solution reads

$$C_s(x) = \frac{3\dot{J}}{4\pi a}\frac{1}{|x|}, \quad |x|\ge R. \tag{A.15}$$

An example: $\dot{J} = 12\,\text{nmol/min}$, $a \approx 0.1\,\text{cm}^2/\text{sec} = 0.0006\,\text{m}^2/\text{min}$ yields

$$C_s(x) = 4775\left[nmol/m^2\right]\frac{1}{|x|}, \quad |x|\ge R. \tag{A.16}$$

At a distance of 10 m this yields 477.5 nmol/m^3 or 0.4775 nmol/l.

Remark 1: Inert debris will raise the concentration and can be taken into account at the first attempt by scaling the distance $|x|$ by a factor $\rho^{1/3}$, $0<\rho=(V_0-V_f)/V_0\le 1$, where V_0 is the volume in the absence of debris and V_f is the volume filled by debris.

$$C_s(x) = \frac{3\dot{J}}{4\pi a}\frac{1}{\rho^{1/3}}\frac{1}{|x|}, \quad |x|\ge R. \tag{A.17}$$

If we assume that the volume of debris is three times the volume of air then

$V_0 := V_{debris} + V_{air}, V_f := V_{debris} = 3V_{air}$.
This yields $\rho = 1/4$ and $1/\rho^{1/3} \approx 1.59$.

Remark 2: In our simple model, we assumed that diffusion is constant and homogenous that allowed for an analytical solution of the problem. Other geometries can be incorporated and computed numerically.

Remark 3: Initially, when a human is suddenly entrapped, the surrounding will show the background level of VOCs. As he/she emits VOCs, these VOCs will diffuse into his/her surroundings and, after a certain time, a constant distribution of VOCs will be established according to formula (A.17). The concentration of these VOCs is proportional to the stream $\dot{J}$ he/she emits and will decrease proportional to the inverse of the distance $|x|$ from him/her and is also inverse proportional to a where a is the diffusion constant.

If there are two or three persons close together within a ball of radius R, then one can simply multiply the stream $\dot{J}$ by a factor of 2 or 3.

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