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Interface for Open Tubular Column Supercritical Fluid Chromatography/Atmospheric Pressure Chemical Ionization Mass Spectrometry

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A new interface for open tubular column supercritical fluid chromatography (SFC) to atmospheric pressure chemical ionization mass spectrometry (APCI-MS) is described. The interface was designed to permit transport of the supercritical mobile phase into the ionization region of the mass spectrometer while maintaining its temperature to within ±1 °C of the chromatographic oven temperature. Temperature control of the interface-transfer line was achieved using preheated gas streams from the chromatographic oven and an active electrical insulation. Ionization was achieved by a point-to-plane corona discharge. The performance of the SFC/MS interface is demonstrated using a number of selected analytes showing preserved chromatographic resolution, inertness in the transfer line, and independence of mobile-phase flow rate on ionization, as well as characterization of ionization and fragmentation patterns for compounds from different chemical classes. Test analytes included a polarity mixture over the solubility range of carbon dioxide. Minimum detectable quantities for anthracene and trilaurin were about 1 ng (S/N = 3) and 10 pg, respectively, while selected ion monitoring was used. An average retention time reproducibility of 0.24% RSD was displayed with an average 2.6% RSD in relative peak height. Retention time correlation between chromatograms obtained with flame ionization detection and mass spectrometric detection is also demonstrated.

INTRODUCTION

Supercritical fluid chromatography (SFC) has been demonstrated for the chromatographic analysis of a wide range of moderately polar, high molecular weight and thermally labile compounds. Open tubular column SFC is particularly useful for applications requiring separation of thermally sensitive compounds in complex mixtures; gas chromatographic (GC) like resolution is provided at temperatures below those causing thermal decomposition and with resolution greater than is provided in routine LC separations (conventional packed column). Open tubular SFC columns are frequently deactivated to such extent that unmodified CO_2 can be used as mobile phase, thus facilitating the use of universal flame ionization detectors (FID). Important applications have included selected biological and environmental samples, pharmaceuticals, and natural products.[1,2]

The interface of chromatographic techniques to mass spectrometry (MS) has proved to be an invaluable analytical tool in recent decades.[3] MS provides a wealth of information about the sample of concern, often permitting positive identification of specific analytes. Its coupling with SFC has thus proved useful for a variety of analytical applications.[4] The availability of both FID and MS detection in SFC is useful for method development, which can be performed with the relatively cheap and rugged FID, while final identification of sample components, advanced trouble-shooting, and method characterization can be done with the mass spectrometer. Publications so far have almost entirely treated conventional (reduced pressure) MS ion sources used in conjunction with open tubular and packed-column SFC.[5] It is, however, difficult to decouple an optimized chromatographic separation from an optimized ionization process with this setup. The ionization conditions will change over a density programmed separation, and cluster formations will influence the sensitivity of the system. More recent reports have demonstrated the suitability and desirability of interfacing SFC to atmospheric pressure chemical ionization (APCI-MS).[6,7]

APCI-MS has attracted considerable interest since its introduction[8,9] and has so far been most rewarding for interfacing mass spectrometry with liquid chromatography. The characteristic feature is the direct inlet of neutral molecules in the gas phase at atmospheric pressure followed by corona discharge ionization and transfer of the ions by electrostatic forces through a small orifice into the vacuum of the mass analyser. Positive ionization at atmospheric pressure is most often achieved through the creation of hydronium ion–water clusters, $H_3O(H_2O)_n^+$, which act as ionizing agents.[10]

Several features of the APCI technique make it attractive for use in conjunction with SFC. As ionization is usually very mild, the large and/or fragile molecules are charged but frequently remain unfragmented. The low fragmentation and high density of ions in the nonevacuated ion chamber of the APCI assists applications requiring detection of trace levels of analytes. Furthermore, since mobile-phase pressure or density frequently is programmed, the volumetric flow from the column increases during an analysis and, thereby, also

(1) Lee, M. L., Markides, K. E., Eds. *Analytical Supercritical Fluid Chromatography and Extraction*; Chromatography Conferences Inc.: Provo, UT, 1990; Chapter 7.

(2) Markides, K. E., Lee, M. L., Eds. *SFC Applications*; Brigham Young University Press: Provo, UT, 1989.

(3) Burlingame, A. L.; Baillie, T. A.; Russell, D. H. *Anal. Chem.* **1992**, *64*, 467R.

(4) Reference 1, Chapter 4.11.

(5) Olesik, S. V. *High Resolut. Chromatogr.* **1991**, *14*, 5.

(6) Huang, E. C.; Henion, J. J.; Covey, T. R. *J. Chromatogr.* **1990**, *511*, 257.

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(8) Horning, E. C.; Horning, M. G.; Carroll, D. I.; Dzidic, I.; Stillwell, R. N. *Anal. Chem.* **1973**, *45*, 936.

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the pressure in the ion source when conventional reduced-pressure ionization is used. Pressure changes in the ion source can have quite dramatic effects on the ionization.[5] When APCI is used in conjunction with capillary SFC, the conditions of the separation have little or no effect on the ionization processes; the two instruments are to a certain extent operating independently of each other. Finally, as ionization is performed outside of the MS vacuum chamber, restrictor maintenance and column changes are significantly more easy as disruption of the vacuum is unnecessary.

In a study by Henion et al., an LC/MS heated pneumatic nebulizer probe was modified to house an SFC restrictor and couple packed-column SFC to an APCI-MS with a corona discharge needle for ionization.[6] In further work[11] the same interface was briefly demonstrated with open tubular column SFC. Separation and detection of a synthetic mixture of anabolic estrogenic compounds (≈20 ng each) was thus permitted while total ion current monitoring was performed. Pleasance and co-workers have also considered the interface of packed-column SFC with APCI-MS.[7] Detection of apolar polyaromatic hydrocarbons was demonstrated with minimum detectable quantities in the order of 100–150 pg of benz[*a*]-anthracene (S/N = 2) for selective ion monitoring.

In the following study, an SFC/MS probe is described which was constructed for nondestructive chromatographic transfer between open tubular column SFC and APCI-MS using corona discharge ionization. The probe could also be used for packed-capillary SFC. Special attention was taken during its construction to eliminate local temperature variations and dead volumes along the column-restrictor/interface system and thus avoid any subsequent adverse effects upon the chromatographic integrity.[12,13] The temperature strongly effects both volatility and solubility of analytes during supercritical fluid analysis. In addition, SFC is used to analyze labile compounds, making local temperature control even more important. The interface was evaluated for open tubular column SFC using a carbon dioxide mobile phase and analytes of varying polarity and ionization character. Retention time correlation between SFC-FID and SFC/MS is presented.

EXPERIMENTAL SECTION

Chemicals. Pentacosanoic acid and its methanoate, trilaurin, and cholesterol and its palmitate were obtained from the Sigma Chemical Co. (St. Louis, MO); prostaglandin $F_{2\alpha}$ was obtained from KABI-Pharmacia Opthalmics (Uppsala, Sweden), and anthracene from Hopkins and Williams (Chadwell Heath, Essex, England). Solutions of these solutes for chromatographic analysis were prepared in hexane at concentrations of 0.6–90 mg/L (1–100 μM).

Supercritical Fluid Chromatography. Open tubular column supercritical fluid chromatography was performed using a Lee Scientific 600 supercritical fluid chromatograph (Dionex, Salt Lake City, UT) controlled by an ADI 386SX personal computer running ACI 600 C software. SFC-grade carbon dioxide (Scott Speciality Gases, Plumsteadville, PA) was selected as the mobile phase throughout this study. Separations were performed with a 10 m × 50 μm i.d. 30% biphenyl-substituted methylpolysiloxane fused-silica open tubular column (0.25-μm stationary-phase film thickness) (Dionex) using density programming. Sample introduction was performed using the injector of the chromatograph (CI4W, Valco, Houston, TX), fitted with a 0.2-μL sample rotor, for direct injections. An injection time of 0.5 s was selected and 50–100% solute transfer presumed.

Postcolumn mobile-phase flow restriction was performed using integral restrictors,[14] the latter produced by melting one end of a 50-μm-i.d. deactivated fused-silica tubing to desired diameter (less than 1 μm). Manufacturing of restrictors by direct melting was possible by the aid of a fusion splicer (PFS500 Fibre Splicer, Power Technology Inc., Little Rock, AR). The main components of the PFS500 are the following: a 50× microscope with illumination, an electric arc with thumbwheel presets for discharge current and time, and mechanics for precision alignment of two optic fibers. By positioning the end of the fused-silica tubing in the electric arc and while monitoring the process in the microscope, applying successive discharges, the first 2–4 at 15 μA and 0.5 s, then 1–5 at 14 μA 0.5 s, and finally 1–2 at 13 μA 0.5 s, integral restrictors could be produced without polishing.

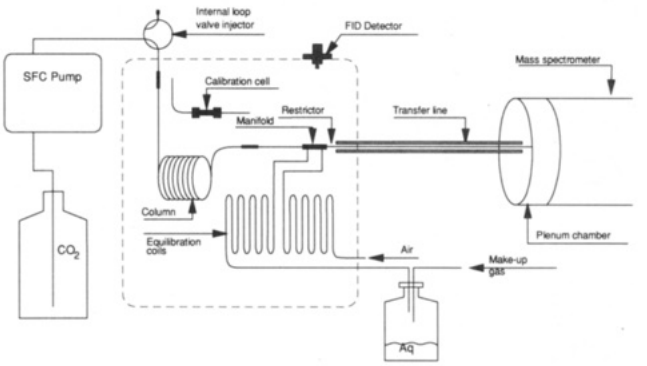

Figure 1. SFC/MS interface schematics. Note that the only point where the restrictor is physically attached to the interface is at the manifold inside the oven.

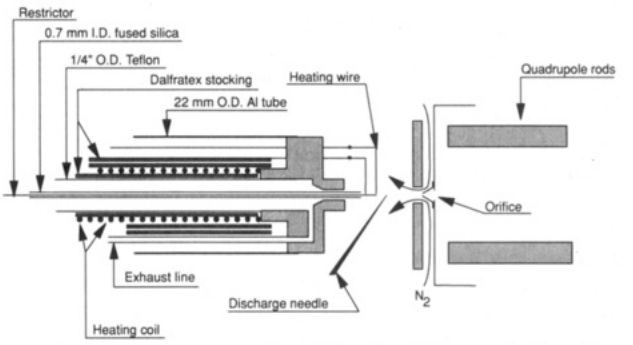

Figure 2. Ion source assembly and details of the transfer line. See text for details.

The restrictors were 0.8–1.0 m long and extended from the oven, through the transfer line, and into the ion source. The column-to-restrictor connection was made inside the oven, using a Valco $^1/_{16}$-in. ZUT union with a length of $^1/_{16}$-in. o.d., 0.01-in.-i.d. PEEK tubing (Scantec, Partille, Sweden) and a single graphitized Vespel ferrule (Valco).

SFC/MS Interface. The interface was designed and constructed in-house and consisted of three major parts (schematically shown in Figure 1): the gas manifold (consisting of two tee connections in series) and temperature equilibration assembly, placed inside the SFC oven; the transfer line, used to transfer the supercritical mobile phase from the oven to the ionization region and, finally, the ion source assembly (Figure 2), where the supercritical fluid mobile phase is vaporized. A temperature limit of 150 °C was considered during the design of the interface-transfer line and manifold. The simplicity of the final construction was such that the restrictor required fixture to the ion source at only one place: the nut and ferrule connection at the gas manifold inside the chromatographic oven.

The restrictor was guided through the transfer line within its central length of 0.7-mm-i.d. fused-silica tubing (PolyMicro Technologies, Phoenix, AZ), through which a make-up flow of synthetic air (FID quality; AGA, Stockholm, Sweden) was passed. The 0.7-mm-i.d. tubing was fixed inside a $^1/_4$-in.-o.d. Teflon tubing, through which a flow of ordinary compressed ("house") air was passed. The compressed air was not allowed to enter the ion source. The make-up gas and the compressed air were both preheated to oven temperature in coiled (2-m-long, $^1/_8$-in.-i.d.) stainless steel tubes placed in the oven. The make-up gas was moistened by sparging it through water before entering the oven.

(11) Reference 1, pp 280–2.
(12) Reference 1, Chapter 4.3.
(13) Reference 1, Chapter 4.10.
(14) Guthrie, E. J.; Schwartz, H. E. *J. Chromatogr. Sci.* **1986**, *24*, 236.

The $^1/_4$-in. flexible Teflon tubing was surrounded by a layer of aluminum foil (household quality), intended to equilibrate local temperature variations. A ceramic fiber fabric high-temperature insulation (Dalfratex stocking, Chemical & Insulating, Darlington, UK) was threaded over the Al foil. Around the Dalfratex stocking, a 0.2-mm heating wire was wound at 1.5 mm/turn followed by four layers of Dalfratex stocking. This heating coil was acting as an "active insulator" not adding heat to the fluid in the transfer line, but supporting the preheated gases to not lose heat over the length of the transfer line. A type J (constantin–iron) thermocouple was placed between the Teflon tube and the Al foil and connected to a temperature controller present in the mass spectrometer. The output of the controller (120 V, PID on/off regulated) was connected to the heating wire coiled around the transfer line. The combination of the flow of oven-preheated gases through the transfer line and the active thermal insulation provided by the electrical heating of the transfer line exterior sought to prevent any net heat transportation to or from the restrictor during its path from the oven to the ion source, thus maintaining the chromatographic integrity. A small heating coil was placed at the restrictor tip in order to avoid increased flow restriction from condensed analytes in the expansion through the restrictor. This was operated from an in-house-built power supply which provided a reading of the power applied. Heating (0.5–1 W) was needed in order to yield stable ion currents.

Mass Spectrometry. The mass spectrometer was a Sciex API III tandem quadrupole (Sciex, Thornhill, ON, Canada), equipped with a corona discharge ion source. For optimization of the SFC interface, an LC precolumn (30 × 4 mm i.d., packed with 5-μm C_{18} SiO_2 particles) was connected between the SFC pump and restrictor. Before use, the column was preloaded with cholesterol palmitate dissolved in hexane and dried with CO_2 using a 50-atm inlet pressure and an unrestricted outlet. This column, saturated with standard and then exposed to dynamic supercritical fluid extraction, provided a reasonable constant signal for tuning mass spectrometric parameters. Alignment and gas flows of the interface were adjusted together with tuning and mass calibration of the mass analyzer while the characteristic ions (m/z = 369, 625) were monitored when the column was extracted with CO_2 at 220 atm and 85 °C (density 0.61 g/mL). During chromatography, either full-scan mass spectra in the range m/z = 20–800 or selected ion chromatograms were recorded.

RESULTS AND DISCUSSION

The SFC/MS interface was constructed to maintain the integrity of the inert and high-resolution chromatographic system and to efficiently produce charged or protonated molecular ions with low fragmentation while bearing in mind the requirements of open tubular column SFC. For example, the normal increase in mobile-phase density and flow during the analysis should not result in altered ionization mechanism and efficiency. A number of criteria were put forward to optimize the interface toward trace analysis of thermally labile moderately polar compounds. These were as follows: carefully controlled interface temperature; inertness; flow dynamics; accurate calibration; minimal dead volume in the interface; ease of changing the restrictor and possibilities to switch between FID and MS detection with preserved retention times.

At constant pressure, the density of the supercritical mobile-phase increases and the volume decreases when the temperature is lowered. An increase in temperature, on the other hand, will lead to decreased density and solvating power of the supercritical fluid. Local temperature variations along the transfer line can, therefore, cause loss of chromatographic resolution and lost correlation in retention times between MS and FID. In an earlier design of the interface, the use of a preheated air stream alone to maintain the oven temperature along the 0.5-m length of the interface failed. The best result obtained with this method was a 6 °C decrease in temperature over the length of the interface, although it provided a transfer line without any local variations in temperature. The primary reason for this was that the diameter of the transfer line, and thereby the thickness of the insulation, was limited by the hole in the inlet adaptor of the mass spectrometer (22-mm i.d.). Although it was possible to build a new inlet adaptor for the MS, allowing thicker insulation, it was not pursued at this time.

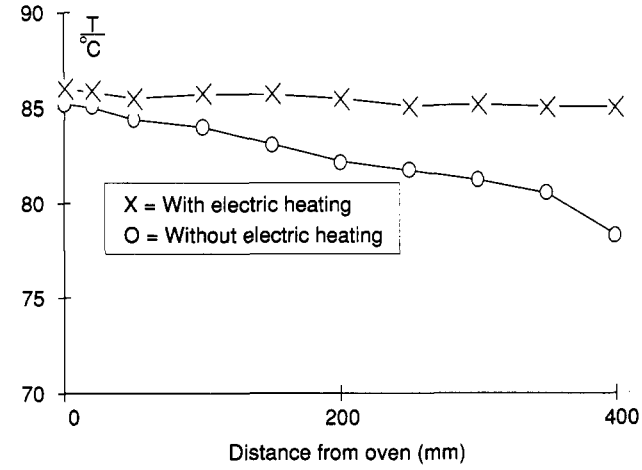

Figure 3. Temperature vs distance from oven.

Attempts to use active electric heating alone resulted in local temperature variations of ±5 °C and long equilibration times (30–45 min). However, through the combination of active electrical insulation and the preheated air stream the supercritical mobile phase was transported into the ionization region of the mass spectrometer while its temperature was maintained to within ±1 °C of the oven temperature. Figure 3 shows the temperature measured inside the outer fused-silica capillary vs distance from the oven when the preheated air stream was used alone and together with active electrical insulation.

The essential role of water for collision-induced dissociation ionization that is known for APCI sources also became apparent during this study. When no moisture was added to the make-up gas, the discharge current became subject to intermittent disrutpion after about 1 h of use. It was concluded that the dry make-up gas and likewise dry CO_2 mobile phase successively displaced any moisture present in the plenum chamber at the beginning of the experiment. The necessity of protonated hydronium ion clusters to act as charge- and proton-transfer intermediates is well-known.[10] The water-rich make-up gas had to be used at over 0.5 L/min to obtain maximum sensitivity, stable ions, and symmetrical peaks. The effect that this flow rate has on local flow dynamics within the ionization region is also recognized and should be a subject for further investigations.

The performance of the SFC/MS transfer line was evaluated by comparing the detector response in FID and MS detection using the same chromatography column and restrictor assembly. The upper trace in Figure 4 is a total ion current (TIC) chromatogram obtained for four medium polar test analytes while the lower trace shows the same analytes detected by FID. Control over the restrictor tip temperature is an important tool for baseline stability and for fine tuning the linear flow velocity of the mobile phase, since different restrictors often are used for the FID and MS detectors. Increasing restrictor temperature leads to decreased flow rate and vice versa.[15] Matched retention times for standard mixtures are demonstrated in Figure 4. The importance of good correlation between FID and MS retention time for the

(15) Smith, R. D.; Fulton, J. L.; Petersen, R. C.; Kopriva, A. J.; Wright, B. W.; *Anal. Chem.* **1986**, *58*, 2057.

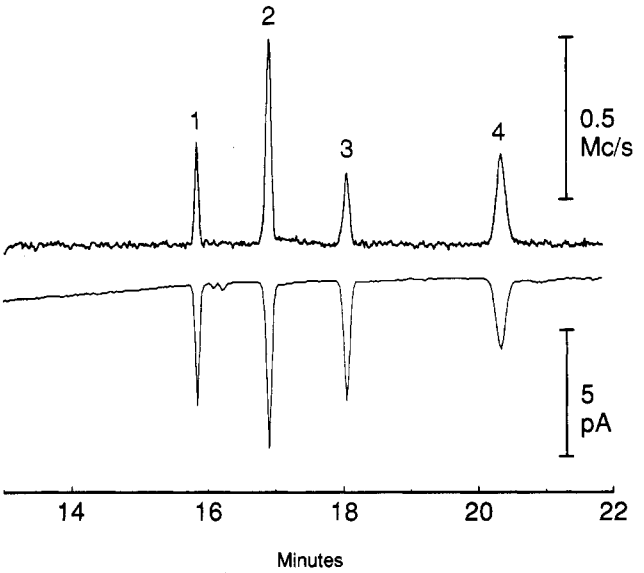

Figure 4. Comparison of SFC/APCI-MS detection and FID detection. Conditions: 10 m × 50 μm i.d. 30% biphenyl-substituted methylpolysiloxane fused-silica open tubular column; density program at 80 °C from 0.170 to 0.77 g/mL at 0.05 g/(mL min) after a 3-min isopycnic period. (A, top) Sum of extracted ions (XIC), scans between *m/z* 290 and 650. Mc/s indicates million counts per second. (B, bottom) FID chromatogram, the same chromatographic conditions as in (A), 240 °C detector temperature. Sample components (10 ng of each): (1) pentacosanoic acid methanoate, (2) trilaurin, (3) cholesterol, and (4) cholesterol palmitate.

Table I. Reproducibility in Retention and Relative Peak Height[a]

		FID			MS		
		average	SD	RSD	average	SD	RSD
rel height	A	35.0	2.18	6.2	19.2	0.43	2.2
	B	26.3	1.00	3.8	41.6	0.38	0.9
	C	29.5	1.52	5.1	18.9	0.60	3.2
	D	9.2	0.42	4.6	20.3	0.81	4.0
retention	A	16.4	0.010	0.06	13.6	0.04	0.28
	B	17.5	0.008	0.05	14.8	0.02	0.13
	C	18.8	0.008	0.04	15.6	0.06	0.38
	D	21.2	0.005	0.03	17.0	0.03	0.17

[a] Reproducibility in relative height (as percent of sum of peak heights) and retention time (minutes) for SFC-FID and SFC/MS (n = 6). Different restrictors were used for FID and MS detection. Sample components: (A) pentacosanoic acid methanoate, (B) cholesterol, (C) trilaurin, and (D) cholesterol palmitate. RSD, relative standard deviation in percent. See text for discussion.

analysis of unknown trace compounds should not be underestimated.

Numerical data from repetitive injections are summarized in Table I. The reproducibility for repetitive injections in the SFC/MS system gave 0.13–0.38% RSD on retention time (average 0.24%, ca. 2 s) and 0.9–4.0% RSD on relative peak height (average 2.6%). This compares with a retention time reproducibility of less than 0.07% and an average relative peak height reproducibility of 4.9% with the FID.

Both chromatograms in Figure 4 (XIC and FID) and the TIC chromatogram in Figure 5 were obtained by injecting 10 ng of each sample component in a standard mixture, indicating a detection limit in the nanogram range for TIC chromatograms. Detection limits when selected ion monitoring (SIM) is performed depend on both ionization efficiency and background interferences. Figure 6 shows the SIM traces obtained after injection of 20 ng of anthracene (A) and 130 pg of trilaurin (B). These two substances represent extremes in detection limits anthracene yields a poor signal in a region

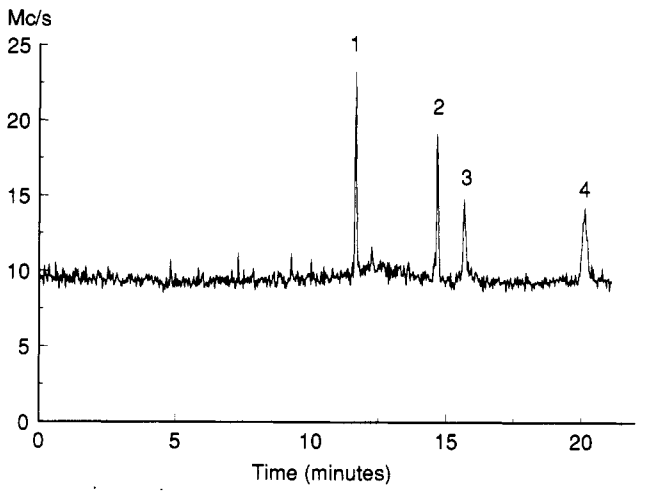

Figure 5. TIC chromatogram. Chromatographic conditions as in Figure 4, but with a different restrictor. Sample components (10 ng of each): (1) stearic acid methanoate, (2) trilaurin, (3) cholesterol, and (4) cholesterol palmitate.

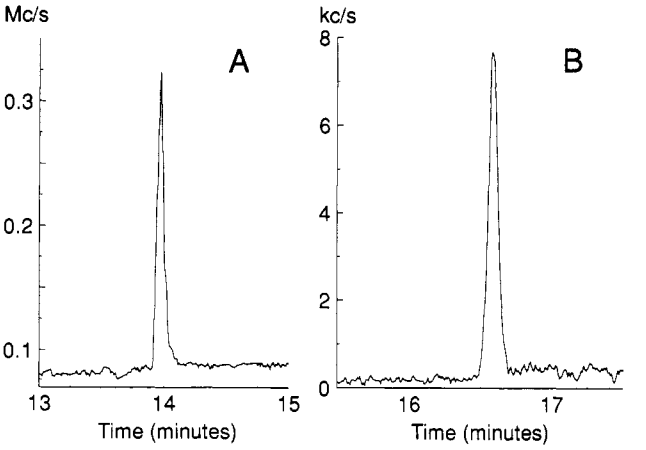

Figure 6. SIM traces obtained after injection of 20 ng of anthracene (A) and 130 pg of trilaurin (B), while the characteristic ions (*m/z*) 179.2 and 639.6, respectively) were monitored. Note that the baseline signal in (A) represents a level 100 times higher than the analyte signal in (B). Chromatographic conditions as in Figure 4.

with high background (m/z = 179.2), while trilaurin yields a high signal in a region essentially without background interferences (m/z = 639.6). The limit of detection in the SIM mode was estimated to be 10 pg for trilaurin and 1 ng for anthracene (S/N = 3).

The ionization characteristics for the test solutes were evaluated using the SFC/MS interface with corona discharge current of 12 μA at atmospheric pressure with the carbon dioxide mobile phase and a make-up flow of moistened air. In this initial study it was found that the different sample components did not all give the characteristic $(M + 1)^+$ protonated molecular ion as a single response. In Figure 7, for example, it can be seen from the mass spectrum for cholesterol that the mass 369 $(M - 17)^+$ is dominant from the loss of the 3′-OH group during ionization. The spectrum for cholesterol palmitate is shown in Figure 8. Here it can be seen that the peak for m/z = 369 also is present in this spectrum, indicating that the ester bond of cholesterol palmitate is broken during ionization. The described fragmentation patterns were reproducible in this instrumental setup. Strong dependence of fragmentation on the orifice potential is expected and can also be seen in Figure 9, which shows the steady-state ion currents for the fragments with m/z = 369 and 642 as a function of the orifice potential when the calibration column is extracted.

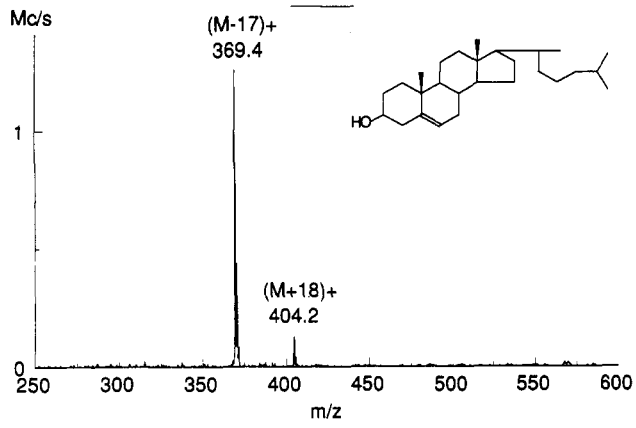

Figure 7. Background-subtracted mass spectrum obtained after injection of 10 ng of cholesterol. Chromatographic conditions as in Figure 4.

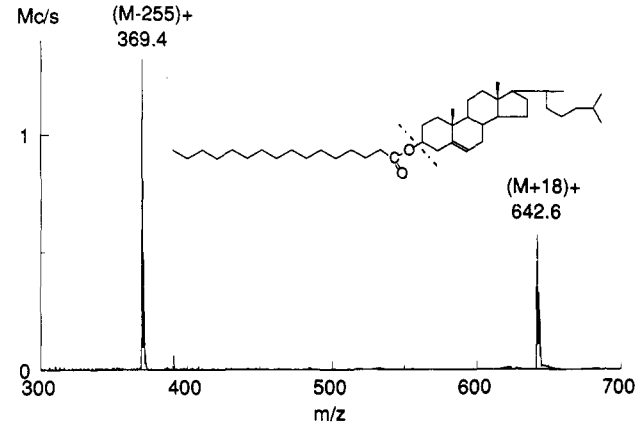

Figure 8. Background-subtracted mass spectrum obtained after injection of 10 ng of cholesterol palmitate. Note that only the M – 17 peak for cholesterol is abundant, which probably is due to the fragmentation mechanism.

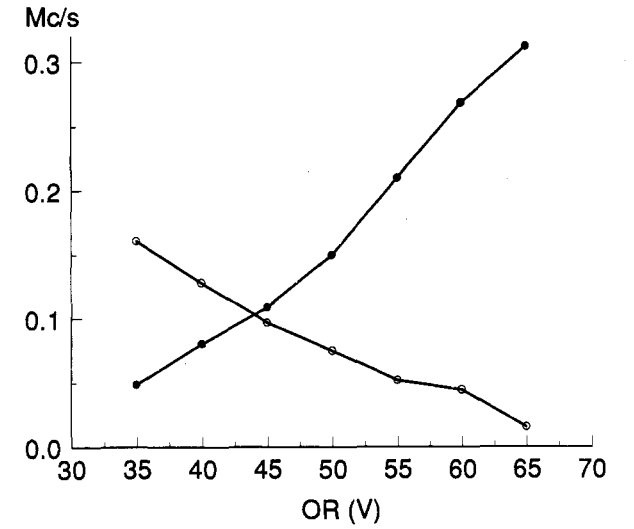

Figure 9. Dependency of steady-state ion currents for cholesterol palmitate (m/z = 642.6, O) and cholesterol (m/z = 369.4, ●) on orifice potential obtained when the calibration column was extracted at 80 °C and 180 atm (ρ = 0.54 g/cm^3). The potential of the first quadrupole was 30 V. Extrapolation of the ion current for cholesterol to 30 V suggests that most of the fragmentation occurs in the region between the orifice and the first quadrupole.

As previously mentioned, supercritical fluid chromatography is known to interfere with traditional (reduced-pressure) chemical ionization and electron impact ionization, this because of the increased gas loads experienced in the ionization chamber during the progress of density/pressure-programmed

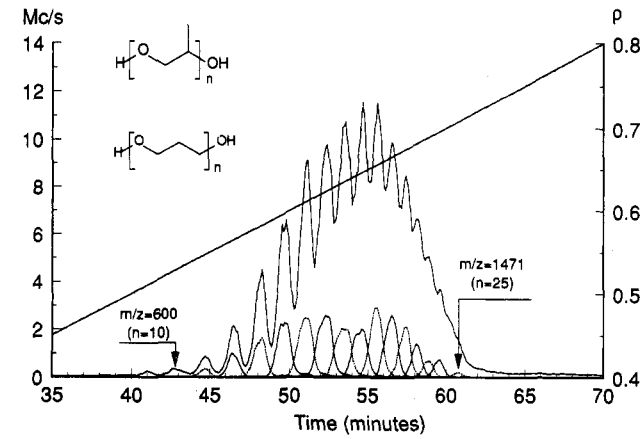

Figure 10. Background-subtracted total ion current (upper trace) and the individually extracted selected ions (lower traces) of a sample of isomeric polyols. Also shown is the density of the mobile phase (straight line, right scale). Both the suggested structures would give rise to the same spectra. Density program at 100 °C from 0.150 to 0.77 g/mL at 0.01 g/(mL min) after a 5-min isopycnic period.

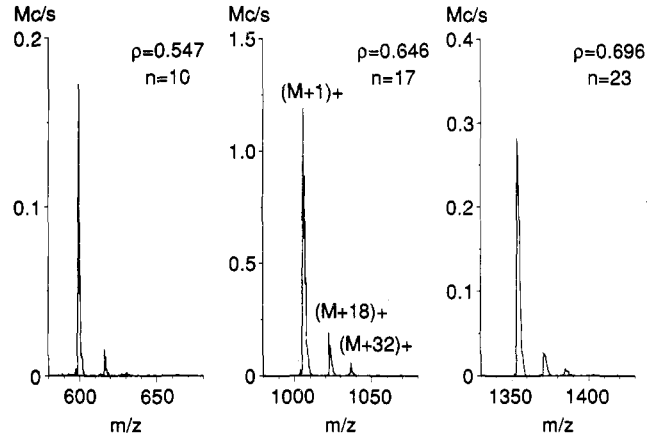

Figure 11. Spectra for three of the polyols. See text for further details and discussion.

separations. In order to investigate the influence of changed CO_2 flow rate, a polymer mixture was injected. Figure 10 shows the background-subtracted TIC and the XIC for the individual polymeric isomers. In Figure 11, three spectra are shown that were obtained in the beginning, middle, and end of the SFC separation. The three spectra all show the same ion pattern of similar relative intensity, suggesting no major influence of the mobile-phase flow rate on the ionization mechanism.

In order to illustrate the characteristics of ionization of compounds from different chemical classes in the SFC/APCI interface, some selected applications are shown in Figure 12. Figure 12A is a background-subtracted mass spectrum of prostaglandin $F_{2\alpha}$ isopropanoate. Prostaglandin derivatives tend to give rise to slightly complex spectra, with complexity being partly controllable by the orifice potential. Figure 12B shows an even more complex mass spectrum obtained by the injection of 20 ng of bis(α-epoxyacrylate). The spectra of trilaurin and stearic acid methanoate in Figure 12C and D, respectively, on the other hand, demonstrate examples of compound types that only show water addition and almost no fragmentation.

The importance of being able to tune the performance of the ion formation for selected analytes eluting from the SFC restrictor to the ion source was considered when this interface was being constructed. While studying the effect of different variables upon ion formation, the performance of a continuous slow supercritical fluid extraction (SFE) of the selected analyte

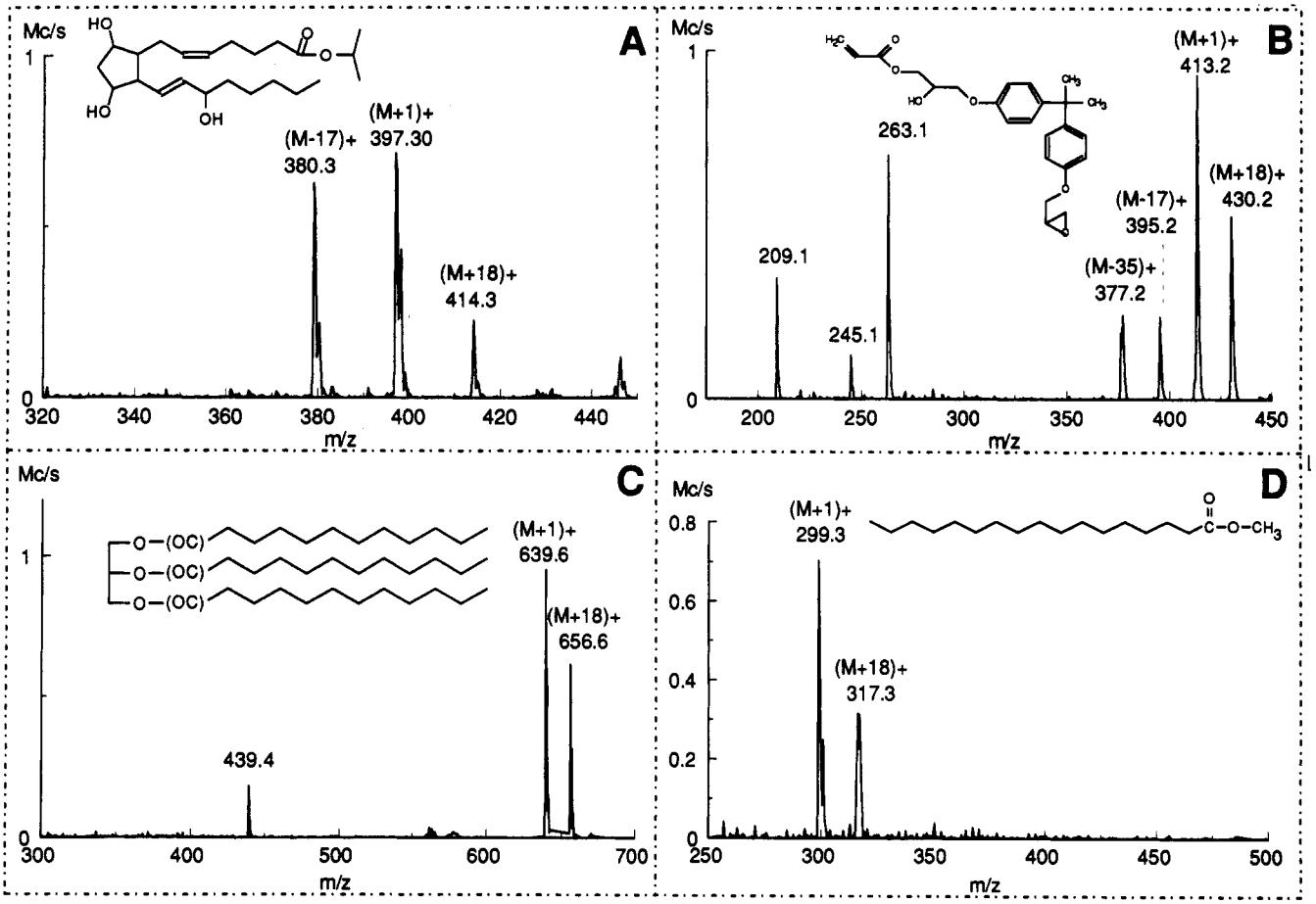

Figure 12. Background-subtracted mass spectra for 10-ng injections of selected analytes: (A) prostaglandin $F_{2\alpha}$ isopropanoate and (B) bis(α-epoxyacrylate), no satisfactory assignment of the peaks below m/z = 300 has been reached yet; (C) trilaurin, note the peak at m/z = 439.4, which corresponds to the loss of one fatty acid chain (m/z 199.2); and (D) stearic acid methanoate.

from an adsorbent through the SFC/MS interface with the same restrictor as used for the chromatography proved to be a particualrly useful method for optimization (see Figure 1). The most obvious parameters such as make-up flow, tip heating, corona discharge current, orifice potential, and position of restrictor tip and discharge needle were thus manipulated. Manual optimization of the mentioned parameters was much faster and easier when a continuous signal was monitored than it would have been if repetitive injections had to be performed.

Finally, the ease of operation was highly valued for the SFC interface. The time required to change restrictor or move the restrictor from the FID to the MS took about 30 min if no tuning was required. The time required to connect the packed calibration column, tune the interface, and reconnect the open tubular column was normally less than 1 h. This was made possible by the 0.7-mm-i.d. fused-silica capillary in the interface acting as a guide for the restrictor.

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