ELSEVIER

Journal of Chromatography A, 703 (1995) 265–276

JOURNAL OF CHROMATOGRAPHY A

Review

Development of the transfer techniques for on-line high-performance liquid chromatography–capillary gas chromatography

Konrad Grob

Kantonales Labor, P.O. Box, CH-8030 Zurich, Switzerland

Abstract

The review passes through nearly 15 years of development of LC–GC transfer techniques, listing the concepts proposed and discussing the reasons why many of them were not followed up. On the one hand, a number of ideas should be re-evaluated in order to check whether the best choices were made, further elongating the list of techniques in use. On the other, success of LC–GC requires that a minimum number of transfer techniques are selected and promoted in order to get them implemented into standardized methods and bring more LC–GC into routine laboratories.

Contents

0021-9673/95/$09.50
SSDI 0021-9673(95)00094-1

1. Introduction

The first on-line coupled LC–GC system was described about 15 years ago [1]. In the meantime, many ideas have been brought up, of which only a few have been worked out to a perfection suitable for routine applications. In fact, only concurrent eluent evaporation with the loop type interface and the retention gap techniques (mostly involving partially concurrent evaporation) with the on-column interface have become routine so far.

1.1. Are we sure about having made the best choices?

This not necessarily disqualifies the other concepts. Evolution of techniques involves a great number of choices and is a process guided by many circumstances, such as the persons involved, their particular preferences, knowledge, and, last but not least, by the job they are really paid for (to my knowledge, there has never been a professional LC–GC developer). Choices are rarely made in an open way —usually some people put efforts in one route, for whatever their reasons are, and others follow without considering possible alternatives. Most likely many of the best ideas have been left idle without sufficient evaluation, maybe simply because of lacking time by the originator to pursue it. A review on transfer techniques was recently published by Vreuls et al. [2].

This paper provides an overview of the LC–GC transfer techniques, listing the successful ones as well as others, of which hardly anybody speaks anymore, discussing the reasons why the latter might not have been prosecuted further. Discussion occurs, of course, from the perception of the author and the applications he thinks LC–GC could be an interesting technique for.

1.2. Why on-line LC–GC?

There are two main reasons why on-line coupling of HPLC to GC should become an important analytical technique. Firstly, HPLC provides far better resolution than conventional techniques of sample preparation, e.g., involving cartridges: the column separates at high efficiency; direct control by the LC detector enables to well optimize conditions and accurately cut the window of the component(s) of interest. Secondly, automation through on-line coupling massively reduces or even virtually eliminates manual sample preparation work, which enhances reliability and saves time —in many cases, a type of complex analysis only becomes feasible in this way.

There also appear, however, to be two reasons against using on-line coupled systems: firstly, knowledge about chromatography tends to diminish; there seem to be ever fewer people capable of developing and handling sophisticated methods. Secondly, quality assurance by paper work around classical methods is more fashionable than analytical improvement. Apparently priorities have changed, maybe because the determining analysts moved into the office.

Whatever the trends are, a good number of methods, applied to thousands of samples, have proven the capabilities of on-line LC–GC. They were summarized by several recent reviews [3–7].

2. At the beginning

In 1980, Majors [1] coupled LC to a conventional vaporizing GC injector via an autosampler. Since only a few microlitres could be transferred, merely a small proportion of the LC fraction of interest was analyzed by GC. For trace analysis, this resulted in poor sensitivity, because the capacity of the LC column does not allow wasting solute material. Secondly, reliability of quantitative determinations was unsatisfactory because slight shifts in LC retention times caused the fraction analyzed by GC to be taken from another intensity of the LC peak. Thirdly, as shown in a directing paper by Apffel and McNair [8] on the analysis of gasoline, group-type analysis was difficult. Partial separation of components within a group, in fact, calls for the transfer of the whole LC fraction.

Raglione et al. [9] improved this kind of LC–

GC transfer by an "isotachic eluent splitter": the large volume of a broad LC fraction was reduced by splitting with a system of bundled capillaries. Sensitivity remained low, however.

On-line LC–GC requires transfer to GC of an LC fraction comprising a whole peak or even a range of peaks. Such LC fractions usually have, however, volumes in the range of 100–1000 μl, even if carefully minimized (relatively short retention time, diameter of the LC column reduced to the minimum determined by the capacity required). For this reason, introduction of large volumes into GC turned out to be the key to on-line LC–GC.

3. On-column transfer

In the early 1980s, on-column injection of large volumes was developed after investigation of the solvent effects for the reconcentration of volatile solutes and the retention gap technique for focusing of bands broadened in space. Simplicity and excellent performance suggested its use for an on-line LC–GC system. Our first applications involved uncoated precolumns of 50–60 m in length and transfer volumes of 300–400 μl [10]. Cortes et al. [11] used an LC column consisting of a packed fused-silica capillary, which reduced the fraction volume to some 40 μl.

Present routine LC–GC nearly exclusively transfers by on-column techniques, although with substantial modifications of conventional syringe on-column injection. By "on-column" we understand any technique involving evaporation in the oven-thermostatted column or precolumn. Table 1 shows an overview.

3.1. Retention gap techniques

Retention gap techniques are characterized by volatile components being reconcentrated through solvent trapping whereas high boiling substances, spread throughout the flooded zone, are focused in the inlet of the separation column through the retention gap effect [12]. As in on-column injection of large volumes, solvent evaporation is performed in an uncoated precolumn kept below the pressure-corrected solvent boiling point. At least part of the sample liquid forms a film on the wall of the uncoated precolumn. In the carrier gas stream, the eluent evaporates from the rear to the front of this film. (Fig. 1).

Small-bore LC columns (0.25–1 mm I.D.) provide fractions with typical volumes between 3 and 100 μl; flow-rates are small (2–70 μl/min). This well fits the conventional retention gap technique, i.e. an uncoated precolumn of, e.g., 15 m × 0.32 mm I.D. without an early vapour exit. LC columns of 2–3 mm I.D. provide fractions larger than can be retained in convenient uncoated GC precolumns, i.e. require partially concurrent eluent evaporation. To protect the GC detector, but also to accelerate solvent evaporation to a rate fitting suitable LC flow-rates (150–300 μl/min), an early vapour exit is used.

Efficient retention of sample liquid on the wall of an uncoated precolumn presupposes the formation of a sample film, i.e. wettability of the

Table 1
On-column LC–GC transfer techniques, the range of fraction volumes and LC columns they are most suitable for, and their applicability to samples containing volatile solutes

Evaporation technique	Volume (μl)	LC column	Volatile solutes?
Conventional retention gap technique	1–150	0.25–1 mm I.D.	Yes
Partially concurrent evaporation	50–800	2–3 mm I.D.	Yes
Concurrent evaporation	100–3000	1–8 mm I.D.	No
Concurrent evaporation with co-solvent trapping	100–1000	1–5 mm I.D.	±
Etzweiler bulb	100–1000	1–5 mm I.D.	±

± = Intermediate performance.

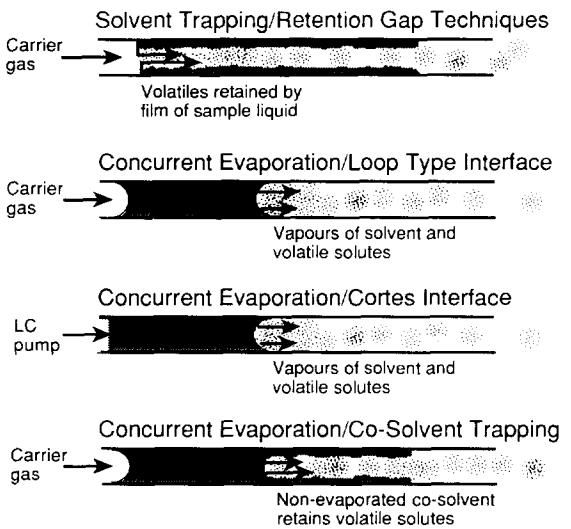

Fig. 1. Modes of solvent evaporation for on-column transfer: evaporation zone in the column inlet.

capillary wall. All organic solvents wet appropriately treated capillary walls, but no surface suiting GC has been found that would be wetted by water [13]. This severely limits the application for reversed-phase LC–GC. Some mixtures of water with organic solvents initially form stable films, but since the organic solvent evaporates more rapidly, it leaves behind an unstable water film. Only mobile phases consisting of propanol with up to 28% water or acetonitrile with up to 16% water can be used. Water in the condensed phase, furthermore, is aggressive and attacks the deactivation of the precolumn [14]. There has been significant progress in producing chemically more stable precolumns, however [15–18].

If a large proportion of the eluent is evaporated during introduction (partially concurrent evaporation, using the on-column interface and an early vapour exit), transfer of 500-μl fractions is easy; 1000 μl is probably the upper limit.

LC–GC transfer by the retention gap techniques provides the most perfect performance: there are no losses (e.g. of high boiling, labile, or adsorptive components) in a vaporizing chamber, and even highly volatile solutes form peaks perfect in shape and area (e.g. heptane can be quantitatively analyzed in pentane).

3.2. Concurrent eluent evaporation

Concurrent eluent evaporation volatilizes all of the eluent during its introduction into the GC precolumn; no liquid floods the GC system. Volatile components are lost by co-evaporation with the solvent, since there is no solvent trapping.

The first experiments were performed with the on-column interface. Using the loop-type interface, however, the transfer is almost completely selfregulated: the eluent flow-rate into GC is automatically adjusted to the evaporation rate, since the carrier gas pushes the liquid against its own vapour pressure (Fig. 1). As only parameter to be adjusted, the oven temperature must exceed the pressure-corrected eluent boiling point. Transfer of 1 ml is easy; the record stands at 20 ml.

Volatile eluents (like pentane) enable to analyze components eluted at oven temperatures above 120–140°C; more volatile components are lost through the early vapour exit and/or form broad peaks. Applicability of the method is, therefore, restricted, but owing to its simplicity and robustness, the method is applied wherever possible —in fact, it is the transfer technique most commonly applied.

Since no film formation in the uncoated precolumn is required, wettability is uncritical, i.e. the method should, in principle, be applicable also for water and water-containing solvent mixtures. Transfer of eluent consisting of methanol–water (6:4) confirmed this, but also indicated that "shooting" liquid (evaporation with delay) may be a problem [19]. Furthermore, as a result of the relatively high transfer temperature and absence of phase soaking, the first perfectly shaped peaks were eluted at 240°C only (250 μl transfer volume). Also this technique has, therefore, limited suitability for water-containing eluents.

The analysis of sterol dehydration products in edible oils may serve to demonstrate the potential of LC–GC. The method, used for the determination of various kinds of adulteration [20–22], replaced a manual method requiring a large amount of time for sample preparation,

column packing material, and solvent: now a 1:5 diluted oil is directly injected. Preseparation involves two-dimensional HPLC and is, of course, more efficient than that by conventional liquid chromatography. On-line clean-up almost completely avoids contamination during sample preparation and enabled reliable detection at low concentrations. Chromatograms in Fig. 2 show the transfer of various LC peaks of interest (500-μl fractions) to GC using concurrent evaporation, as actually used for peak identification by on-line LC–LC–GC–MS. Over 3000 samples were analyzed by this method, which would not have been possible without virtually complete automation.

3.3. Cortes interface

The Cortes interface [10,23] pumps the LC fraction into the GC precolumn while the carrier gas supply is stopped. At column temperatures

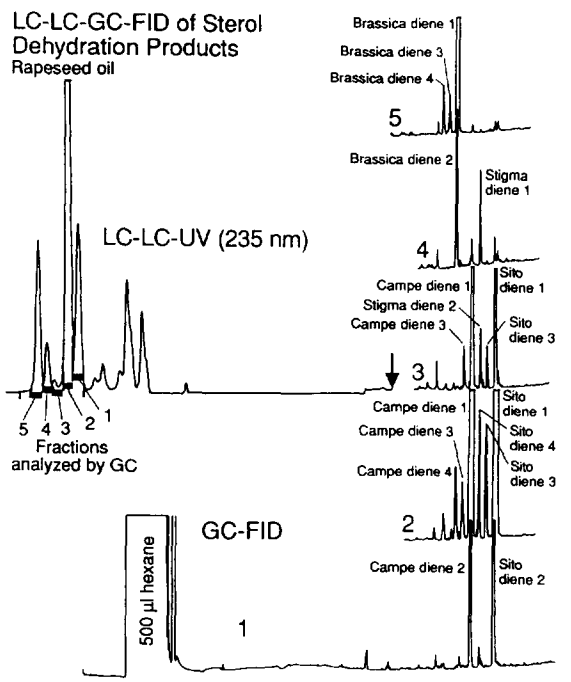

Fig. 2. LC–LC–UV chromatogram of the sterol dehydration products of a refined rapeseed oil and LC–LC–GC–flame ionization detection (FID) chromatograms of the LC peaks of interest (fractions 1–5). From [22].

below the standard eluent boiling point, the fraction floods the precolumn; evaporation only starts after transfer is completed. Used in this way, performance corresponds to the on-column interface (i.e. solvent trapping enables analysis of the volatile solutes), but partially concurrent evaporation is not feasible and the fraction volume is, therefore, limited to about 100 μl (depending on the size of the uncoated precolumn).

When the column temperature during transfer is kept above the standard boiling point, eluent evaporates at the front of the flooded zone by a kind of overflow: beginning with the transfer, vapours are discharged as a result of expansion and a vapour pressure exceeding ambient pressure (Fig. 1). At the end of the transfer, the valve is switched back and the carrier gas returns to the column, spreading the remaining liquid deeper into the uncoated precolumn. Evaporation is partially or fully concurrent, depending on the oven temperature during transfer (vapour pressure driving the eluent vapours through the column or the early vapour exit). This kind of partially concurrent evaporation does not, however, result in complete retention of volatile solutes, i.e. it does not enable quantitative analysis of early-eluted components. Excellent results were described for many applications involving relatively small transfer volumes. Transfer of volumes exceeding 100 μl should be possible, but no results have been published.

3.4. Co-solvent trapping

Co-solvent trapping was investigated because of its potential of reducing losses of volatile components during concurrent evaporation of the main eluent. If solvent trapping could be achieved within the concurrent evaporation/loop-type interface system, the on-column interface would no longer be needed.

The co-solvent consists of a small amount of a higher-boiling solvent added to the eluent. Transfer was performed with the loop-type interface and an early vapour exit [24], adjusting conditions and concentrations such that the main solvent evaporated concurrently, but a limited

amount of condensed co-solvent was left behind to trap the volatile solutes (bottom of Fig. 1).

The technique was first investigated for pentane with heptane as co-solvent [25], looking for a concentration of heptane which exceeded that co-evaporating with the pentane, but did not overtax the capacity of the uncoated precolumn to retain liquid. Suitable heptane concentrations depended on conditions, particularly the column temperature during evaporation. Perfectly shaped peaks of accurate area were obtained for components as volatile as the xylenes when introducing 500 μl of a pentane solution with 5% heptane. The uncoated precolumn was merely 4 m long (0.53 mm I.D.). However, optimization required a fair amount of experimentation and no simplifying working rules could be derived.

Co-solvent trapping was never routinely applied to the transfer of normal-phase eluents because partially concurrent evaporation with the on-column interface was more simple to apply. It was occasionally used for other techniques, such as for retaining volatile solutes in solvent-split programmed-temperature vaporizing (PTV) injection (Termonia et al. [26]). Our experience indicated, however, that the range of suitable conditions is narrow and that co-solvent trapping with ideally evaporating mixtures presupposes accurately controlled temperature (a problem in PTV injection, because the injector temperature drops during solvent evaporation).

Co-solvent trapping was primarily of interest for the transfer of water-containing eluents, because it seemed to be a promising solution for the main problems of the retention gap techniques: concurrent evaporation does not require wettability, and co-solvent trapping retains the volatile solutes. Since transfer must occur at 110–120°C, the first solutes amenable to GC analysis could be those eluted at these temperatures.

Formation of azeotropic mixtures between water and the co-solvent was helpful for the optimization of conditions: the co-solvent concentration just had to slightly exceed that of the azeotropic mixture. The latter is known and only weakly depends on conditions. Of the numerous organic (co-)solvents tested, butoxyethanol was found best suited (b.p. 171°C, azeotropic mixture with 78% water, boiling at 99°C) [27]. Results were, in fact, promising: the methyl ester of the C_{12} fatty acid could be quantitatively analyzed [28]. In reversed-phase LC, butoxyethanol seemed acceptable, since it does not disturb UV detection and the increase in eluent viscosity is not severe.

Experimentation was stopped, however, because of lack of uncoated precolumns resisting condensed water. Leached and silylated fused-silica tubing became highly adsorptive after few transfers (water vapours passing though the separation column, on the other hand, proved to be harmless). Water films act as efficient temporary deactivation, but the system was unreliable: once water penetrated further into the precolumn, a zone of high activity was formed which was no longer deactivated by subsequent transfers. The first precolumn system withstood some 70 transfers of 200–1000 μl, the second hardly 15. High-boiling components (methyl esters of more than 22 carbon atoms) could, furthermore, not be analyzed, apparently because the deactivating layer of water was removed from the precolumn surface before these solutes were volatilized. Stability of the precolumn deactivation was improved in the mean time. It was primarily lacking interest in reversed-phase LC for coupling to GC which prevented us from re-evaluating this promising approach.

3.5. Concurrent evaporation with the on-column interface?

Barcarolo [29] reduced the loss of volatile components during concurrent eluent evaporation by lowering the transfer temperature. Firstly, the LC fraction (containing organochlorine pesticide residues from fat) was vaporized in a capillary section of some 10 cm length separately heated to a temperature above that of the oven. Oven temperature had, therefore, only to be high enough to prevent recondensation and flooding (vaporization in an oven-thermostatted capillary requires a temperature somewhat above the pressure-corrected boiling point because heat

consumption cools the evaporation site and delayed evaporation causes "shooting" liquid [30]). Secondly, the solvent vapours were diluted with carrier gas. Barcarolo used an on-column interface (actually an on-column autosampler), because the gas must enter the evaporation site from the side. Dilution reduces the dew point, i.e. enables further reduction of the oven temperature. It also increases the gas volume advancing the components, but retention of volatile solutes nevertheless improves. Actually isooctane (standard boiling point, 100°C) was evaporated at 57°C oven temperature.

Vapour dilution, i.e. use of the on-column interface, indeed substantially improved performance of concurrent evaporation for the volatile solutes. It seemed, however, to be an unattractive compromise: performance is still far from that of the retention gap techniques, i.e. it cannot replace the latter. Nor would it replace transfer by the loop-type interface, because adjustment of conditions is more demanding: the LC flow-rate must be adjusted to achieve dilution of the vapours by a factor of 2–4, which requires a fair amount of experimental optimization.

3.6. Etzweiler bulb

In 1985, Etzweiler [31] described a device for large volume on-column injection which obviated the need for long uncoated precolumns: the liquid was not retained as a layer on a capillary wall, but as bulk in a bulb (Fig. 3). The carrier gas pushed the sample into the bulb from the bottom. The internal diameter of the bulb was wide enough to enable the carrier gas to bubble through the liquid, i.e. to avoid plug formation and liquid being pushed into the capillary tubing beyond. The solvent evaporated in the bulb and probably retained the volatile solutes up to the end of its vaporization. Bands broadened during slow transfer from the bulb into the column were probably refocused in the inlet of the coated column by the retention gap effect.

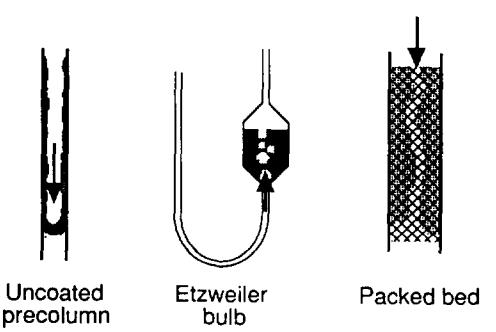

Fig. 3. Three basic concepts of retaining large volumes of liquid within a vaporizing chamber.

Heo and Suh [32] proposed a similar system for on-line LC–GC. It differs from that of Etzweiler inasfar as there was an additional vapour exit from the evaporation cavity. It was used for the transfer of LC fractions of 500 μl volume.

The Etzweiler bulb did not find wider use and was probably not even really evaluated. Its principle convinces by simplicity, but little is known about drawbacks. Cleanliness of the bulb could be critical because the solutes must be released at a temperature low enough to provide a sufficient retention gap effect; deposition of a rather small amount of involatile material would build up too much retention power. Since the bulb cannot be replaced as easily as a precolumn, cleaning and re-deactivation could be a problem.

3.7. Separate heating of the uncoated precolumn

Reconcentration by the retention gap effect is based on a large difference in retention power in the precolumn and the separation column. This is achieved by a deactivation of the precolumn resulting in minimum retention power. Deposition of a rather small amount of involatile sample by-products may, however, increase the latter to an extent that reconcentration is no longer sufficient [33]. Hiller et al. [34] as well as Hagman and Roeraade [35] proposed heating the precolumn more rapidly than the separation column in order to overcome such retention power. Effectiveness of this approach was demonstrated. If, however, higher temperatures are required in order to solve problems by "dirt",

use of open tubular evaporators (precolumns) should be re-evaluated against packed evaporation chambers, e.g., in a PTV injector.

4. Vaporization in packed beds

There are, in fact, several reasons to prefer packed vaporizing chambers to open tubular ones (capillary precolumns): (i) they retain more liquid per unit internal volume; (ii) wettability is not as critical for the retention of liquid; (iii) packing materials like Tenax are chemically more stable, i.e. better resist water than precolumns the backbone of which is a silica; and (iv) they are more easily heated than capillary precolumns.

Packed evaporation chambers exhibit higher retention power than capillary precolumns and must be heated above the column temperature to release the solutes, i.e. require a separate heating, such as a PTV-type injector. This release is known to be a problem for labile, adsorptive, and extremely high-boiling components.

For ordinary injection into GC there is the choice between on-column injection and injection into vaporizing chambers, the temperature of the latter either being permanently high or programmable. On-column injection provides the most accurate and reliable results, but vaporizing chambers are more tolerant for "dirty" samples. The same could apply to LC–GC transfer.

HPLC preseparates the sample at high efficiency, which also efficiently removes material potentially contaminating the GC system. Improved clean-up is, however, often used for introducing larger aliquots of sample material in order to lower detection limits, which also carries along more involatile byproducts and offsets the improvement at least partly.

4.1. PTV solvent splitting

Introduction of large volumes in the PTV solvent-split mode (also called "split/splitless") is known since the late 1970s [36] and always seemed to be an obvious idea for interfacing LC to GC. Maybe the idea was so obvious that nobody picked it up for a long time.

Solvent evaporation is performed in the packed bed of a cool injector (Fig. 4); vapours are largely removed through the split outlet in order to accelerate their discharge and to protect the detector. Introduction of volumes exceeding the capacity of the chamber to retain liquid must be performed slowly (adjusted to the solvent evaporation rate), but this is no severe problem for LC–GC with a regulated LC eluent flow-rate. Use of 2–3 mm I.D. vaporizing chambers, however, instead of the usual liners of about 1 mm I.D., improves on this [37]. Volatile components evaporate together with the solvent and are largely lost through the split outlet.

Recently Staniewski and co-workers [38–40] optimized large-volume PTV injection and its use for LC–GC, looking at liners and conditions minimizing losses of volatile components. They showed that reduction of the injector temperature substantially reduces the losses of volatiles: as mentioned above for concurrent evaporation, increase of retention power at reduced temperature outweighs the massively increased volume of gas passing through the injector.

Packings of the insert with polymers, such as Tenax, provide best retention for volatiles, but also cause the release of the high boilers to

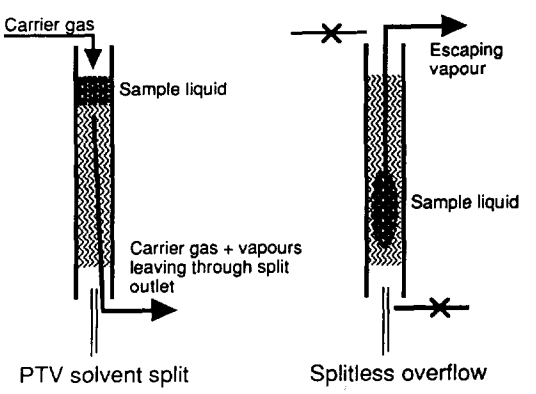

Fig. 4. Vaporization in packed beds: vapours discharged by the carrier gas flow, as in PTV solvent-split injection, or by overflow, as in splitless injection of large volumes.

become difficult. Tenax is, furthermore, the chemically most inert material available.

Retention by solvent (solvent trapping) has the advantage of collapsing at the end of the evaporation process, which enables desorption of the high boiling solutes at moderate temperatures. It is, however, difficult to make use of solvent trapping inside an injector. Staniewski and co-workers used liners with sintered glass beads filling half of the cross-section. Resembling the concept of Apps et al. [41], called "dynamic solvent effect", the solvent is supposed to evaporate from this bed and to support the retention of volatile solutes. The systems differ in the supply of the liquid: instead of being introduced from the bottom against the stream of carrier gas (sucked upwards by capillary forces), it enters from the same side as the gas. Furthermore, it is difficult to adjust the introduction rate such that neither all of the solvent evaporates during introduction nor an excessive amount of liquid floods the system.

4.2. Splitless injection with vapour overflow

In splitless injection, sample volumes could be increased up to 2 ml when applying vapour overflow [42–44]. The sample is injected into a packed liner, where the liquid cools the evaporation region to the solvent boiling point (corrected for pressure). The solvent evaporates fairly selectively, leaving higher boiling solutes behind. Vapours were discharged backwards through the septum purge outlet (Fig. 4).

Overflow means discharge of the vapours by expansion and a vapour pressure exceeding the pressure of the environment. If pressure is ambient, the evaporation site must, therefore, be at a temperature exceeding the solvent boiling point. A lower temperature is sufficient if vacuum is applied.

The main advantage of overflow is its simplicity regarding optimization of conditions: the flow-rate of the leaving vapours automatically adjusts itself to a minimum, being determined by the volume of the vapours. This eliminates the need for accurately adjusting the rate of introduction to the conditions and minimizes losses of volatile components. Discharge, furthermore, comes to a stop when evaporation is completed —in contrast to solvent split injection, where delayed closure of the split exit causes volatile material to be rinsed from the vaporizing chamber by the carrier gas.

Overflow has been explored for splitless injection into a permanently hot injector (since these injectors are most readily available). The injector temperature is determined by the desorption of the highest boiling solutes of interest. Using Tenax as packing material, this was usually 280–330°C. Such high temperatures cause, e.g., 500 μl of solvent to evaporate in 2–5 s, i.e. by a violent process. Performing the same technique in an injector with variable temperature (PTV), solvent evaporation could occur under milder conditions. Preliminary experiments were described in [45].

5. Solid-phase extraction

Intermediate trapping in a solid phase enables to eliminate troublesome eluent, first of all water and salts. If direct introduction into GC should definitively turn out impossible, it could be the way to go for automated water analyzers and reversed-phase LC–GC.

5.1. LC solvent exchange

The first approach, investigated primarily by the group of Brinkman (e.g. [46,47]), involved solvent exchange within the LC system: extraction into a bed of reversed-phase LC material, followed by drying and extraction with a solvent suitable for transfer into GC. Since the solutes of interest are eluted at the front of the transfer eluent and even accurate cuts between the water-containing eluent and the desorption medium cannot prevent transfer of some water, residual water was evaporated before transfer was started. Drying in a gas stream is, however, time-consuming and risks loss of volatile components.

5.2. Open tubular trap

Stimulated by the experiments described by Zlatkis et al. [48], an attempt was made to achieve solid-phase extraction into the stationary phase of a coated GC precolumn of 2 m in length, which was positioned in the GC oven [49]. Film thickness of the stationary phase was about four times below that of the coated column in order to achieve reconcentration of bands in the inlet of the separation column. The aqueous phase was moved through the precolumn by a weak vacuum at an outlet located between the precolumn and the separation column. As the main advantage of using an open tubular extractor for a non-wetting liquid, less than 1 μl of liquid was left behind on the wall of the precolumn. The exit was closed then and the chromatogram run normally, the solutes being desorbed from the precolumn as after normal on-column injection.

Results were disappointing: complete extraction of solutes of intermediate to high molecular mass required LC flow-rates below 50 μl/min, and only components of rather low polarity were trapped. Particularly regarding reversed-phase eluents containing elevated proportions of organic solvents, the approach did not seem promising.

Mol et al. [50] returned to this concept. Extraction efficiency was enhanced increasing film thickness to 5 μm. They made, furthermore, use of phase soaking, swelling the stationary phase with a solvent such as dichloromethane. This indeed substantially improved extraction efficiencies even for some more polar solutes. The thick coating prevented, however, thermal desorption in the column oven. Solutes were desorbed and transferred to GC using solvent and a PTV injector.

5.3. Thermal desorption from packed interface bed

As diffusion speeds within liquids are too low to enable sufficiently rapid extraction into a stationary phase film of an open tubular trap, packed extractors became interesting again. Packed beds also exhibit higher retention power. Desorption was performed thermally in order to avoid the need for an additional solvent and evaporation step [51].

Extraction was performed in the liner of a PTV injector. Carrier gas served for drying the packed bed before the outlet was closed, the chamber heated, and the solutes transferred into the column in splitless mode.

The packing material turned out to be the critical part: the high retention power advantageous for efficient extraction turns into a drawback for thermal desorption. Alkylated silica gels showed better extraction properties and less retention power for desorption than Tenax, but desorption temperatures were restricted to about 250°C owing to reduced stability of these materials. The concept was further investigated by Vreuls et al. [52] and Mol et al. [53].

6. Only a few methods will survive

The above list of concepts on how to transfer 100–1000 μl LC fractions to GC is long and nevertheless incomplete. It represents a rich source of ideas from which the best should be picked, combined, and further elaborated.

Rather than being a scientific field on its own, LC–GC is a technique supposed to serve as a tool. Ideas must be turned into devices and working instructions for routine application. Not all the many concepts, however, can become standard methods and somebody will have to select. It will be essential for the future of LC–GC that progress is made towards accepted methods and broad use in routine laboratories. More than at earlier times, success of a technique presupposes extreme simplicity.

For injection of normal (1–2 μl) samples, three GC injectors emerged, for each of which there are good reasons to keep it in use. On-column injection provides the most quantitative and reliable results and should be preferred whenever possible. Excessively "dirty" samples, however, i.e. samples carrying along a substantial amount of non-evaporating material, require preseparation in a separately thermostatted vap-

orizing chamber, from where only material enters the column that can also be eluted. Analogous considerations for LC–GC suggest using an on-column and a PTV interface. There is, however, also the distinction between transfer with and without solvent trapping which, with the large volumes involved, requires different interface and precolumn systems. It could, therefore, be preferable to start out from on-column systems and to find ways to incorporate a (maybe PTV-like) vaporizing chamber into them when necessary. It is too early to make final choices, but its time to work purposefully towards a system which combines simplicity with a maximum of versatility.

References

[1] R.E. Majors, *J. Chromatogr. Sci.*, 18 (1980) 571.
[2] J.J. Vreuls, G.J. de Jong, R.T. Ghijsen and U.A.Th. Brinkman, *J. Assoc. Off. Anal. Chem. Int.*, 77 (1994) 306.
[3] M.-L. Riekkola, *J. Chromatogr.*, 473 (1989) 315.
[4] I.L. Davies, K.E. Markides, M.L. Lee, M.W. Raynor and K. Bartle, *J. High Resolut. Chromatogr.*, 12 (1989) 193.
[5] K. Grob, *On-Line Coupled LC–GC*, Hüthig, Heidelberg, 1991.
[6] H.J. Cortes, *J. Chromatogr.*, 626 (1992) 3.
[7] K. Grob, in P. Sandra (Editor), *Proceedings of the 16th International Symposium on Capillary Chromatography, Riva del Garda, 1994*, Hüthig, Heidelberg, 1994.
[8] J.A. Apffel and H. McNair, *J. Chromatogr.*, 279 (1983) 139.
[9] Th.V. Raglione, J.A. Troskosky and R.A. Hartwick, *J. Chromatogr.*, 409 (1987) 205, 213.
[10] K. Grob, D. Fröhlich, B. Schilling, H.P. Neukom and P. Nägeli, *J. Chromatogr.*, 295 (1984) 55.
[11] H.J. Cortes, C.D. Pfeiffer and B.E. Richter, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 8 (1985) 469.
[12] K. Grob, *On-Column Injection in Capillary GC*, Hüthig, Heidelberg, 1987, 1991.
[13] K. Grob and Z. Li, *J. Chromatogr.*, 473 (1989) 381.
[14] K. Grob, H.P. Neukom and Z. Li, *J. Chromatogr.*, 473 (1989) 401.
[15] A. Pouwelse, D. de Jong and J.H.M. van den Berg, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 11 (1988) 607.
[16] E.C. Goosens, D. de Jong, J.H.M. van den Berg, G.J. de Jong and U.A.Th. Brinkman, *J. Chromatogr.*, 552 (1991) 489.
[17] K. Grob and A. Artho, *J. High Resolut. Chromatogr.*, 14 (1991) 212.
[18] G.R. van der Hoff, P. van Zoonen and K. Grob, *J. High Resolut. Chromatogr.*, 17 (1994) 37.
[19] K. Grob and Z. Li, *J. Chromatogr.*, 473 (1989) 423.
[20] A. Lanzon, A. Cert and T. Albi, *Grasas Aceites*, 40 (1989) 385.
[21] K. Grob and M. Bronz, *Fat Sci. Technol.*, 96 (1994) 252.
[22] K. Grob, A.M. Giuffré, M. Biedermann and M. Bronz, *Fat Sci. Technol.*, 96 (1994) 341.
[23] H.J. Cortes, *J. Chromatogr.*, 626 (1992) 3.
[24] K. Grob and E. Müller, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 11 (1988) 388.
[25] K. Grob and E. Müller, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 11 (1988) 560.
[26] M. Termonia, B. Lacomblez and F. Munari, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 11 (1988) 890.
[27] K. Grob and E. Müller, *J. Chromatogr.*, 473 (1989) 411.
[28] K. Grob, *J. Chromatogr.*, 477 (1989) 73.
[29] R. Barcarolo, *J. High Resolut. Chromatogr.*, 13 (1990) 465.
[30] K. Grob and Th. Läubli, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 10 (1987) 435.
[31] F. Etzweiler, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 8 (1985) 85.
[32] G.S. Heo and J.K. Suh, *J. High Resolut. Chromatogr.*, 13 (1990) 748.
[33] K. Grob, *J. Chromatogr.*, 287 (1984) 1.
[34] J.F. Hiller, T. McCabe and P.L. Morabito, *J. High Resolut. Chromatogr.*, 16 (1993) 5.
[35] G. Hagman und J. Roeraade, in P. Sandra and M.L. Lee (Editors), *Proceedings of the 14th International Symposium on Capillary Chromatography, Baltimore, MD, 1992*, Hüthig, Heidelberg, 1992, p. 224.
[36] W. Vogt, K. Jacob and H.W. Obwexer, *J. Chromatogr.*, 174 (1979) 437.
[37] H.G.J. Mol, H.-G. Janssen, C.A. Cramers and U.A.Th. Brinkman, *J. High Resolut. Chromatogr.*, 18 (1995) 19.
[38] J. Staniewski and J.A. Rijks, in P. Sandra (Editor), *Proceedings of 13th International Symposium on Capillary Chromatography, Riva del Garda, 1991*, Hüthig, Heidelberg, 1991, p. 1334.
[39] J. Staniewski und J.A. Rijks, *J. High Resolut. Chromatogr.*, 16 (1993) 182.
[40] J. Staniewski, H.-G. Janssen, C.A. Cramers and J.A. Rijks, *J. Microcol. Sep.*, 4 (1992) 331.
[41] P.J. Apps, V. Pretorius, K.H. Lawson, E.R. Rohwer, M.R. Centner, H.W. Wiljoen and G. Hulse, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 10 (1987) 122.
[42] K. Grob, S. Brem and D. Fröhlich, *J. High Resolut. Chromatogr.*, 15 (1992) 659.
[43] K. Grob and S. Brem, *J. High Resolut. Chromatogr.*, 15 (1992) 715.

[44] K. Grob and D. Fröhlich, *J. High Resolut. Chromatogr.*, 15 (1992) 812.
[45] K. Grob, *J. High Resolut. Chromatogr.*, 13 (1990) 540.
[46] E. Noroozian, F.A. Maris, M.W.F. Nielen, R.W. Frei, G.J. de Jong and U.A.Th. Brinkman, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 10 (1987) 17.
[47] A.-J. Bulterman, J.J. Vreuls, R.T. Ghijsen and U.A.Th. Brinkman, *J. High Resolut. Chromatogr.*, 16 (1993) 397.
[48] A. Zlatkis, F.-S. Wang and H. Shanfield, *Anal. Chem.*, 54 (1982) 2406; 55 (1983) 1848.
[49] K. Grob and B. Schilling, *J. High Resolut. Chromatogr. Chromatogr. Commun.*, 8 (1985) 726.
[50] H.G.J. Mol, H.-G. Janssen and C.A. Cramers, *J. High Resolut. Chromatogr.*, 16 (1993) 413.
[51] J.J. Vreuls, U.A.Th. Brinkman, K. Grob and A. Artho, *J. High Resolut. Chromatogr.*, 14 (1991) 455.
[52] J.J. Vreuls, G.J. de Jong, R.T. Ghijsen and U.A.Th. Brinkman, *J. Microcol. Sep.*, 5 (1993) 317.
[53] H.G.J. Mol, H.-G. Janssen and C.A. Cramers, *J. High Resolut. Chromatogr.*, 16 (1993) 459.