View metadata, citation and similar papers at core.ac.uk

brought to you by CORE

provided by University of Liverpool Repository

Journal of Breath Research

ACCEPTED MANUSCRIPT

Advances in chemical sensing technologies for VOCs in breath for security/threat assessment, illicit drug detection, and human trafficking activity

To cite this article before publication: Stamatios Giannoukos *et al* 2017 *J. Breath Res.* in press https://doi.org/10.1088/1752-7163/aa95dd

Manuscript version: Accepted Manuscript

Accepted Manuscript is “the version of the article accepted for publication including all changes made as a result of the peer review process, and which may also include the addition to the article by IOP Publishing of a header, an article ID, a cover sheet and/or an ‘Accepted Manuscript’ watermark, but excluding any other editing, typesetting or other changes made by IOP Publishing and/or its licensors”

This Accepted Manuscript is **© 2017 IOP Publishing Ltd**.

During the embargo period (the 12 month period from the publication of the Version of Record of this article), the Accepted Manuscript is fully protected by copyright and cannot be reused or reposted elsewhere.
As the Version of Record of this article is going to be / has been published on a subscription basis, this Accepted Manuscript is available for reuse under a CC BY-NC-ND 3.0 licence after the 12 month embargo period.

After the embargo period, everyone is permitted to use copy and redistribute this article for non-commercial purposes only, provided that they adhere to all the terms of the licence https://creativecommons.org/licences/by-nc-nd/3.0

Although reasonable endeavours have been taken to obtain all necessary permissions from third parties to include their copyrighted content within this article, their full citation and copyright line may not be present in this Accepted Manuscript version. Before using any content from this article, please refer to the Version of Record on IOPscience once published for full citation and copyright details, as permissions will likely be required. All third party content is fully copyright protected, unless specifically stated otherwise in the figure caption in the Version of Record.

View the article online for updates and enhancements.

This content was downloaded from IP address 138.253.72.186 on 21/11/2017 at 16:13

Advances in chemical sensing technologies for VOCs in breath for security/threat assessment, illicit drug detection, and human trafficking activity

S. Giannoukos,[a] A. Agapiou,[b,] * S. Taylor[a, c,] *

[a] University of Liverpool, Department of Electrical Engineering and Electronics, Liverpool, L69 3GJ, UK

[b] University of Cyprus, Department of Chemistry, P.O. Box 20357, 1678 Nicosia, Cyprus

[c] Q Technologies Ltd, 100 Childwall Road, Liverpool, L15 6UX, UK

*Corresponding authors: e-mail: agapiou.agapios@ucy.ac.cy; S.Taylor@liv.ac.uk

Keywords: human chemical signatures, chemical sensing technologies, national security

ABSTRACT

On-site chemical sensing of compounds associated with security and terrorist attacks is of worldwide interest. Other related bio-monitoring topics include identification of individuals posing a threat from illicit drugs, explosive manufacturing, as well as searching for victims of human trafficking and collapsed buildings. The current status of field analytical technologies is directed towards the detection and identification of vapours and volatile organic compounds (VOCs). Some VOCs are associated with exhaled breath; where research is moving from individual breath testing (volatilome) to cell breath (microbiome) and most recently to crowd breath metabolites (exposome). In this paper, an overview of field deployable chemical screening technologies (both stand-alone and those with portable characteristics) is given with application to early detection and monitoring of human exposome in security operations. On-site systems employed in exhaled breath analysis i.e. mass spectrometry (MS), optical spectroscopy and chemical sensors are reviewed. Categories of VOCs of interest include: a) VOCs in human breath associated with exposure to threat

compounds, and b) VOCs characteristic of, and associated with, human body odour (e.g. breath, sweat). The latter are relevant to human trafficking scenarios. New technological approaches in miniaturised detection and screening systems are also presented (e.g. non-scanning digital light processing linear ion trap MS (DLP-LIT-MS), nanoparticles, mid-infrared photo-acoustic spectroscopy and hyphenated technologies). Finally, the outlook for rapid and precise, real-time field detection of threat traces in exhaled breath is revealed and discussed.

Introduction

The world community is witnessing a complex, multilevel and rapidly evolving international security crisis. This involves terrorist activities using chemical means (chemical weapons, biological threats, etc.), bombing attacks, illicit drug transportation and illegal human trafficking. On-site and real-time sensing (detection and monitoring) of chemical analytes indicating human presence in confined spaces or identifying suspect human motives (e.g. people under stress) during security and forensic operations is an emerging area of high scientific, political and public interest. On-site drug-testing is also a significant challenge. Human exposome consists of characteristic chemical markers of the human body odour (breath and skin), which can be applied for non-invasive extraction of molecular information for medical diagnostics, psychological, criminal, law enforcement and other applications [1]. The complexity and richness of human volatilome (components from exhaled breath, skin emanations, urine, saliva, human breast milk, blood and feces) has been reviewed [2, 3].

This article outlines: a) the chemistry of human body odour with the principal focus being human detection and tracking in security applications, b) the breath detectable illegal activities associated with exposures to threat compounds (e.g. drug-testing) and provides c) an overview of the current technological status of field deployable systems focusing on human exposome and breath screening capabilities.

Human odour screening in national security scenarios

National security authorities (i.e. the Department of Homeland security, the U.S. Immigration and Customs Enforcement, the U.K. Border Force and the E.U. border control security services such as the FRONTEX, border police, coast guards and civil defence) target the timely and precise detection and identification of hidden people travelling illegally or passengers who have the intention to perform malicious actions or carrying hazardous and/or illegal substances. People under the light or heavy influence of narcotics are also under the eye of the law enforcement personnel. Human body chemistry and specifically human body odour may reveal such activities.

The principle responsibilities of the border control agencies are a) to perform custom controls for people and goods entering a country with physical and technological means, b) to rapidly identify possible threats and c) to ensure national safety and wellbeing. In this content, they develop risk analysis plans for designated stand-alone or joint actions for migrants or refugees' detection, train staff members and border guard teams to work effectively, invest in the development and use of innovative technologies, develop best practices for migrants return operations and share information via online platforms and workshops.

The composition of human body odour is the combination of VOCs originating from both the exhaled breath and secreted sweat from the human skin. Human breathing is a dynamic process, which entails a continuous exchange of both inorganic gasses and VOCs with the ambient environment (e.g. household or workplace environment). The composition of human exhaled VOCs depends on endogenous sources (e.g. biological processes, oxidative stress or inflammation) and exogenous factors such as environmental exposures. The main compounds found in the exhaled breath (872 VOCs) of healthy humans have been recently revised [3].

Human sweat is produced by the three types of skin glands (eccrine, sebaceous and apocrine). These are unevenly distributed and/or sometimes overlapping in various regions of the human body with different microbiota composition. The primary form of human sweat is an odourless liquid, with different formation depending on the type of the secreting gland. Eccrine glands secrete mainly water with traces of proteins, ammonia, urea and lactic acid. Sebaceous glands produce sebum consisting of lipids and apocrine glands produce lipids and proteins. These are transformed into an odorous matrix due to bacterial metabolic processes on the surface of the human body [1-4]. Volatile emissions identified in human skin can be classified according to their body source and include compounds such as alkenes, alcohols and phenols, aldehydes, esters, short and long chain carboxylic acids, aromatic compounds, ketones and steroids [1]. Most of the volatile chemical moieties found in human body odour in normal conditions (excluding VOCs for medical diagnostics) are easily revealed through numerous studies with the existing technologies available in the market. However, the overall chemical profile of human presence in enclosed areas with complicated chemical background chemistries has not been extensively studied [1-7] and thus further investigation is needed. Such studies should relate to all possible environmental exposures and complex situational factors and how they interact with and influence the human chemical profile.

On-site chemical detection of human body VOCs in security checkpoints such as airports, land ports, sea ports, cargo services, etc. is challenging compared to the traditional laboratory analysis due to the trace levels of such compounds and the continuously dynamic complex background environment. Another important issue, is the ethical protocol needed for such studies, limiting the time and activities of researchers. Characteristic research on the chemical signs of human life in confined spaces was conducted within simulation environments during the trapped human experiment (THE) [8, 9] with bench top and portable molecular sensing instrumentation (thermal desorption-gas chromatography-mass spectrometry (TD-GC-MS), GC-differential mobility spectrometry (GC-DMS) and multi-capillary column-ion mobility spectrometry (MCC-IMS)) at the University of Loughborough and during the human detection experiments [6, 7] in a container simulator using portable membrane inlet mass spectrometry (MIMS) at the University of Liverpool. The front-end applications of the above projects were different (search and rescue for the first and homeland security for the second). Both experiments targeted the generation of the chemical profile of live humans in defined spaces over a period of 6 hours, the study of human body odour under various conditions and alongside background events. Experimental observations showed that CO_2, NH_3, and VOCs such acetone, isoprene and volatile fatty acids (e.g. butyric acid, propanoic acid, lactic acid) could be possible indication markers of human presence in confined spaces. Experimental data showed that the relative intensities and the ratios of such compounds to each other is of importance. In a similar confined space, twelve skin VOCs were detected using an on-line selective reagent ionization time-of-flight mass spectrometry with NO^+ system (SRI-TOF-MS (NO^+) [10]. Table 1 presents human body VOCs detected in various confined space scenarios. This evidence shows the uniqueness of human body odour, and allows differentiation between the chemical profiles of different genders, in the determination of people with deceptive behaviours via their body odour. This latter features highlight a possible application for the integration of molecular sensors (either handheld or stand-off) with human exposome screening capabilities in border security checkpoints and customs [11].

Table 1: Volatiles detected in confined spaces under different entrapment scenarios

Volatiles	Instrument	Confined space	Reference
acetone, isoprene, ammonia	MCC-IMS, GC-DMS	In-house made entrapment simulator: (a) environmental chamber (gas-tight glass-lined tank with an internal volume of approximately 500 dm^3 (2010 mm × 510 mm × 505 mm), (b) void simulator (2 m long, 72 cm wide and 51 cm high) and (c) collapsed building simulator (glass column 1.5 m long, 15 cm ID fitted with layers of construction materials)	[8]
2-ethyl-1-hexanol, acetone, acetophenone, ammonia, benzaldehyde, benzene, 1-methylethyl, decanal, hexanal limonene, octanal, nonanal	MCC-IMS and TD-GC-MS		[9]
propanal, hexanal, heptanal, octanal, nonanal, 2-methyl 2-propenal, acetone, 2-butanone, 3-buten-2-one, 6-methyl-5-hepten-2-one, 2-methyl 2-pentene, dl-limonene	SRI-TOF-MS-NO^+	A body plethysmography chamber, BodyScope (Ganshorn Medicin Electronic GmbH, Germany), with interior dimensions of 82 × 63 × 161 cm	[10]
acetone, acrolein, 2-methylpropanal, ethyl formate, 2-methyl-1-propanol, 3-methylbutanal, 2-ethacrolein, ethyl propionate, acetic acid, 2-pentanone, 4-methyl-2-pentanone, vinyl butyrate, n-hexanal, butyl acetate, ethyl isovalerate, n-heptanal, benzaldehyde	MCC-IMS		[12]
methanol, acetaldehyde, hexane, lactic acid, nonanal, isoprene, acetone, limonene, phenol, pentane, heptane, 1-pentene, hexanal, isopropanol, 2-nonenal, ethanol, propanoic acid	Membrane Inlet Mass Spectrometry (MIMS)	Container simulator using eight different experimental setups (3.37 m × 5.00 m × 2.50 m)	[6]

Illegal human trafficking has been observed in shipping containers, maritime cargos, trucks, coffins or boxes. People being trafficked often lack of personal hygiene due to few or many days without showering, and urination or defecation residues onto clothes. In addition, the victims often have limited opportunity for food consumption, and experience increased levels of fear, stress and hardship. The above factors affect the chemical composition of the human body odour, either by introducing VOCs from biological secretions or by altering the intensities and/or proportions of endogenous VOCs (as specific metabolic pathways are triggered). For example, the concentration of breath acetone is highly increased after fasting [13]. However, research on a common core of chemical substances characteristic of human body odour could be utilised for the field detection and localisation of the emitting source [6, 14].

Breath detectable illegal activities

Increased use of psychotropic narcotics (e.g. marijuana, cocaine) can cause abnormal and dangerous behaviours in public places. A characteristic recent example is the cocaine intake of three men in the plane toilets during an Easyjet flight (June 2017) [15]. Conventional drug testing techniques utilize blood, saliva or urine testing in the laboratory. However, many drugs of abuse can be metabolised quickly from the human body, making their detection difficult or even sometimes impossible. Hand-held breathalysers allow the instantaneous detection of drugs of abuse in the exhaled human breath of a suspect *in-situ* [16]. Recently, Cannabix Technologies Inc. and the Yost Group (University of Florida) worked together and developed a lightweight handheld device (similar to the alcohol breathalysers) based on field asymmetric ion mobility spectrometry (FAIMS) for the detection of (-)-trans-Δ9-tetrahydrocannabinol (THC) in human breath [16, 17]. Hound labs Inc. have also developed a miniature portable breath THC detection device with a patent-pending approach with low detection limits (below 500 pg) [18].

Laboratory-based breath testing using bench top instrumentation such as liquid chromatography tandem mass spectrometry (LC-MS-MS) equipped with positive electrospray ionisation and selected reaction monitoring and gas chromatography (GC) coupled with MS have shown the capability of multiple detection of drugs of abuse in exhaled breath [19-21]. The outcomes are encouraging, allowing testing of such compounds in exhaled breath using portable miniaturised MS systems with both in vacuo and ambient environment ionisation techniques and further commercial exploitation. Compared to the demanding requirements of laboratory analysis (e.g. specialised personnel, sample preparation, time and cost consuming), in-field breath testing could be a fast and valid analytical methodology for law enforcement that will provide accurate, confident and efficient scientific evidence of acquittal or guilt at the point-of-analysis.

Field deployable chemical sensing technologies and instrumentation

Traditionally, canines are considered to be the gold-standard for threat and hidden human detection. However, due to the requirements for extensive training and their maintenance costs, limited working lifetime and other shortcomings, there is a need for development and deployment of portable artificial sniffers, with advanced chemical sensing characteristics including high sensitivity and specificity and ease of use. Machine olfaction mimics natural olfactory processes to enable the deep sensory comprehension of the nature and consistency of the threat and threat related compounds. The information obtained is required during decision making at the point-of-analysis (e.g. scene of arrest) [22].

Existing analytical approaches [1] for the qualitative detection and quantitative determination of VOCs in human body odour in the laboratory, employ mainly GC-MS [5], GC coupled to ion mobility spectrometry (IMS), multi-capillary columns (MCC)-IMS [23], GC connected to flame ionisation detection (FID), thermal desorption (TD)-GC-MS, proton transfer reaction mass spectrometry (PTR-MS) [24], selected ion flow tube mass spectrometry (SIFT-MS) [25-28], laser spectroscopy [29] and electronic noses [30]. GC-MS techniques have powerful detection and quantification capabilities due to the 3D acquired data (retention time, intensity, *m/z* ratio), assisted by very well developed and integrated spectral libraries of millions of chemical compounds. Other mass spectrometric techniques, such as PTR-MS, SIFT-MS and IMS, although offering near-real time monitoring of analytes of interest, they lack spectral libraries. Flame-aerosol synthesis enabled the development of nanostructured metal-oxide sensors Si:WO_3, Ti:ZnO and Si:MoO_3 for the selective identification of breath acetone [31], isoprene [32] and ammonia [33] in the low ppbv levels, respectively. Demands for real time measurements of VOCs of interest and threats in a systematic way, have led to the development and system integration of either handheld or remotely controlled devices equipped with smart molecular sensorial or sampling approaches.

In the last 5 years, the European Union has funded several large security projects (e.g. SNIFFLES, SNOOPY, DOGGIES) [34-36] to investigate the operational challenges of human body VOCs detection in urban areas and border checkpoints in order to offer reliable and user-friendly portable technological solutions based on gas sensing. Characteristically, during the SNIFFLES project [34], a portable MS sensor based on a novel non-scanning linear ion trap (LIT) technology was designed and developed for hidden human and threat compound screening and detection [38, 39]. The prototype unit was fabricated using digital light processing (DLP), which is a low-cost rapid manufacturing technique for realisation of complex 3D structures. Compared to other rapid prototyping techniques, such as selective laser ablation (SLA), DLP offers exceptional nanoscale surface smoothness which is essential for accurate and reliable mass analysis required in the development of commercial systems. The non-scanning mode allows the selective and rapid detection and/or monitoring of mass fragments of interest with optimal RF and DC voltages on the LIT electrodes for each ion mass, speeding up chemical analysis in the field. Experiments with threat simulants showed encouraging results. The SNOOPY [35] and DOGGIES [36] project were running in parallel with the same aim. The SNOOPY prototype sniffer was based on chemi-resistor and microbalance gas sensors, coated with layers of either porphyrins or corroles, targeting the detection of hidden humans in vehicles and cargos. The above sensors were developed using novel materials based on nanoparticles, nanowires and metallo-porphyrines/-corroles and the prototype e-nose was evaluated in trials with human participants. The DOGGIES project developed a novel orthogonal gas sensing approach consisting of mid-infrared photo-acoustic spectroscopy (MIR-PAS) and GC-IMS for olfactory traces detection. For gas sampling, a fast pre-concentrator (few seconds) was deployed and the data obtained created a database of characteristic chemical signatures of VOCs found in human scent (mainly volatile short-chain fatty acids such as the (E)-3-Methylhex-2-enoic acid and in the headspace area above illicit drugs and explosives. Remarkably, human detection (after 15 minutes of human presence) in a confined area of 50m^3 was demonstrated [37]. These results are promising, considering that illegal immigrant concealment cases take place in much smaller spaces and for longer times, allowing significant built-up of concentrations of characteristic markers of human presence.

Machine olfaction intends to complement sniffer dogs' work for detection of hidden persons and illicit compounds on-site. Artificial sniffers do not target the replacement of canines, but aim at a thorough comprehension and reproduction of the sniffing process with appropriate analogies and metaphors. For example, a 16-fold improvement was demonstrated on a commercial trace vapor detector when biomimetic sniffing was applied [40]. Compared to detection dogs, electronic noses offer both qualitative and quantitative information of a potential threat component, however in contrast to canines, they lack fast response times and the ability to locate the emitting source. In contrast to machine olfaction, detection dogs may give unreliable behaviour due to distractions, loss of attention and/or boredom. This requires sufficient pausing of their operation for a 'rest break' or for retraining purposes. The olfactory capabilities of sniffer dogs' are debated in the literature [1, 41] as an alternative to sensorial approaches.

More recently, Q-Technologies Ltd. (United Kingdom) [42] has developed the VapourSense-500, a robust, portable dual filter quadrupole MS system with two sample introduction techniques (a membrane inlet and a short-length heated capillary column) and mass range up to 500 amu, allowing direct detection and online monitoring of VOCs from humans in security operations. A signal processing algorithm developed in the University of Liverpool, UK may also be implemented with the above system to extract ultra low-intensities peaks of interest from the noise level. This is important for field applications, where usually analytes of interest have concentration levels in very low levels.

Future perspectives

Investigation plans for hidden human detection in the field using artificial sniffing integrate a multilevel operational approach (from a science and technology perspective to everyday policy making). Molecular sensing systems are required to provide answers regarding human presence in confined spaces in real-time, both for localisation and identification purposes and also to supplement canines use. Prediction alarm tools (with 24-7 service capabilities) for humans with possible malicious intent based on human exposome or breath testing need to be developed and implemented at all possible security checkpoints (e.g. in lorries, shipping containers, airports, subways/train stations, stadiums or shopping malls, etc.) to assist in the safe transportation of passengers and goods [43, 44].

Portable MS and IMS analysis can provide spatio-temporal information regarding the tracking history of a suspect through monitoring of bio- or odour-print residues. Hand-held or stand-off distance analytical tools with real time accurate gas sniffing and trace detection capabilities can accommodate the creation of human exposome storage databases and the use of breath and skin VOCs as biometric identifiers alongside fingerprint, face recognition and retinal scans. The development of complete personalised human exposome databases could ensure the continuous tracking of illegal activities. Current analytical means and technological expertise has the potential to explain the chemical complexity of threatening challenges-scenarios.

In this regard, the continued evolution of field chemical analysis (FCA) to mitigate the escalating chemical threats is an urgent necessity. FCA is a vital and integrated part of emergency preparedness and planning, early warning and control to mitigate and manage threats and attacks. Integration of miniaturised analytical apparatuses with unmanned ground vehicle (UGV) and unmanned aerial vehicle (UAV) technologies have clear potential for rapid (i) detection, (ii) localisation and (iii) monitoring of threatening actions while guaranteeing maximum flexibility. Integration of FCA with olfactory or data communication networks for the transmission of encrypted information on human exposome or exhaled breath in distant areas could enhance national security diagnostics through better identification of individuals. A characteristic application could be the usage of human breath as an advanced level molecular security key.

Combining odour data with visual and/or other data for transmission over the internet and re-creation elsewhere, allows odour teleportation to locations elsewhere. The key aspects here are the abilities to identify and to re-create a given odour. The former may be accomplished using a mass spectrometer and the latter by use of an odour generation device [45, 46]. These latest developments illustrate the future of exhaled breath analysis: handheld point-of-use or wearable devices [47] for applications outside the laboratory, such as personal or crowd medical, identification and security applications.

Acknowledgements

The research leading to these results has received funding from the Engineering and Physical Sciences Research Council (EPSRC) under grant agreement: EP/M029425/1 ‘Creating a Stink - Investigating Olfactory Transport Streams’. The authors acknowledge useful discussions with Prof R. G. Cooks (Purdue University)

References

[1] Giannoukos S, Brkić B, Taylor S, Marshall A and Verbeck G F 2016 Chemical sniffing instrumentation for security applications *Chem. Reviews* **116** 8146-8172

[2] Smallegange R C, Verhulst N O and Takken W 2011 Sweaty skin: an invitation to bite? *Trends Parasitol.* **27** 143–148

[3] Costello B de Lacy, Amann A, Al-Kateb H, Flynn C, Filipiak W, Khalid T, Osborne D and Ratcliffe N M 2014 A review of the volatiles from the healthy human body *J. Breath Res.* **8** 1-30

[4] Jacoby R B, Brahms J C, Ansari S A and Mattai J 2004 Detection and quantification of apocrine secreted odor-binding protein on intact human axillary skin *Int. J. Cosmetic Sci.* **26** 37–46

[5] Curran A M, Rabin S I and Furton K G 2005 Analysis of the uniqueness and persistence of human scent *Forensic Sci. Commun.* **7** 1607–1619

[6] Giannoukos S, Brkić B, Taylor S and France N 2014 Monitoring of human chemical signatures using membrane inlet mass spectrometry *Anal. Chem.* **86** 1106−1114

[7] Giannoukos S, Brkić B, Taylor S and France N 2015 Membrane inlet mass spectrometry for homeland security and forensic applications *J. Am. Soc. Mass Spectrom.* **26** 231-239

[8] Huo R, Agapiou A, Bocos-Bintintan V, Brown L J, Burns C, Creaser C S, Devenport N A, Gao-Lau B, Guallar-Hoyas C, Hildebrand L, Malkar A, Martin H J, Moll V H, Patel P, Ratiu A, Reynolds J C, Sielemann S, Slodzynski R, Statheropoulos M, Turner M A, Vautz W, Wright V E and Thomas C L P 2011 The trapped human experiment *J. Breath Res.* **5** 1–12

[9] Vautz W, Slodzynski R, Hariharan C, Seifert L, Nolte J, Fobbe R, Sielemann S, Lao B C, Huo R, Thomas C L P and Hildebrand L 2013 Detection of Metabolites of Trapped Humans Using Ion Mobility Spectrometry Coupled with Gas Chromatography *Anal. Chem.* ***85*** 2135-2142

[10] Mochalski P, Unterkofler K, Hinterhuber H, and Amann A 2014 Monitoring of Selected Skin-Borne Volatile Markers of Entrapped Humans by Selective Reagent Ionization Time of Flight Mass Spectrometry in NO^+ Mode *Anal. Chem.* **86,** 3915-3923

[11] Furton K G, Caraballo N I, Cerreta M M and Holness H K 2015 Advances in the use of odour as forensic evidence through optimizing and standardizing instruments and canines *Plil. Trans. B* **370** 20140262

[12] Mochalski P, Wiesenhofer H, Allers M, Zimmermann S, Guntner A T, Pineau N J, Agapiou A, Mayhew C A, Ruzsanyi V Monitoring selected skin- and breath-borne volatile organic compounds emitted from the human body using gas chromatography ion mobility spectrometry (GC-IMS), submitted 2107.

[13] Statheropoulos M, Agapiou A and Georgiadou A 2006 Analysis of expired air of fasting monks at Mouth Athos *J Chromat. B* **832** 274-279

[14] Wongchoosuk C, Lutz M and Kerdcharoen T 2009 Detection and Classification of Human Body Odor Using an Electronic Nose *Sensors* **9** 7234-7249

[15] http://www.mirror.co.uk/news/uk-news/easyjet-flight-tenerife-stormed-cops-10647543

[16] Costanzo M T, Boock J J, Kemperman R H J, Wei M S, Beekman C R and Yost R A 2016 Portable FAIMS: Applications and future perspectives *Int. J. Mass Spectrom.* https://doi.org/10.1016/j.ijms.2016.12.007

[17] Cannabix Technologies Inc., BC, USA, http://www.cannabixtechnologies.com/

[18] Hound labs Inc., CA, USA, http://houndlabs.com/

[19] Beck O, Sandqvist S, Dubbelboer I and Franck J 2011 Detection of Δ^9-Tetrahydrocannabinol in Exhaled Breath Collected from Cannabis Users *J. Anal. Toxicol.* **35** 541-544

[20] Pleil J D, Risby T and Herbig J 2016 Breath biomonitoring in national security assessment, forensic THC testing, biomedical technology and quality assurance applications: report from PittCon 2016 *J. Breath Res.* **10** 1-3

[21] Beck O, Stephanson N, Sandqvist S and Franck J 2013 Detection of drugs of abuse in exhaled breath using a device for rapid collection: comparison with plasma, urine and self-reporting in 47 drug users *J. Breath Res.* **7** 026006

[22] Li S 2014 Recent Developments in Human Odor Detection Technologies *J. Forensic Sci Criminol* **1** doi: 10.15744/2348-9804.1.S104

[23] Armenta S, Alcala M and Blanco M 2011 A review of recent, unconventional applications of ion mobility spectrometry (IMS) *Anal. Chim. Acta* **703** 114–123

[24] Amann A, Poupart G, Tesler S, Ledochowski M, Schmid A and Mechtcheriacov S 2004 Applications of breath gas analysis in medicine *Int. J. Mass Spectrom.* **239** 227–233

[25] Turner C, Spanel P and Smith D 2006 A longitudinal study of ammonia, acetone, and propanol in the exhaled breath of 30 subjects using selected ion flow tube mass spectrometry, SIFT-MS *Physiol. Meas.* **27** 321–337

[26] Turner C, Spanel P and Smith D 2006 A longitudinal study of breath isoprene in healthy volunteers using selected ion flow tube mass spectrometry (SIFT-MS) *Physiol. Meas.* **27** 13–22

[27] Turner C, Spanel P and Smith D 2006 A longitudinal study of ethanol and acetaldehyde in the exhaled breath of healthy volunteers using selected ion flow-tube mass spectrometry *Rapid Commun.Mass Spectrom.* **20** 61– 68

[28] Turner C, Spanel P and Smith D 2006 A longitudinal study of methanol in the exhaled breath of 30 healthy volunteers using selected ion flow tube mass spectrometry, SIFT-MS *Physiol. Meas.* **27** 637–648

[29] Wang C and Sahay P 2009 Breath analysis using laser spectroscopic techniques: breath biomarkers, spectral fingerprints, and detection limits *Sensors* **9** 8230–8262

[30] Natale C D, Macagnano A, Paolesse R, Tarizzo E, Mantini A and Amico A D 2000 Human skin odor analysis by means of an electronic nose *Sensor. Actuat. B-Chem.* **65** 216–219

[31] Righettoni M, Tricoli A, Gass S, Schmid A, Amann A, Pratsinis S E 2012 Breath acetone monitoring by portable Si:WO3 gas sensors *Anal. Chim. Acta* **738** 69-75

[32] Güntner A T, Pineau N J, Chie D, Krumeich F, Pratsinis S E 2016 Selective sensing of isoprene by Ti-doped ZnO for breath diagnostics *J. Mater. Chem. B* **4** 5358-5366

[33] Güntner A T, Righettoni M, Pratsinis S E 2016 Selective sensing of NH3 by Si-doped α-MoO_3 for breath analysis *Sens. Actuators B* **223** 266-273

[34] SNIFFLES, http://www.sniffles.eu/

[35] SNOOPY, http://www.snoopy-project.eu/

[36] DOGGIES, http://cordis.europa.eu/project/rcn/103810_en.html

[37] Daniilidis I, Filippi J -J, Vautz W, Dalcanale E, Zampolli S, Leventakis G, Kauppinen I, Sinisalo S, Tsoulkas V, Kassouras V, Carras M, Gerard B, Pinalli R, Ragnoni A, Dujourdy L, Zavali D, Brun M, Grizis V, Argyris A and Syvridis D 2014 Detection of Olfactory Traces by Orthogonal Gas Identification Technologies – DOGGIES *IEEE Joint Intel. Secur. Informat. Conf.* DOI 10.1109/JISIC.2014.76

[38] Brkić B, Giannoukos S, France N, Murcott R, Siviero F and Taylor S 2014 Optimized DLP linear ion trap for a portable non-scanning mass spectrometer *Int. J. Mass Spectrom.* **369** 30-35

[39] Brkić B, Giannoukos S, France N, Janulyte A, Zerega Y and Taylor S 2013 Modeling of an ion source lens system for sensitivity enhancement in a non-scanning linear ion trap *Int. J. Mass Spectrom.* **353** 36-41

[40] Staymates M E, MacCrehan W A, Staymates J L, Kunz R R, Mendum T, Ong Ta-H, Geurtsen G, Gillen G J, Craven B A 2016 Biomimetic sniffing improves the detection performance of a 3D printed nose of a dog and a commercial trace vapour detector *Scientific Reports* **6** Article number: 36876

[41] Hackner K, Pleil J D 2017 Canine olfaction as an alternative to analytical instruments for disease diagnosis: understanding 'dog personality' to achieve reproducible results *J. of Breath Res.* 11 1–5

[42] Q-Technologies Ltd., Liverpool, UK, http://q-technologies.co.uk/.

[43] Williams J, Pleil J D 2016 Crowd-based breath analysis: assessing behaviour, activity, exposures, and emotional response of people in groups *J. Breath Res.* **10** 1-5

[44] Bean H D, Pleil J D and Hill J E 2015 Editorial: new analytical and statistical approaches for interpreting the relationships among environmental stressors and biomarkers *Biomarkers* **20** 1–4

[45] Statheropoulos M, Pallis G, Mikedi K, Giannoukos S, Agapiou A, Pappa A, Cole A, Vautz W and Thomas C L P 2014 A dynamic vapor generator that simulates transient odor emissions of victims entrapped in the voids of collapsed buildings *Anal. Chem.* **86** 3887–3894

[46] Giannoukos S, Marshall A, Taylor S and Smith J 2017 Molecular communication over gas stream channels using portable mass spectrometry *J. Am. Soc. Mass Spectrom.* DOI: 10.1007/s13361-017-1752-6

[47] Guay P, Gorgutsa S, LaRochelle S and Messaddeq Y 2017 Wearable Contactless Respiration Sensor Based on Multi-Material Fibers Integrated into Textile *Sensors* **17** 1-13