International Journal of Mass Spectrometry 278 (2008) 15–19

Contents lists available at ScienceDirect

International Journal of Mass Spectrometry

journal homepage: www.elsevier.com/locate/ijms

Aldehyde and ketone discrimination and quantification using two-stage proton transfer reaction mass spectrometry

Robert S. Blake[a], Milan Patel[a], Paul S. Monks[a], Andrew M. Ellis[a,*], Satoshi Inomata[b], Hiroshi Tanimoto[b]

[a] Department of Chemistry, University of Leicester, University Road, Leicester LE1 7RH, UK
[b] Atmospheric Environment Division, National Institute for Environmental Studies, 16-2 Onogawa, Tsukuba 305-8506, Ibaraki, Japan

ARTICLE INFO

Article history:
Received 5 June 2008
Received in revised form 3 July 2008
Accepted 8 July 2008
Available online 25 July 2008

Keywords:
Proton transfer
Volatile organic compounds

ABSTRACT

A two-stage proton transfer reaction mass spectrometry (PTR-MS) technique has been demonstrated recently in which the normal proton transfer reagent, H_3O^+, is mixed with a chosen volatile organic compound, designated VOC_1, upstream of an analyte gas flow. This process can be used to make protonated VOC_1, which in turn can react with volatile organic compounds (VOCs) (designated collectively as VOC_2) in an analyte gas stream. Here we show that this approach can be adapted to discriminate between isobaric aldehydes and ketones, which are notoriously difficult to distinguish using conventional PTR-MS with H_3O^+ as the reagent ion. The approach is shown to yield accurate quantification of the individual components in isobaric aldehyde/ketone pairs. Variation of the compound used as VOC_1 also provides a simple and quick means of 'bracketing' the proton affinity of a particular organic species and we demonstrate this methodology for hexanal, whose proton affinity has not previously been reported. The proton affinity of hexanal is found to lie within the range $794.4\,kJ\,mol^{-1} < PA(hexanal) < 797.0\,kJ\,mol^{-1}$.

1. Introduction

Proton transfer reaction mass spectrometry (PTR-MS) is now an established technique for detecting a wide range of volatile organic compounds (VOCs) in the gas phase. The strengths and weaknesses of the technique are well known and documented [1–4]. Strengths include high detection sensitivity (down to approx. 10 pptV) coupled with the ability to determine the concentrations of individual trace compounds in minutes or even seconds. However, one of the main weaknesses of PTR-MS is its reliance solely on mass spectrometry for discriminating between molecules, which frequently means that isobaric species cannot be distinguished. This is in sharp contrast to gas chromatography–mass spectrometry (GC–MS), where the chromatographic separation step prior to mass spectrometry allows almost complete resolution of individual VOCs, albeit with a concomitant and profound loss of speed of measurement.

Solutions to the isobaric problem in PTR-MS have been proposed. One possibility is to employ an ion trap as the mass spectral device, which makes it possible to use energy-controlled collision-induced dissociation to selectively discriminate between isobaric species [5–8]. However, this approach requires careful data analysis and the fact that most current PTR-MS instruments do not employ ion traps makes it of limited appeal. An alternative approach has been demonstrated by Wyche and co-workers in which alternative chemical ionization (CI) reagents, including NH_4^+ and NO^+, were employed [9,10]. Many isobaric pairs, such as aldehydes and ketones, demonstrate quite different ion products with different CI reagents, which can potentially allow discrimination. However, this approach tends to rely on differences in ion fragmentation patterns, which is not the best solution when working with complex mixtures of VOCs.

Recently, Inomata and Tanimoto have demonstrated a two-stage ion source for PTR-MS which makes it simple to use protonated VOCs as proton sources instead of H_3O^+ [11]. The technique works by introducing an excess of the chosen VOC, referred to as VOC_1, into the drift tube upstream of the analyte gas inlet. Proton transfer from H_3O^+ to VOC_1 creates a new proton transfer source with different characteristics. In particular, by using protonated VOCs as the proton source, there is the option of choosing a compound for VOC_1 with a proton affinity that discriminates between two isobaric species, providing that they possess substantially different proton affinities. This approach was demonstrated by Inomata and Tanimoto using ethyl acetate and 1,4-dioxane as the test species

---

* Corresponding author. Tel.: +44 116 252 2138; fax: +44 116 252 3789.
E-mail address: andrew.ellis@le.ac.uk (A.M. Ellis).

1387-3806/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.ijms.2008.07.010

[11]. Both of these molecules are protonated by H_3O^+, but switching to protonated acetone removed all signal from to ethyl acetate, leaving only contributions from 1,4-dioxane.

Inomata and Tanimoto also suggested that their two-stage source might provide effective discrimination between isomeric aldehydes and ketones. Aldehydes and ketones have a number of sources, both biogenic and anthropogenic, and it is sometimes important to be able to distinguish between isobaric pairs. For example, butanal has mainly biogenic sources [12,13], whereas butanone in the atmosphere derives mainly from man-made sources, such as vehicle emissions [14]. Methacrolein and methyl vinyl ketone represent another pair of isomers, both of which are known oxidation products of isoprene in the atmosphere [15,16]. Consequently, the demonstration of a simple, quick and effective means of distinguishing between isomeric aldehyde/ketone pairs will strengthen the utility of PTR-MS in atmospheric VOC monitoring.

In this paper we explore the use of the two-stage ion source for discriminating between isomeric aldehydes and ketones. Several aldehyde/ketone pairs have been investigated, including butanal/butanone and methacrolein/methyl vinyl ketone. We show that the two-stage source provides an effective means of separating the respective contributions of these isomers in a given mixture by a means which is straightforward and rapid to implement. We have also applied this approach to the hexanal/2-hexanone/3-hexanone triumvirate. In addition to separating aldehyde from ketone signals, we show that the two-stage source methodology is suitable for estimating unknown proton affinities by a bracketing procedure. Here we use this to report the first experimental determination of the proton affinity of hexanal.

2. Experimental

Experiments were performed at two locations and with two distinct instruments. Initial work was carried out at NIES in Tsukuba using a PTR-MS instrument with a time-of-flight (TOF) mass analyzer that has been described previously in the literature [17]. The two-stage ion source has also recently been described [11] and so only brief details will be given here. Ion production starts with a discharge source, which generates H_3O^+ (hydronium). The hydronium ions enter a drift tube and meet the incoming flow of VOC_1, efficiently transferring charge from H_3O^+ to VOC_1 to produce VOC_1H^+ in the upstream part of the drift tube. The analyte gases (whose VOC components are referred to collectively as VOC_2) are added through a second entrance port further downstream where they encounter the flowing protonated VOC_1 ions. After flowing several further centimeters the gas stream is sampled through a pinhole aperture and enters the source region of a home-made linear time-of-flight mass spectrometer.

Later experimental work was carried out in Leicester using another PTR-TOF-MS instrument. This particular instrument was on loan from the University of York and has also been described previously in the literature [18]. As with the Tsukuba instrument, an electrical discharge ion source is combined with a time-of-flight mass spectrometer (TOF-MS). However, the York instrument has a reflectron TOF-MS, which offers a higher mass resolution than the Tsukuba instrument. The significant point about the experiments carried out at Leicester was that further investigation was carried out to find the best location for adding VOC_1. One area considered was addition of VOC_1 to the source drift region of the ion source, rather than in the upstream part of the drift tube. This was shown to yield highly effective protonation of VOCs in the analyte stream but there was an increased tendency for fragmentation of protonated VOC_1, as might be expected given the proximity to the highly energetic discharge region. An alternative choice was also explored, addition of excess VOC_1 in the analyte inlet tube. This was the preferred operating configuration and benefits from the fact that no modification to the drift tube is required [11]. Whichever configuration was employed, the ability to discriminate between isomeric aldehydes and ketones did not differ in any substantive way and so no distinction is made here between the Tsukuba and Leicester findings when reporting the results of this work.

Typical drift tube conditions in both the Leicester and Tsukuba experiments were as follows: pressure 1.5 mbar, E/N ratio = 100, and temperature 23 °C.

Analyte gases were delivered to the instruments *via* simple headspace extraction of the vapor above the chosen pure compound. For experiments where both VOC_1 and VOC_2 were delivered through the same inlet, mixtures of the two gases were prepared in Tedlar bags, with VOC_1 in at least a 20-fold excess over VOC_2. Samples were produced by introducing microlitre quantities of the VOC material into 10 l Tedlar bags, which were then inflated to atmospheric pressure with N6.0 nitrogen (99.9999% pure). The initial mixtures were too concentrated (typically 200 ppmV) so a further (1000-fold) dilution was carried out by extracting 10 ml of the mixture with a gas syringe and introducing it into an empty 10 l Tedlar bag.

The ability to provide quantitative information on individual isomers in a two-compound mixture was explored *via* dynamic dilution. In these experiments a twin-oven diluter (Kintek 491 M) was employed with appropriate permeation tubes for gas calibration.

3. Results and discussion

The proton affinity of water is 691 kJ mol^{-1} [19]. A wide variety of organic compounds possess higher proton affinities than water, and so all are possible candidates for VOC_1. However, in practice more exacting criteria need to be applied to find a suitable VOC_1. In addition to an acceptable proton affinity, the chosen compound should be readily available, sufficiently volatile, and should produce little or no fragmentation when accepting a proton.

Crucial to the success of the current experiments is the significant difference (where known) in the proton affinities of isomeric aldehyde/ketone pairs. Table 1 shows that the ketone(s) possesses higher proton affinities than the corresponding aldehyde. Consequently, if a VOC with a proton affinity lying between that of the aldehyde and ketone is employed as VOC_1 in an experiment with a two-stage source the mass spectrum should, in principle, yield signal from the ketone only. This proposition is the cornerstone of

Table 1
Comparison of aldehyde and ketone proton affinities[a] relevant to this work

Molecule	Proton affinity (kJ mol^{-1})
H_2O	691.0
Acetone (propanone)	812.0
Butanal	793
Butanone	827
Pentanal	797
2-Pentanone	833
3-Pentanone	837
Hexanal	–
2-Hexanone	–
3-Hexanone	843.2
Methacrolein	808.7
Methyl vinyl ketone	834.7

[a] Taken from Hunter and Lias [19].

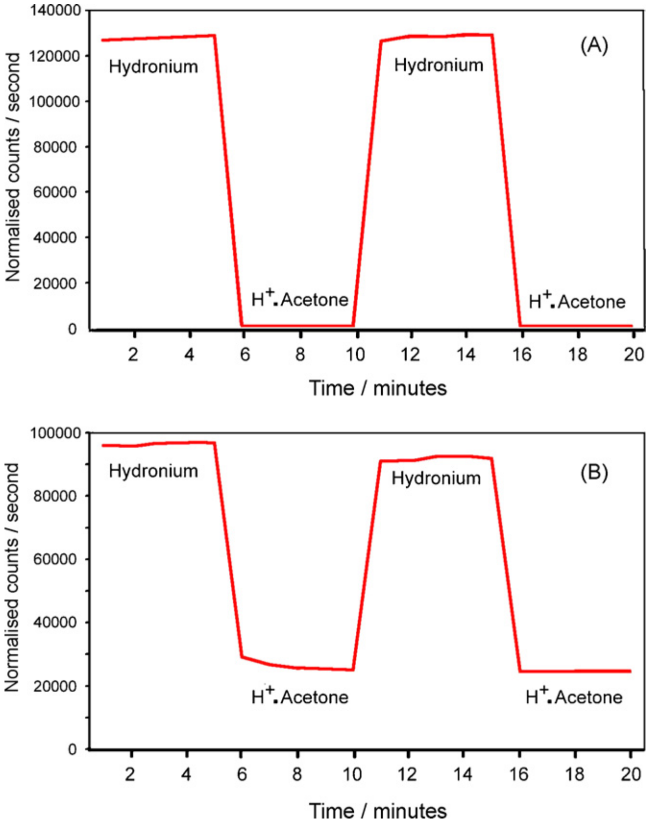

Fig. 1. (a) Signal seen for protonated butanal (monitored at the fragment peak at m/z 55) as the proton source is switched between H_3O^+ and protonated acetone. (b) Corresponding results for butanone, in this case monitored at m/z 73. The switch from H_3O^+ to H^+.Acetone brings about a roughly threefold drop in the m/z 73 signal.

the current work and its effectiveness for isolating the ketone-only signal has been explored with several illustrative isomeric compounds, the results from each of which are described below.

3.1. Butanal and butanone

Butanone yields mainly the protonated parent molecule (m/z = 73) in reactions with H_3O^+, whereas the major product for butanal is the dehydrated ion $[MH–(H_2O)]^+$ at m/z = 55. Consequently, use of H_3O^+ in PTR-MS already provides a means of potentially discriminating between the two isomers. Nevertheless, the fact that butanal and butanone have distinct mass spectra is convenient for an initial test of the two-stage method. It should also be noted that mass channel 55 also coincides with the signal from $H_3O^+(H_2O)_2$, which is always seen in spectra where H_3O^+ is used as the proton source. Consequently, distinguishing butanal and butanone in real gas mixtures using H_3O^+ alone would be extremely difficult.

According to Table 1, which shows only a very limited subset of possible compounds that could act as VOC_1, using acetone as VOC_1 should yield signal only from butanone since its proton affinity lies roughly midway between those of butanal and butanone. Experiments have confirmed this, showing almost complete disappearance of any signal from butanal at m/z = 55 when switching from H_3O^+ to protonated acetone as reagent ion (see Fig. 1(a)). In the case of butanone, the switch to acetone as VOC_1 retains a substantial protonated parent peak at m/z 73, but this peak is much smaller than seen with H_3O^+ as the proton source (see Fig. 1(b)). This is presumably due to a smaller rate constant for the reaction between protonated acetone and butanone when compared to the corresponding H_3O^+ reaction. Nevertheless, a substantial protonated butanone signal remains and consequently this simple test demonstrates the feasibility of switching from H_3O^+ to VOC_1H^+ in order to distinguish isobaric compounds. It is worth emphasizing that this switch can be achieved relatively rapidly (<2 min).

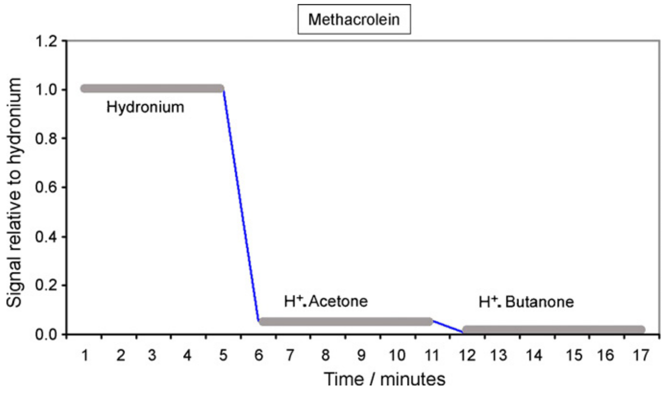

Fig. 2. Signal seen for protonated methacrolein as the proton source is switched between H_3O^+, protonated acetone and protonated butanone.

3.2. Methacrolein and methyl vinyl ketone

In contrast to butanal and butanone, methacrolein (MA) and methyl vinyl ketone (MVK) both yield protonated parent molecules as the dominant signal in their PTR-MS spectra. Consequently, some additional means is essential to quantify these two species separately *via* PTR-MS. Two-stage experiments with acetone as VOC_1 yield good separation, but the MA signal does not disappear completely when switching from H_3O^+ to protonated acetone, as can be seen from Fig. 2. This incomplete separation is understandable given that the proton affinity of acetone is only 3 kJ mol^{-1} above that of MA. Uncertainties in the measured proton affinities coupled with residual thermal energy can account for the non-zero signal from MA.

From Table 1, butanone looks a better choice as VOC_1 since it has a proton affinity some 8 kJ mol^{-1} below that of MVK and well above that of MA. Experiments on MA confirm this choice, almost completely removing all reaction products when using butanone as VOC_1 (see Fig. 2). The two-stage source is thus seen to be a highly effective means of discriminating between MA and MVK, but the downside is that when butanone is used as VOC_1 this comes at the cost of a major loss in ion count rate, as will be clear from inspection of Fig. 3, which shows the signal obtained from MVK as the proton donor is altered. For circumstances where sensitivity is important,

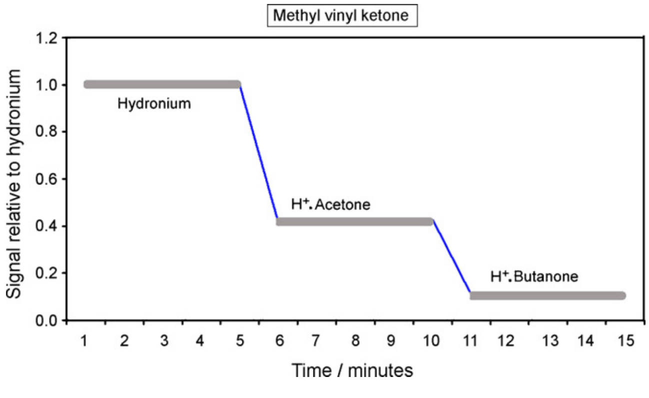

Fig. 3. Signal levels seen for protonated methyl vinyl ketone as the proton source is switched between H_3O^+, protonated acetone and protonated butanone.

acetone may be a better proton source for quantifying MVK, despite the residual contribution from MA.

The decline in signal levels as the switch is made from one proton source to another correlates with the reaction enthalpy. It has been noted in several previous studies (see, for example Betowski et al. [20] and Bouchoux et al. [21] and references therein) that the proton transfer efficiency begins to drop significantly below that expected on the basis of capture theories for reactions with exothermicities <−40 kJ mol^{-1}. In the reaction between MVK and protonated acetone the enthalpy of reaction is −23 kJ mol^{-1} whereas the reaction between MVK and protonated butanone has an enthalpy change of only −15 kJ mol^{-1}. These values are thus well within the range where an effect is expected and are consistent with the fact that the protonated MVK signal declines in the order $H_3O^+ > H^+$.Acetone > H^+.Butanone.

3.3. Hexanal/2-hexanone/3-hexanone

The proton affinities of hexanal and 2-hexanone have not been reported in the literature, although that of 3-hexanone is known (843.2 kJ mol^{-1} [19]). However, on the basis of the known proton affinities for lighter aldehydes and ketones (see Table 1), we can estimate likely values for hexanal and 2-hexanone. For hexanal the expectation is a proton affinity near 800 kJ mol^{-1}, whereas the similarity of the proton affinities of 2-pentanone and 3-pentanone suggests that 2-hexanone should have a proton affinity just below that of 3-hexanone, close to 840 kJ mol^{-1}. On the basis of these predictions it will prove impossible to choose a VOC_1 that can completely discriminate between 2-hexanone and 3-hexanone, but the much lower proton affinity of hexanal should suffice to remove any trace of signal from this compound by suitable choice of VOC_1. Several candidates for VOC_1 would be ideal in this regard, with proton affinities above that expected for hexanal but well below those of 2- and 3-hexanone.

Like butanal, proton transfer from H_3O^+ and other proton sources, such as protonated acetone, to hexanal tends to result in ion dehydration, whereas the hexanones yield mainly protonated parent ions. The dehydration of hexanal is extensive, with the protonated parent peak at m/z 101 accounting for only about 1% of the contribution to the mass spectrum. The dehydrated fragment ion at m/z 83 amu was therefore used for monitoring hexanal in the current experiments.

The ability to vary VOC_1 provides the opportunity to determine the proton affinity of hexanal through a bracketing procedure. Table 2 summarizes the findings of these bracketing measurements. The proton affinity is found to lie within the range 794.4 kJ mol^{-1} < PA(hexanal) < 797.0 kJ mol^{-1}, providing the first experimental determination of the proton affinity of hexanal. These limits provide a proton affinity of hexanal which is in line with that anticipated by extrapolation from the lighter aldehyde/ketone pairs. Of course this simple bracketing procedure provides a relatively crude estimate of the proton affinity of a VOC, but it also provides a straightforward and quick means of accessing this information that can easily be applied to many other compounds with unknown proton affinities.

Table 2
Outcome of hexanal proton affinity bracketing experiments

VOC_1	PA of VOC_1 (kJ mol^{-1})	Product ion(s) seen?
Toluene	784.0	Yes
p-Xylene	794.4	Yes
Acrolein	797.0	No
Furan	803.4	No
Acetone	812.0	No

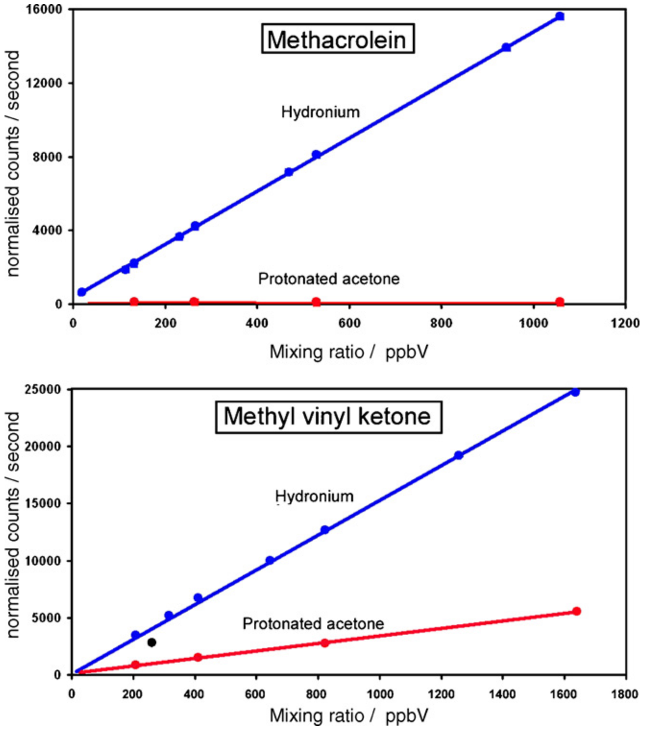

Fig. 4. Calibration plots obtained for methacrolein (MA) and methyl vinyl ketone (MVK) using hydronium and protonated acetone as proton donors. Permeation tubes were used as VOC_2 sources. For further details see text.

3.4. Quantification of isobaric components

The results presented above show that aldehydes can be distinguished from their isomeric ketone partners by choice of an appropriate VOC_1. However, for practical applications it is important that the aldehydes and ketones can be separately quantified. To demonstrate that this is possible, we return to MA and MVK.

Dynamic gas dilution was employed to produce known concentrations of MA and MVK separately, as well as a mixture of both. Calibration curves for each compound were obtained using both hydronium and protonated acetone as proton sources, in order to obtain compound sensitivities prior to analyzing a mixture (see Fig. 4). These calibration curves were obtained by varying a supply of nitrogen through temperature-regulated permeation tubes containing either MA or MVK. The MA permeation tube (Kin-Tek) was specified for a leak rate of 92.9 ng min^{-1} at an operating temperature of 60 °C, while that for MVK (purchased from Metronics/Dynacal) gave a leak rate of 144 ng min^{-1} at 50 °C.

Having obtained independent calibration curves, measurements were then carried out on a mixture of MA and MVK. Both permeation tubes were employed and a common oven temperature of 50 °C was employed, which allowed the delivery of a pre-determined amount of MVK but an unknown amount of MA. The experiment to determine the composition of the mixture was carried out using two flow rates (0.3 and 0.6 l min^{-1}) from the diluter, in effect giving two different concentrations of each compound in the mixture. Separate concentration determinations were then made using the same conditions but using one permeation tube only and using hydronium as the ion source. The sensitivities obtained from the initial calibrations provide reference concentrations of MA and MVK which can be compared with those derived from the mixture. The concentrations determined in the mixture were obtained by measurements using protonated acetone and then H_3O^+ as the ion source. The latter should give the combined

Table 3
Quantitative experiment results on MA and MVK

	[MA] (ppbV)		[MVK] (ppbV)	
Flow rate ($\mathrm{l\,min^{-1}}$)	0.3	0.6	0.3	0.6
Single permeation tube	1220 ± 40	637 ± 30	1510 ± 50	801 ± 30
Mixture	1271 ± 50	619 ± 30	1620 ± 40	830 ± 40

MVK + MA concentration whereas the former should give MVK only.

The results obtained are shown in Table 3. The agreement between the reference concentrations (single permeation tubes) of MA and MVK and the values derived from the two mixtures are excellent, demonstrating that the switch between proton transfer sources can be used successfully to independently quantify MA and MVK.

4. Conclusions

The lower proton affinities of aldehydes relative to their isomeric ketone partners provides a means of distinguishing between and quantifying isomeric aldehydes and ketones by PTR-MS. Two-stage PTR-MS provides a simple and effective technique for achieving this. To separately quantify these compounds, an initial experiment using H_3O^+ as the proton source is required to provide the total VOC concentration in a given mass channel. A subsequent experiment using a VOC_1 with a proton affinity above that of the aldehyde but below that of the ketone switches off any aldehyde contribution and allows the ketone(s) to be quantified. Finally, these two measurements can be combined to provide separate quantification of the aldehyde and ketone. This ability to separate isobaric VOCs on the basis of differences in their proton affinities provides a valuable extra dimension to PTR-MS.

It is worth emphasizing that, while simple to implement, the two-stage approach does have its limitations. These include the possibility that a suitable choice of VOC_1 for separating the contributions of two isomeric or isobaric compounds is unavailable. It is also possible that more than two compounds may contribute to a given mass channel. A good example of this is crotonaldehyde, which is isomeric with two of the compounds considered in the current study, methacrolein and methyl vinyl ketone. The proton affinity of crotonaldehyde lies at 823 $\mathrm{kJ\,mol^{-1}}$ [19], which is roughly midway between methacrolein and methyl vinyl ketone. Protonated acetone would switch off only the methacrolein contribution whereas protonated butanone would allow both methacrolein and crotonaldehyde signals to be removed from the mass spectrum. Consequently, by switching from H_3O^+ to protonated acetone to protonated butanone, we would collect data sufficient to quantify all three compounds. Of course, such a quantification process would require prior compound calibration using known gas standards to allow for the changes in detection sensitivity as the proton source is altered.

The ability to switch easily from H_3O^+ to another proton source in the two-stage experiment also provides a simple and quick means to estimate proton affinities of compounds. This bracketing approach has been used here to estimate the proton affinity of hexanal, which has not previously been reported and which is found to lie in the range $794.4\ \mathrm{kJ\,mol^{-1}} < \mathrm{PA(hexanal)} < 797.0\ \mathrm{kJ\,mol^{-1}}$.

Acknowledgements

AME and RSB would like to thank the Daiwa Foundation for awarding a travel grant in support of this work. SI acknowledges the financial support for this work by Asahi Breweries Foundation (FY2007). Dr. Lucy Carpenter is gratefully acknowledged for the loan of a PTR-TOF-MS instrument during the course of this investigation.

References

[1] W. Lindinger, A. Hansel, A. Jordan, Int. J. Mass Spectrom. Ion Process. 173 (1998) 191.
[2] W. Lindinger, A. Jordan, Chem. Soc. Rev. 27 (1998) 347.
[3] C.N. Hewitt, S. Hayward, A. Tani, J. Environ. Monit. 5 (2003) 1.
[4] J.A. de Gouw, C. Warneke, Mass Spectrom. Rev. 26 (2007) 223.
[5] P. Prazeller, P.T. Palmer, E. Boscaini, T. Jobson, M. Alexander, Rapid Commun. Mass Spectrom. 17 (2003) 1593.
[6] C. Warneke, S. Rosen, E.R. Lovejoy, J.A. de Gouw, R. Fall, Rapid Commun. Mass Spectrom. 18 (2004) 133.
[7] C. Warneke, J.A. de Gouw, E.R. Lovejoy, P.C. Murphy, W.C. Kuster, R. Fall, J. Am. Soc. Mass Spectrom. 16 (2005) 1316.
[8] M.M.L. Steeghs, C. Sikkens, E. Crespo, S.M. Cristescu, F.J. Harren, Int. J. Mass Spectrom. 262 (2007) 16.
[9] K.P. Wyche, R.S. Blake, K.A. Willis, P.S. Monks, A.M. Ellis, Rapid Commun. Mass Spectrom. 19 (2005) 3356.
[10] R.S. Blake, K.P. Wyche, A.M. Ellis, P.S. Monks, Int. J. Mass Spectrom. 254 (2006) 85.
[11] S. Inomata, H. Tanimoto, J. Am. Soc. Mass Spectrom. 19 (2008) 325.
[12] J. Wildt, K. Kobel, G. Schuh-Thomas, A.C. Heiden, J. Atmos. Chem. 45 (2003) 173.
[13] H. Hellén, H. Hakola, A. Reisell, T.M. Ruuskanen, Atmos. Chem. Phys. 4 (2004) 1771.
[14] D. Grosjean, E. Grosjean, A.W. Gertler, Environ. Sci. Technol. 35 (2001) 45.
[15] R. Atkinson, J. Arey, Atmos. Env. 37 (2003) S197.
[16] S.E. Paulson, R.C. Flagan, J.H. Seinfeld, Int. J. Chem. Chem. Kinet. 24 (1992) 103.
[17] H. Tanimoto, N. Aoki, S. Inomata, J. Hirokawa, Y. Sadanaga, Int. J. Mass Spectrom. 263 (2007) 1.
[18] C.J. Ennis, J.C. Reynolds, B.J. Keely, L.C. Carpenter, Int. J. Mass Spectrom. 247 (2005) 72.
[19] E. Hunter, S. Lias, J. Phys. Chem. Ref. Data 27 (1998) 413.
[20] D. Betowski, J.D. Payzant, G.I. Mackay, D.K. Bohme, Chem. Phys. Lett. 31 (1975) 321.
[21] G. Bouchoux, J.Y. Salpin, D. Leblanc, Int. J. Mass Spectrom. 153 (1996) 37.