Application Note

Dielectric barrier discharge ionization (DBDI) as a universal atmospheric pressure ion source (API) for the hyphenation of gas chromatographic, liquid chromatographic and supercritical fluid chromatographic separations with the same time-of-flight mass spectrometer

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Abstract

Dielectric barrier discharge ionization (DBDI) was coupled to a high resolution and high accuracy mass spectrometer (HRMS) as universal atmospheric pressure ion source (API). Most importantly, this is the first time that gas-, liquid- and supercritical fluid chromatography instruments could be hyphenated by one single ion source to the same API-'LC'-mass spectrometric instrument. Gas-, liquid- and supercritical fluid chromatography was hyphenated with a SICRIT® DBDI source to an Agilent time-of-flight mass spectrometer. The interface (with only minor modifications caused by the chromatographic outlet) was designed in a universal style and is presented here in novelty. The source was tested with the same set of analytes (with various polarities) separated in several chromatographic techniques. The investigated set-ups allowed to analyze samples with three different and highly orthogonal separation techniques and to successfully detect most analytes. As a result, data are comparable in accuracy and reliability and can be evaluated in parallel. Results can be directly compared, because the same software platform is used for separation-independent data evaluation. The parallel use of different orthogonal separation techniques with the same mass spectrometric detector provides significant benefits, especially if analyzing complex samples and detecting new or unknown compounds in forthcoming non-target screening workflows.

Introduction

The molecular analysis of (complex) samples, containing a huge number of various chemical compounds can be a challenging task. Due to the physico-chemical diversity of investigated analytes, such multi-residue analyses often require the use of more than one analytical technique gaining a comprehensive view on a sample. Typical examples can be found in the field of pesticide analytics in food and beverages or the analysis of environmental samples (like surface or ground water and others). Thereby gas chromatography (GC), liquid chromatography (LC), and supercritical fluid chromatography (SFC) are often used in parallel to separate complementary and orthogonal volatile and non-volatile compounds.[1–6] Mass spectrometry (MS) and mainly tandem mass spectrometry (MS/MS) is commonly used as detection system for such complex analyses. It allows a sensitive and mass selective detection of ionizable compounds. In our days, the coupling of mass spectrometry to gas chromatography by ionization sources mostly depends on (very) low pressure setups like electron impact (ionization; i.e. EI) and chemical ionization (CI).[7] The coupling of mass spectrometry to liquid chromatography (including SFC) by ionization sources mostly depends on atmospheric pressure ionization sources like electrospray ionization (ESI), atmospheric pressure chemical ionization (APCI), atmospheric pressure photo ionization (APPI), and most recently low temperature plasma ionization (LTPI).[8] Later atmospheric pressure ionization sources, i.e. APCI, APPI, ESI, LTPI and also atmospheric pressure laser ionization (APLI) became in the last years more and more compatible and useable as 'soft' ionization source in GC-MS.[9]

Dielectric barrier discharge ionization (DBDI) [10] is an recently developed atmospheric pressure ionization technique with powerful potential providing a sensitive and soft ionization source for a broad range of analytes eluting from the three separation techniques GC, LC and SFC, respectively. Based on a cold plasma, compounds are ionized by protonation as well as APCI-related mechanisms and DBDI unique mechanisms resulting in the formation of protonated analyte ions, radical molecular ions and others.[11] DBDI plasma sources, such as the commercially available SICRIT® (SI) source can be coupled directly to MS instruments, designed for LC application. This allows to couple GC and (nano) LC instruments to the same MS instrument and also to perform fast and sensitive solid phase micro extraction (SPME) analyses.[10,12,13]
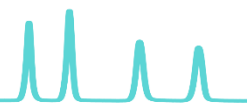
Usually, GC and LC analyses require different MS ionization interfaces. As a consequence, mass spectrometric instruments are GC- or LC- specific and cannot be used for the other chromatographic technique. Consequently, when analyzing a sample by a GC-MS or a LC-MS instrument (with different results and performance) often different software and data handling concepts have to be used. The SICRIT® ionization source can be independent from chromatographic systems and applicable with most commercially available LC-MS instruments. This allows the hyphenation of GC instruments with MS instruments (originally designed for LC-MS applications). In this publication we demonstrate the universal usability of the SICRIT® ionization source coupled to a (LC-) single-ToF (i.e., time-of-flight) MS in hyphenation with GC, LC and SFC separations, respectively. Best to our knowledge this is the first note that three fully orthogonal separation techniques have been coupled to the same mass spectrometer for the detection of a comprehensive set of analytes.

Materials and methods

Materials

Acetonitrile and methanol (HiPerSolv Chromasolv LC-MS grade) were purchased from VWR (Darmstadt, Germany). Water (LC-MS grade) and dichloromethane were obtained from Sigma-Aldrich, (Seelze, Germany). Carbon dioxide (purity 4.5) was purchased from Westfalen AG (Muenster, Germany) and nitrogen (purity 5.0) from Air Liquide (Duesseldorf, Germany). Reference compounds were obtained from Dr. Ehrenstorfer (Augsburg, Germany), Fluka (Buchs, Switzerland), Merck (Darmstadt, Germany) PAH Institute Dr. Schmidt (Greifenberg, Germany), Roth (Karlsruhe, Germany) and Sigma Aldrich (Seelze, Germany). Details about the reference standards and distributors are summarized in Table 2.

Reference standards

Reference standards were dissolved to standard solutions containing 60 mM of each analyte. Acetonitrile was used as solvent and for the dissolution of oxy-PAHs 1% dichloromethane was added

to the solutions. For chromatographic separations, working standard mixes containing 10 µM or 100 µM in acetonitrile of each analyte were created.

GC separation

An HP 5890 series II GC system (Hewlett-Packard, Wilmington, USA) was used for the GC-SICRIT®-MS coupling. The chromatograph was equipped with a HP-5MS column (30 m x 0,25 mm, Agilent Technologies, Santa Clara, USA) and operated with nitrogen (head pressure: 20 psi) as carrier gas in splitless mode. The outlet of the analytical capillary was directly introduced into the SICRIT® GC/SPME-module (see details given in the section 'compound ionization and mass spectrometric detection').

GC separation was executed according to the following temperature protocol: After manual sample injection (injector temperature: 275°C), the sample was equilibrated at 40°C for 2 min. Afterwards, the GC oven temperature was increased by a ramp rate of 10°C/min to 250°C and hold for 3 min (total run time: 26 min). 1 µL of the 10 µM working standard mix was injected in the system.

LC separation

An Agilent 1260 LC system (Agilent Technologies, Waldbronn, Germany) was used for the LC-SICRIT®-MS coupling. It consisted of a degasser, a binary pump, a high-performance auto-sampler, a column oven equipped with a Phenomenex Luna Omega PS C18 column (100 x 2.1 mm, 1.6 µm; Phenomenex LTD, Aschaffenburg, Germany) and a UV detector. Compounds were eluted using a mobile phase gradient of water and methanol at a constant flow rate of 80 µL/min, increasing the methanol content from 10 to 100% within 30 minutes and kept constant for further 25 minutes before re-equilibration. The outlet of the UV detector was connected by a T-piece to an isocratic pump. The isocratic pump provided a constant flow of 0.01 mL/min of mass calibrant (6.25 nM HP 921 and 125 nM purine in methanol/water (90/10, v/v)) (both Agilent Technologies, Santa Clara, USA). 1 µL of the 100 µM working standard mix was injected.

SFC separation

An analytical 1260 Infinity SFC system (Agilent Technologies, Waldbronn, Germany) consisting of a degasser, a binary pump, an auto-sampler, a column oven, equipped with a HILIC column (150 x 2.0 mm, 5 µm, KNAUER, Berlin Germany), a UV detector and a back-pressure regulator. The mobile phase consisted of carbon dioxide and methanol containing 20 mM ammonium acetate (modifier). Compounds were eluted using a binary gradient from 5 to 40% modifier within five minutes. After one minute at 40%, modifier content was decrease to 5% within one minute for re-equilibration. Back-pressure was set at 100 bar, the flow rate of the mobile phase was held constant at 2.0 mL/min and column temperature was set to 40°C. An isocratic pump (Agilent Technologies, Waldbronn, Germany) was connected to the outlet of the back-pressure regulator by a T-piece. The pump provided a constant flow 0.5 mL/min of mass calibrant containing 6.25 nM HP 921 and 125 nM purine in methanol/water (90/10, v/v) (both Agilent Technologies, Santa Clara, USA). 1 µL of the 100 µM working standard mix was injected.

Compound ionization and mass spectrometric detection

Compounds were ionized using a SICRIT® ionization source (Plasmion GmbH, Augsburg, Germany). It is based on a cold plasma ignited at high-frequency AC high-voltages. The SICRIT® SC-20 control unit works at a permanent frequency of 10 kHz and the AC voltage output was set to 1.5 kV for all experiments.

The ionization conditions were adjusted to the different separation techniques. The ionization set-ups are visualized in Figure 1. The outlet of the GC capillary was directly connected with the SICRIT® solid phase micro extraction (SPME) desorption module by a heated transfer line (300°C). The desorption heater was set to a temperature of 275°C. In all experiments humidified nitrogen was used as substitution/carrier gas for the GC/SPME module (Figure 1 a,). The outlet of the GC/SPME module was directly connected to the SICRIT® ionization source at the MS.

For LC and SFC separations, the outlet of the chromatographic systems was connected to a nebulizer (Agilent Technologies, Santa Clara, USA), which is usually used for the spray generation in electrospray

ionization. The nebulizer was located in a heating cartridge which was held constant at 300°C. The outlet of the cartridge allowed the dried spray to exit or to move in a 90-degree angle to the SICRIT® ion source (Figure 1 b,).
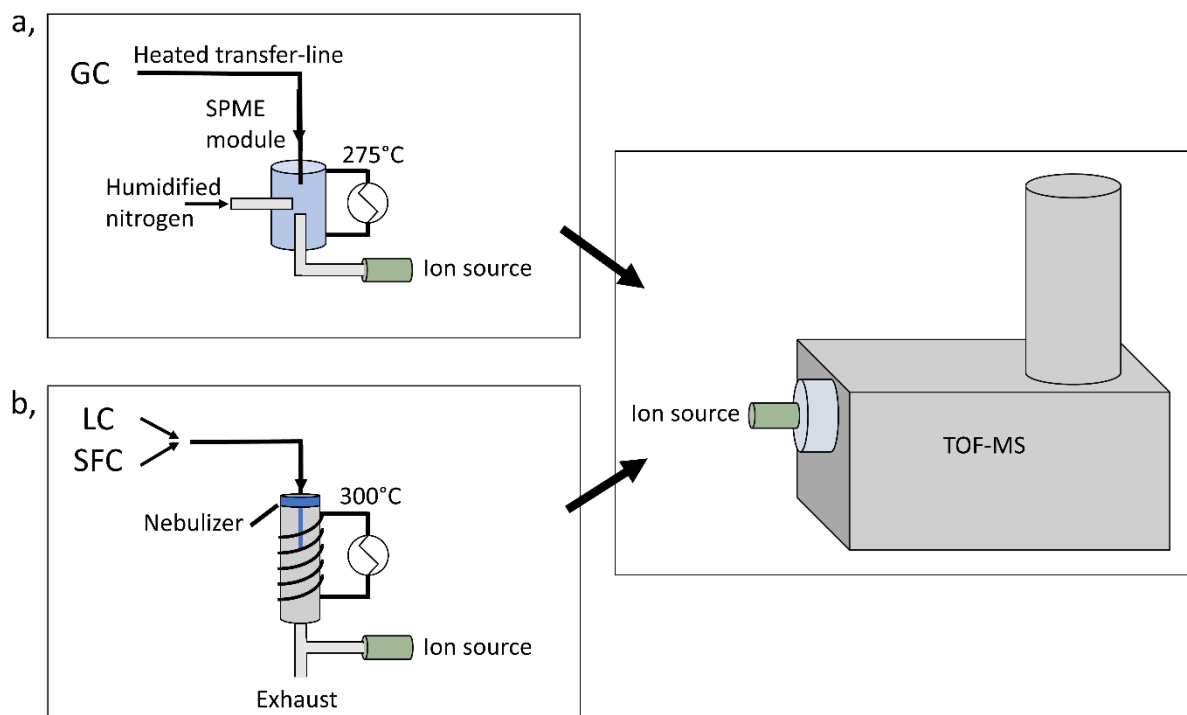

Figure 1: Set-ups for the connection of GC (a,) and LC as well as SFC (b,) to the SICRIT® ion source, connected to the ToF-MS.

A 6230 time-of-flight MS (Agilent Technologies, Santa Clara, USA) was used for accurate mass spectrometric detection. The MS parameters, which were adjusted for each separation technique, are summarized in Table 1. For the detection of SFC and LC separated compounds, the added mass calibrants were used for continuous mass recalibration. All analyzes were performed in positive ionization mode.

Table 1: MS parameters, adjusted to individual separation techniques.

Separation technique	Drying Gas Temperature [°C]	Drying Gas Rate Flow [L/min]	Fragmentor Voltage [V]	Capillary Voltage [V]	Nebulizer Pressure [psi]
GC	365	10	200	0	5
LC	360	10	225	0	45
SFC	365	10	250	0	5
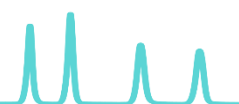
Data evaluation

Data were evaluated using Agilent ProFinder software (B.06.00) and Agilent MassHunter Qualitative Analysis (B.08.00). Compounds were identified by targeted feature extraction using the elemental formula (and including potential adducts as well as radical cations for each compound) and an expected mass accuracy better than 20 ppm for SFC and LC separated compounds and 30 ppm for GC separated compounds.

Results and discussion

In this study a SICRIT® soft-ionization (SI)-source, coupled to a single ToF MS, commonly used to detect compounds separated by liquid chromatography, was used as a novel detector for GC, LC and SFC separated compounds, respectively. Therefore, coupling interfaces between the separation instrument and the MS were adjusted. The aim was to establish a universal detection system with comprehensive ionization abilities. The set of 41 analytes consisted of 31 pesticides and three pharmaceuticals which are commonly analyzed using GC-MS and/or LC-MS techniques.[14] In addition, seven oxy-polycyclic aromatic hydrocarbons (oxy-PAHs) were added to the set of analytes. For the ionization of oxy-PAHs, APCI or APPI are usually required, because of low ionization energy in ESI.[15] Although, selected compounds are commonly analyzed, applying GC- and LC-MS, SFC as an emerging technique has also been shown to be suitable for the detection of these compounds using ESI- and APCI-MS detection. [16–18]

35 of the 41 investigated compounds could be detected by GC-SI-MS, 38 compounds by LC-SI-MS and 31 compounds by SFC-SI-MS. Details are shown in Figure 2 and Table 2. Therein it can be seen that chlorpropham and pyrenol were exclusively detected by GC-SI-MS, while 2-naptholic acid, ibuprofen and pyraclostrobin could solely be verified by LC-SI-MS. In total, 27 analytes could be separated and detected with all investigated set-ups. GC and LC are highly orthogonal techniques as well as LC and SFC are. The high degree of orthogonality of later has recently been shown.[19] So, the detectability of compounds with both (or several) techniques is a special benefit, when aiming to identify new or

unknown compounds. Further, the complementary of all three techniques is a comprehensive benefit in the screening for new compounds in complex samples.

The investigated instrumental set-up can be used separating samples with three independent separation techniques, and to detect the analytes with the same MS in all cases. This allows to evaluate data of all separation together and to directly compare results, spectra and further MS(/MS) data, without the necessity to use different software platforms (Figure 2).
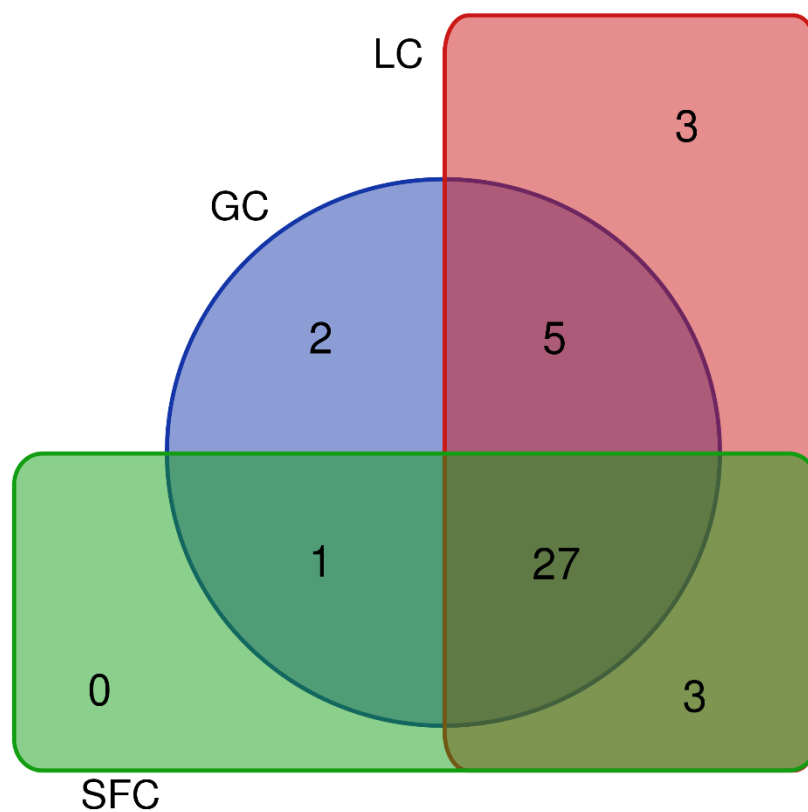

Figure 2: Venn-Diagram of separation techniques and according numbers of compounds which could be detected with each technique (like shown in http://bioinformatics.psb.ugent.be/webtools/Venn/)
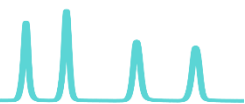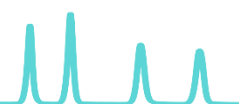
Table 2: Reference compounds, used in the present study (sorted by log D (pH 7)) with retention times of compounds separated and detected by different instrumental set-ups. Signal heights of 10^3 to 10^4 are marked with '+', signal heights of 10^5 to 10^6 with '++' and signal heights of 10^7 and higher are marked with '+++'

Compound name	CAS Number	Empirical formula	log D (pH 7)	Monoisotopic mass [Da]	Retention times [min]			Signal heights		
					GC	LC	SFC	GC	LC	SFC
Chloridazon [S, b]	1698-60-8	C10H8ClN3O	1.11	221.0356	24.4	29.6	2.6	++	++	++
Coumarin [P, a]	91-64-5	C9H6O2	1.40	146.0368	13.98	41.3	0.7	++	+	++
Carboxin [D, b]	5234-68-4	C12H13NO2S	1.51	235.0667	22.8	35.3	1.1	++	++	++
Azamethiphos [F, b]	35575-96-3	C9H10ClN2O5PS	1.52	323.9737	24.0	33.8	n.d.	++	++	-
Chlorsulfuron [S, b]	64902-72-3	C12H12ClN5O4S	1.56	357.0299	17.0	38.4	1.3	+	+	+
Carbetamide [S, b]	16118-49-3	C12H16N2O3	1.65	236.1161	20.7	33.4	n.d	++	++	-
Oxadixyl [S, b]	77732-09-3	C14H18N2O4	1.79	278.1267	23.6	32.9	n.d.	++	++	-
Malathion [S, b]	121-75-5	C10H19O6PS2	1.86	330.0361	20.4	39.0	0.4	++	++	+
5-Hydroxy-1,4-naphthaquinone [R, a]	481-39-0	C10H6O3	1.90	174.0317	n.d.	33.4	1.1	-	+	+
Monuron [S, b]	150-68-5	C9H11ClN2O	1.93	198.056	9.7	33.9	1.3	+	++	++
Metribuzin [S, b]	21087-64-9	C8H14N4OS	1.96	214.0888	19.4	34.3	0.7	++	++	++
Alpha-Tetralon [P, a]	529-34-0	C10H10O	2.00	146.0732	13.1	n.d.	0.5	++	-	+
2,6-Dichlorbenzamide [S, b]	2008-58-4	C7H5Cl2NO	2.03	188.9748	17.0	21.5	1.9	++	++	++
Carbofuran [F, b]	1563-66-2	C12H15NO3	2.05	221.1052	17.9	34.3	0.8	+++	++	++
Atrazine [S, b]	1912-24-9	C8H14ClN5	2.20	215.0938	17.9	36.7	0.6	+++	++	++
Metobromuron [S, b]	3060-89-7	C9H11BrN2O2	2.24	258.0004	19.1	36.3	0.7	++	++	+
Chlorotoluron [S, b]	15545-48-9	C10H13ClN2O	2.44	212.0716	n.d.	36.3	1.3	-	++	+
Carbamazepine [S, c]	298-46-4	C15H12N2O	2.45	236.095	24.4	35.3	1.5	++	++	++
N,N-Diethyl-meta-toluamide (DEET) [S, b]	134-62-3	C12H17NO	2.50	191.131	15.8	36.7	0.5	+++	++	+
Linuron [S, b]	330-55-2	C9H10Cl2N2O2	2.68	248.0119	20.3	38.4	0.8	++	++	+
1-Naphthol [M, a]	90-15-3	C10H8O	2.80	144.0575	22.3	40.3	0.6	++	+	++

Compound name	CAS Number	Empirical formula	log D (pH 7)	Monoisotopic mass [Da]	Retention times [min]			Signal heights		
Chlorbromuron [D, b]	13360-45-7	C9H10BrClN2O2	2.85	291.9614	21.4	38.7	0.8	++	++	+
Metazachlor [S, b]	67129-08-2	C14H16ClN3O	2.98	277.0982	21.3	36.5	n.d.	++	++	-
Diethofencarb [S, b]	87130-20-9	C14H21NO4	3.00	267.1471	20.5	38.1	0.6	++	++	+
Chlorpropham [S, b]	101-21-3	C10H12ClNO2	3.21	213.6608	16.7	n.d.	n.d.	++	-	-
2-Naphtholic acid [P, a]	93-09-4	C11H8O2	3.30	172.0524	n.d.	39.1	n.d.	-	+	
Metolachlor [S, b]	51218-45-2	C15H22ClNO2	3.45	283.1339	20.6	40.2	0.4	++	++	++
Alachlor [F, b]	15972-60-8	C14H20ClNO2	3.59	269.1183	19.8	40.2	0.4	++	++	+
Diclofenac [S, c]	15307-86-5	C14H11Cl2NO2	3.90	295.0167	n.d.	38.0	3.4	-	+	+
Ibuprofen [S, c]	15687-27-1	C13H18O2	3.97	206.1307	n.d.	36.7	n.d.	-	++	-
Prosulfocarb [S, b]	52888-80-9	C14H21NOS	4.17	251.1344	20.0	42.7	0.4	++	++	+
Diazinon [D, b]	333-41-5	C12H21N2O3PS	4.19	304.101	18.5	41.3	0.4	+++	++	++
Benzanthrone [P, a]	82-05-3	C17H10O	4.30	230.0732	25.9	33.9	n.d	++	++	-
Chlorfenvinphos [S, b]	470-90-6	C12H14Cl3O4P	4.30	357.9695	21.5	41.0	0.4	++	++	++
Picoxystrobin [S, b]	117428-22-5	C18H16F3NO4	4.31	367.1031	22.3	40.3	0.6	++	++	+
Pyrenol [P, a]	5315-79-7	C16H10O	4.60	218.0732	25.7	n.d.	n.d.	++	-	-
Flurtamone [S, b]	96525-23-4	C18H14F3NO2	4.64	333.0977	26.2	38.3	1.6	++	++	++
Pyraclostrobin [S, b]	175013-18-0	C19H18ClN3O4	4.70	387.0986	n.d.	41.3	n.d.	-	++	-
Boscalid [S, b]	188425-85-6	C18H12Cl2N2O	4.92	342.0327	29.3	38.4	1.3	++	++	++
Quinoxyfen [S, b]	124495-18-7	C15H8Cl2FNO	4.98	306.9967	24.2	44.1	0.5	++	++	++
Fenazaquin [S, b]	120928-09-8	C20H22N2O	5.42	306.1732	25.8	46.4	0.4	++	++	+

Footnotes:
Distributor: [D,] Dr. Ehrenstorfer; [F,] Fluka; [M,] Merck; [P,] PAH Institute Dr. Schmidt; [S,] Sigma-Aldrich
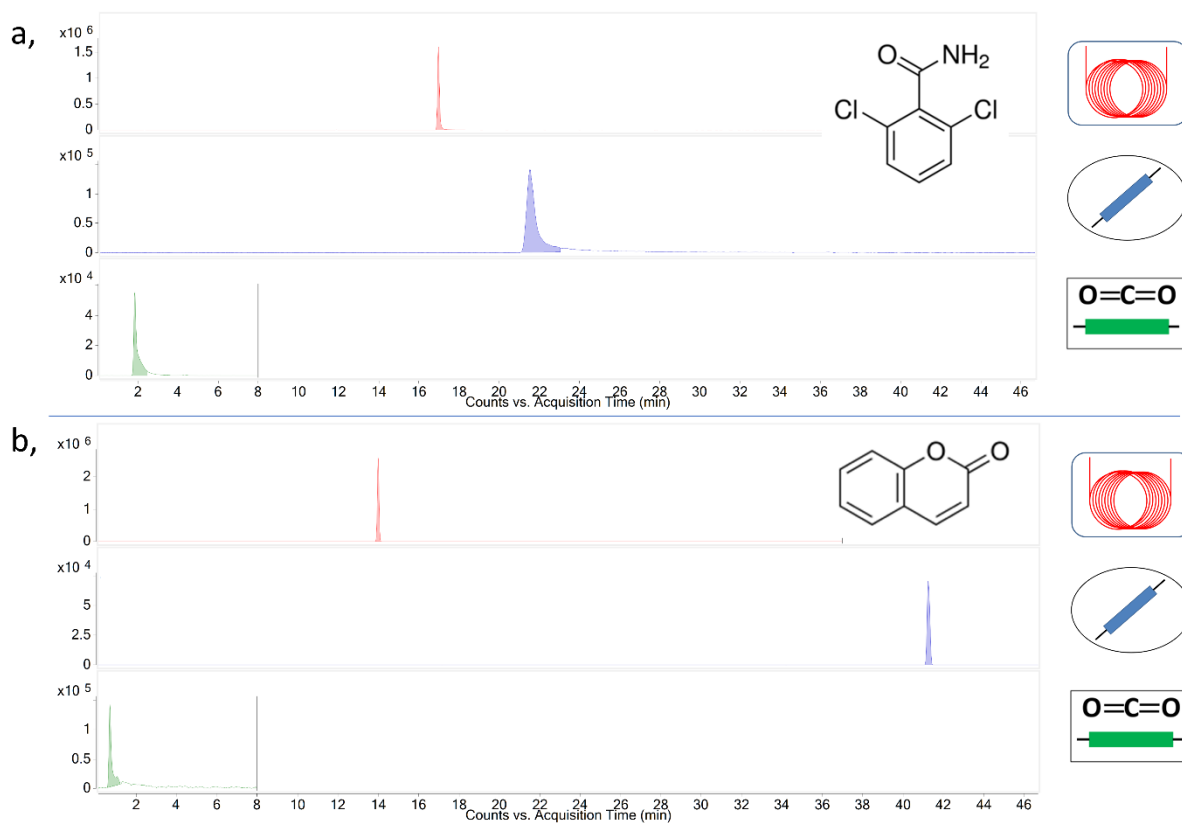Usage/Classification: [a,] Oxy-PAH; b, Pesticide; c, Pharmaceutical
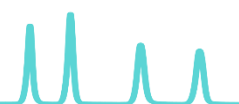
Figure 3: Extracted ion chromatograms of 2,6 dichlorbenzamid (a,) and coumarin (b,) obtained from GC (upper chromatogram), LC (middle chromatogram) and SFC separations (bottom chromatogram).

Across the investigated separation techniques, differences in the formation of ion species by SI could be observed. In Figure 3, the mass spectra of 2,6 dichlorbenzamid and linuron are shown. In all cases, the protonated ion [M+H]$^+$ could be detected as the dominant species. In LC measurements, the ammonium adduct [M+NH$_4$]$^+$ showed higher abundance compared to the protonated ion species, than in GC or SFC analyses. In addition, for some compounds (e.g., linuron) radical cations [M]$^{\bullet+}$ could be observed in GC or LC analyses. To support the ionization in GC, humidified water was added to the gas flow and in LC water was part of the mobile phase. In SFC separation, which were conducted without the use of water, methanol is likely to act as ionization supporting solvent. Thus, these differences in ionization and observed ion species can be explained by the mobile phase, used in separations.[11]
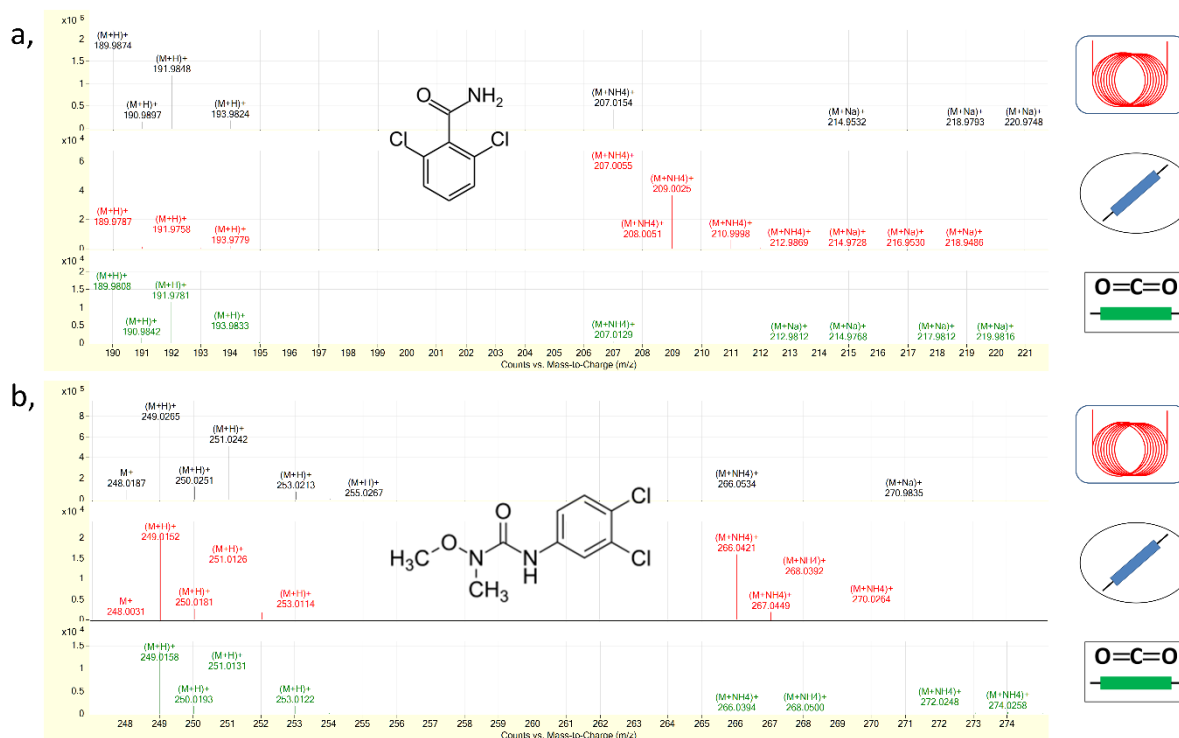
Figure 4: Mass spectra of 2,6 dichlorbenzamid (a,) and linuron (b,), obtained from GC-, LC- and SFC-SI-MS analyses.

The investigated set of analytes contained molecules, which can be ionized by soft ionization techniques, such as ESI, and molecules which require harder ionization types such as APCI (EI, etc.). Since harder ionization techniques can result in a fragmentation of labile molecules, the choice of the ionization techniques is usually depending on the nature of the analytes. So, when analyzing complex samples, containing very different analytes, it is difficult to achieve a comprehensive ionization for all analytes, because a soft ionization might not be intensive enough for some compounds and a harder ionization might be too strong for labile molecules. The SI-source, investigated in this study allows to broaden the ionization range significantly and to use one MS as a universal detector for GC, LC and SFC separations. The combination of complementary and orthogonal separation techniques with a comprehensive ionization and a universal MS detection are highly beneficial for the analysis of complex samples and the screening for new or unknown compounds.

Conclusions

The investigated SI-source allows to connect GC, LC and SFC to the same MS and to use this as a universal detector. Thus, it is possible to analyze samples with orthogonal separation techniques, allowing to gain information about compound characteristics on the basis of different retention mechanisms and to record data with the same MS. As a consequence, data can be evaluated in parallel and results of e.g., GC, LC and SFC analyses can directly be compared on the same software platform. This provides significant benefits when analyzing complex samples, such as environmental waters, food, or beverages, aiming to identify new relevant compounds.

Acknowledgements

References

[1]   Alder, L., Greulich, K., Kempe, G., Vieth, B., Residue analysis of 500 high priority pesticides: Better by GC–MS or LC–MS/MS? *Mass Spectrom. Rev.* 2006, 25, 838–865.

[2]   Schymanski, E. L., Singer, H. P., Slobodnik, J., Ipolyi, I. M., Oswald, P., Krauss, M., Schulze, T., Haglund, P., Letzel, T., Grosse, S., Thomaidis, N. S., Bletsou, A., Zwiener, C., Ibáñez, M., Portolés, T., de Boer, R., Reid, M. J., Onghena, M., Kunkel, U., Schulz, W., Guillon, A., Noyon, N., Leroy, G., Bados, P., Bogialli, S., Stipaničev, D., Rostkowski, P., Hollender, J., Non-target screening with high-resolution mass spectrometry: critical review using a collaborative trial on water analysis. *Anal. Bioanal. Chem.* 2015, 407, 6237–6255.

[3]   Chatterjee, N. S., Utture, S., Banerjee, K., Ahammed Shabeer, T. P., Kamble, N., Mathew, S., Ashok Kumar, K., Multiresidue analysis of multiclass pesticides and polyaromatic hydrocarbons in fatty fish by gas chromatography tandem mass spectrometry and evaluation of matrix effect. *Food Chem.* 2016, 196, 1–8.

[4]   Petrie, B., Youdan, J., Barden, R., Kasprzyk-Hordern, B., Multi-residue analysis of 90 emerging contaminants in liquid and solid environmental matrices by ultra-high-performance liquid chromatography tandem mass spectrometry. *J. Chromatogr. A* 2016, 1431, 64–78.

[5]   Danezis, G. P., Anagnostopoulos, C. J., Liapis, K., Koupparis, M. A., Multi-residue analysis of pesticides, plant hormones, veterinary drugs and mycotoxins using HILIC chromatography – MS/MS in various food matrices. *Anal. Chim. Acta* 2016, 942, 121–138.

[6]   Bieber, S., Letzel, T., Orthogonal Separation Techniques to Analyze (Very) Polar Molecules in Water Samples: Assessing SFC and Reversed-Phase LC–HILIC. *LCGC Eur.* 2018, 31, 602–606.

[7]   Hübschmann, H.-J., Handbook of GC-MS. Wiley-VCH Verlag GmbH & Co. KGaA, Weinheim, Germany 2015.

[8]   Kiontke, A., Billig, S., Birkemeyer, C., Response in ambient low temperature plasma ionization compared to electrospray and atmospheric pressure chemical ionization for mass spectrometry. *Int. J. Anal. Chem.* 2018, 2018, DOI: 10.1155/2018/5647536.

[9]   Li, D.-X., Gan, L., Bronja, A., Schmitz, O. J., Gas chromatography coupled to atmospheric pressure ionization mass spectrometry (GC-API-MS): Review. *Anal. Chim. Acta* 2015, 891, 43–61.

[10]   Mirabelli, M. F., Wolf, J.-C., Zenobi, R., Atmospheric pressure soft ionization for gas chromatography with dielectric barrier discharge ionization-mass spectrometry (GC-DBDI-MS). *Analyst* 2017, 142, 1909–1915.

[11]   Wolf, J.-C., Gyr, L., Mirabelli, M. F., Schaer, M., Siegenthaler, P., Zenobi, R., A Radical-Mediated Pathway for the Formation of [M + H]+ in Dielectric Barrier Discharge Ionization. *J.*

Am. Soc. Mass Spectrom. 2016, 27, 1468–1475.

[12]   Mirabelli, M. F., Gionfriddo, E., Pawliszyn, J., Zenobi, R., A quantitative approach for pesticide analysis in grape juice by direct interfacing of a matrix compatible SPME phase to dielectric barrier discharge ionization-mass spectrometry. *Analyst* 2018, 143, 891–899.

[13]   Mirabelli, M. F., Wolf, J.-C., Zenobi, R., Pesticide analysis at ppt concentration levels: coupling nano-liquid chromatography with dielectric barrier discharge ionization-mass spectrometry. *Anal. Bioanal. Chem.* 2016, 408, 3425–3434.

[14]   Moschet, C., Lew, B. M., Hasenbein, S., Anumol, T., Young, T. M., LC- and GC-QTOF-MS as Complementary Tools for a Comprehensive Micropollutant Analysis in Aquatic Systems. *Environ. Sci. Technol.* 2017, 51, 1553–1561.

[15]   Grosse, S., Letzel, T., Liquid chromatography/atmospheric pressure ionization mass spectrometry with post-column liquid mixing for the efficient determination of partially oxidized polycyclic aromatic hydrocarbons. *J. Chromatogr. A* 2007, 1139, 75–83.

[16]   Moyano, E., McCullagh, M., Galceran, M. ., Games, D. ., Supercritical fluid chromatography– atmospheric pressure chemical ionisation mass spectrometry for the analysis of hydroxy polycyclic aromatic hydrocarbons. *J. Chromatogr. A* 1997, 777, 167–176.

[17]   Ishibashi, M., Ando, T., Sakai, M., Matsubara, A., Uchikata, T., Fukusaki, E., Bamba, T., High-throughput simultaneous analysis of pesticides by supercritical fluid chromatography/tandem mass spectrometry. *J. Chromatogr. A* 2012, 1266, 143–148.

[18]   Desfontaine, V., Nováková, L., Guillarme, D., SFC–MS versus RPLC–MS for drug analysis in biological samples. *Bioanalysis* 2015, 7, 1193–1195.

[19]   Bieber, S., Greco, G., Grosse, S., Letzel, T., RPLC-HILIC and SFC with Mass Spectrometry: Polarity-Extended Organic Molecule Screening in Environmental (Water) Samples. *Anal. Chem.* 2017, 89, 7907–7914.

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