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Elsa Lundanes, Léon Reubsaet and Tyge Greibrokk

Chromatography

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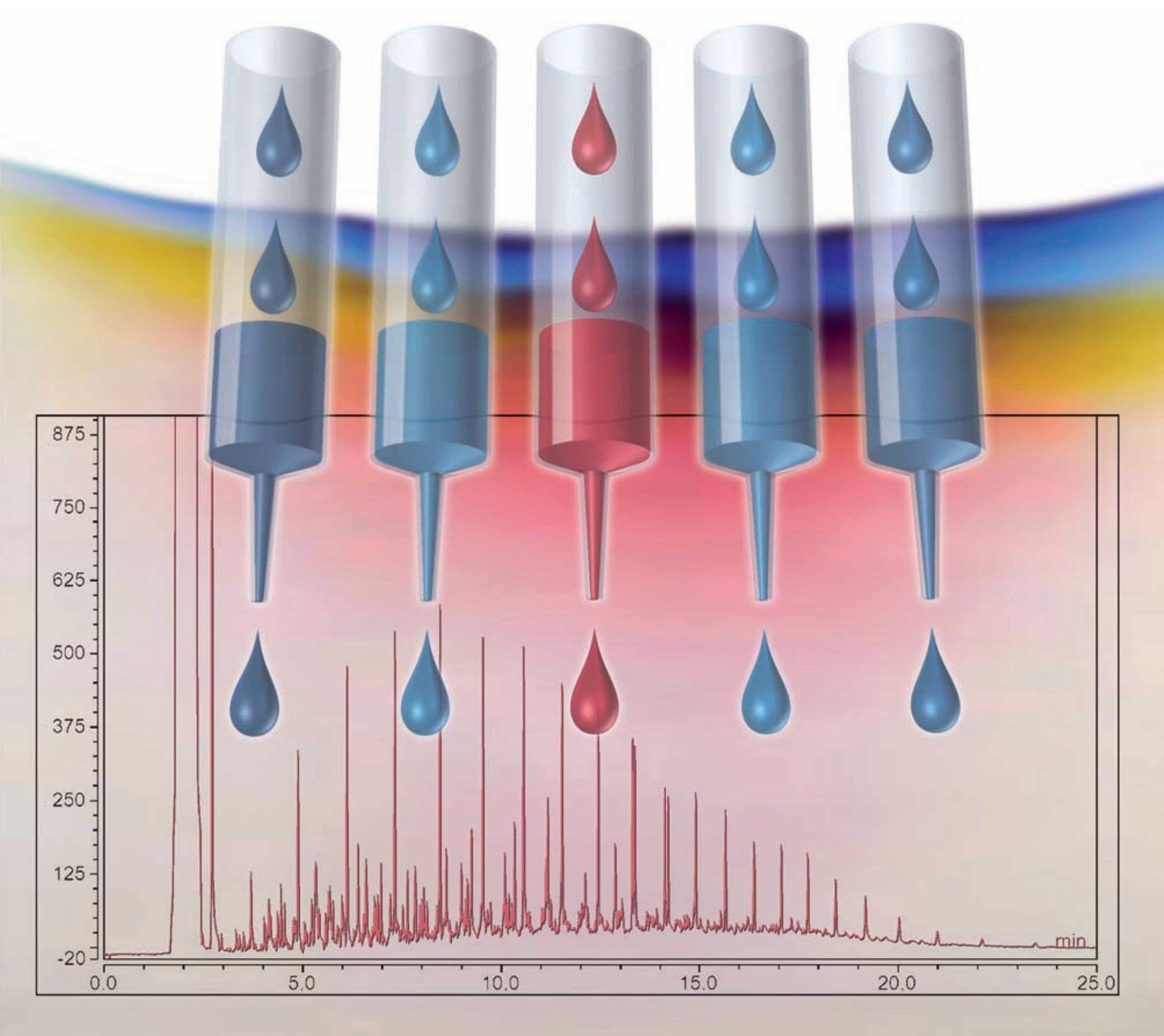

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Basic Principles, Sample Preparations and Related Methods

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Preface

Although the basis of chromatography was developed a century ago, new separation methods still continue to appear. Today the technological developments allow identification and determination of compounds at levels not attainable a few years ago. Attomole concentrations of biomarkers can be determined, and for specific compounds even single cells can be analyzed.

This book aims to aid new users of chromatography, independent of background, in understanding the basics, and also can be used as a textbook for courses at the undergraduate and graduate levels.

The major chromatographic techniques have been included. However, the book does not intend to give a comprehensive overview of the historic developments in separation science, and some classical techniques that are not in use today have not been covered. An example is paper chromatography, which was replaced by the more efficient thin layer chromatography a long time ago. Another example is column liquid–liquid partition chromatography, which more or less disappeared after the introduction of chemically bonded phases in HPLC.

Electrophoresis, although basically not a chromatographic technique, is included due to its close relationship to chromatography and since some chromatographic techniques are hybrids of electrophoresis and chromatography. A chapter on field-flow fractionation has also been included, due to the chromatography-like properties and the increasing recent interest in the technique.

A chapter on sample preparation has been considered important, especially for newcomers to chromatography, since preparing the sample is often more time consuming than the analysis itself. In addition, choosing the right or wrong sample preparation may be decisive for the ability to find analytes at low concentration levels. There is some overlap in describing molecular interactions in Chapters 3 and 9, but this is done on purpose allowing the chapters to be read independent of each other.

Trying to look into the crystal bowl is a difficult task, but it is hard to see a reduced need for chromatography in a time where more and more emphasis is placed on determining trace amounts of both known and unknown compounds.

How important the concept of miniaturized systems like lab-on-a-chip will be for analytical chemistry in the future remains to be seen, but miniaturization is definitely a trend of our time.

Elsa Lundanes
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Tyge Greibrokk

1 General Concepts

1.1 Introduction

The concept of separating sample components in a column was first developed in 1903 by Mikhail Tswett, who introduced the term chromatography in 1906. Unfortunately, his contemporaries showed little interest for the idea and almost 30 years went by before scientists in Germany rediscovered the principle of column liquid chromatography (LC). Then, in 1943 Arne Tiselius (in Sweden) classified chromatography into three modes: frontal, elution, and displacement. The elution mode actually became synonymous with almost all chromatography, but in recent years the displacement mode has attracted new interest, particularly in the separation of proteins.

In the years immediately prior to and during the Second World War, the principles of ion exchange chromatography (IEC) and liquid–liquid partition chromatography began to develop into crude technical solutions. Then after the war, in the early 1950s, the new technique of thin layer chromatography (TLC) came to light and gradually improved the partition principles used in paper chromatography. A. Martin and R.L.M. Synge (in the United Kingdom) received the Nobel Prize in 1952 for the invention of partition chromatography. Martin with James had also developed gas–liquid chromatography at this time. Gas chromatography (GC) was readily accepted by research chemists at the major oil companies, who understood the large potential of this technique and participated in developing the new instrumentation.

Size exclusion chromatography (SEC) was developed in Sweden by Porath and Flodin with dextrin materials (1959), by Hjertén with polyacrylamide (1961) and agarose (1964) materials, and by Moore in the United States with polystyrene–divinylbenzene (PS-DVB) materials (1964).

Supercritical fluid chromatography was demonstrated as early as 1962, but it did not receive much interest until the technology was improved more than 20 years later.

The introduction of open tubular columns into gas chromatography revolutionized GC, first with glass capillaries in the 1970s and then with fused silica columns in the 1980s. A similar revolution started with the gradual development of new

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Table 1.1 Properties of chromatographic techniques.

Technique	Mobile phase	Driving force	Stationary phase
GC	Gas	Gas pressure/flow	Solids, liquid films
HPLC	Liquid	Pump flow	Solvated solids
SFC	Supercritical fluid	Pump flow	Solids, liquid films
TLC	Liquid	Capillary forces	Solids
EC	Liquid	Electric field	Solids
MEKC	Liquid	Electric field	Micelles

columns and instrumentation in liquid chromatography. With columns filled with small particles, the high-pressure liquid chromatography of the 1970s–1980s was later renamed high-performance liquid chromatography (HPLC).

Gel electrophoresis (GE) was developed in the 1940s, while capillary electrophoresis appeared 40 years later. Then chromatography with electric potential-driven liquid flow also developed into micellar electrokinetic chromatography (MEKC) and electrochromatography (EC), both with capillary columns. Electrophoresis, thus, is not a chromatographic technique, since there is no stationary phase, except in MEKC and EC.

To date, HPLC has become the dominating chromatographic technique, with capillary GC being second only to it (for the more volatile analytes). Both GC and HPLC are mature separation techniques today; however, HPLC is still being developed toward faster and more efficient separations and also partially toward miniaturized columns, particularly for applications in the life science area. The majority of the other techniques already mentioned are niche techniques today, but still important for a relatively smaller number of users compared to HPLC and GC. Electric potential-driven techniques have an added opportunity for new technology on microchips.

Some of the properties of the chromatographic techniques are shown in Table 1.1.

1.2 Migration and Retention

1.2.1 General

In a chromatographic system, the sample is introduced in a small volume at the inlet of a column or another carrier of the stationary phase. The mobile phase transports the sample components in contact with the stationary phase throughout the column.

Due to different interactions between the sample components and the stationary phase, the sample components migrate through the system at different speeds and elute from the column with different retention times.

The retention time is defined as the time between the sample introduction and the elution from the column.

At the end of the column, a detector provides a signal for all eluting components (universal detection) or for a limited number (selective detection).

In a sample with many components, some compounds will coelute, partly or completely, depending on the complexity of the sample and the peak capacity of the column.

With mass spectrometric detection, even coeluting components can be identified.

1.2.2
Mobile and Stationary Phases

The sample components (solutes) can interact directly with components of the mobile phase, except in gas chromatography where there are no such interactions and the mobile phase is simply a carrier gas for the sample components.

When the stationary phase is a solid, often with polar surface groups, and the mobile phase is either a gas (in GC) or an organic solvent (in LC), the separation principle is based on adsorption, and the term adsorption chromatography can be used. Other not so commonly used terms are gas–solid chromatography and liquid–solid chromatography. The adsorption forces include dispersion interactions, dipolar interactions, acid–base interactions, complexation, and so on.

In gas chromatography, the stationary phase can also be a liquid, where the separation principle is based on partition between the two phases. This was also the case formerly in liquid chromatography, but after the introduction of chemically bonded stationary phases into HPLC, the stationary phase cannot be described as a liquid anymore.

1.2.3
Chromatograms

When the sample components are separated and detected by a detector connected to the outlet of the column and the signals from the detector are visualized as a function of time, a chromatogram is obtained, as shown in Figure 1.1.

In a chromatogram, the elution time is found at the x-axis, while the y-axis constitutes the size of the detector signal.

Depending on the conditions, the separation of the sample components as well as the time of analysis can be adjusted, as shown in Figure 1.2.

With isocratic elution (constant composition of the mobile phase), the peak width will increase with increasing elution time. This cannot be seen clearly in Figure 1.2b as the elution mode is gradient elution (changing composition of the mobile phase).

1.2.4
Retention Factor

At any given time during the migration through the system, there is a distribution of molecules of each component between the two phases:

$$n_s/n_m,$$

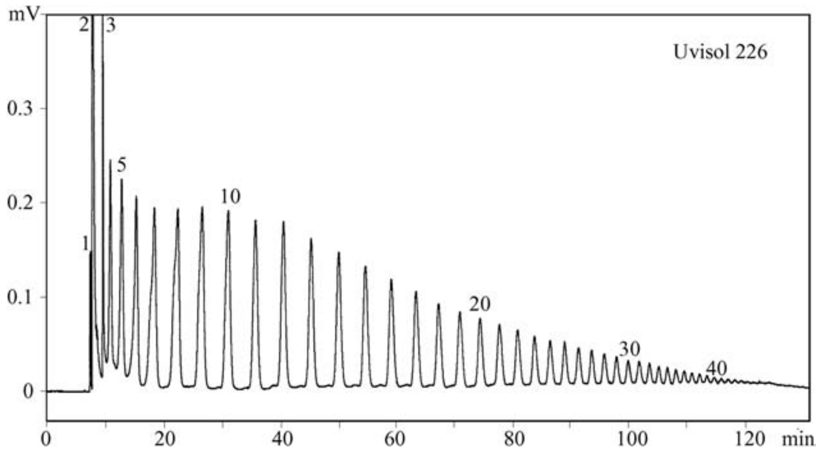

Figure 1.1 Chromatogram of polymeric amines separated by gradient elution in HPLC.

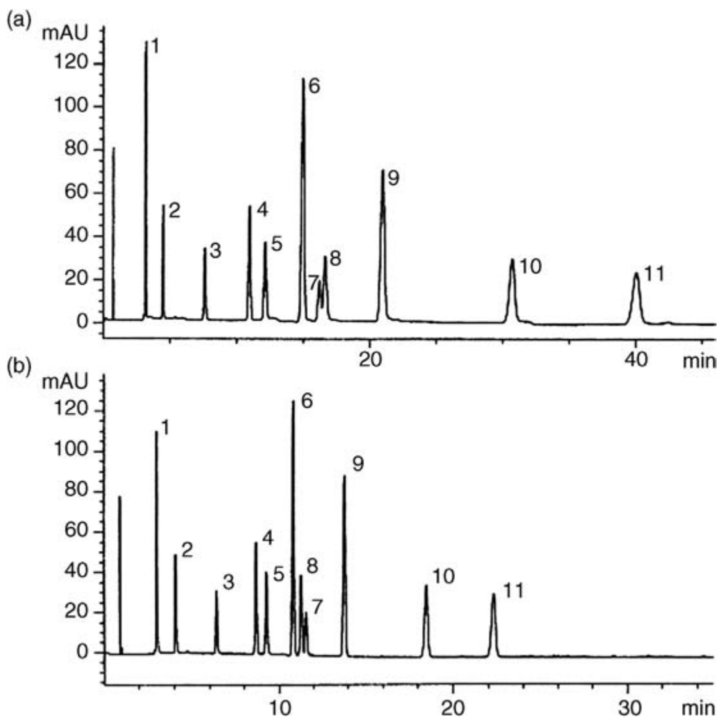

Figure 1.2 Reducing the time of analysis by gradient elution (b) compared to isocratic elution with constant mobile phase composition (a). (From Ref. [7], with permission.)

where n_s and n_m are the number of molecules in the stationary and mobile phases, respectively, at a given time. When n_s is much larger than n_m, the migration is very slow and the analyte elutes with high *retention*. In Figure 1.2, compound **11** has the highest retention:

$k = n_s/n_m$ is called the *retention factor*.

Info-box 1.1
k is the recommended symbol by IUPAC for describing the retention of a compound; it is independent of flow rate, column dimensions, and so on [1].

If one component migrates through the column in the mobile phase only, with no interactions with the stationary phase, the migration time is called t_M. An analyte with interactions with the stationary phase will be retained and will elute at t_R:

$$t_R = t_M + t_M k = t_M(1 + k).$$

The t_M can be determined by injecting a component known to have no interactions with the stationary phase.

From Equation 1.1, we can obtain a method for measuring k:

$$k = (t_R - t_M)/t_M. \qquad (1.1)$$

Time units can also be replaced with volume units:

$$V_R = V_M(1 + k).$$

1.3 Band Broadening

A sample is injected in a limited volume at the column inlet. If there were no band broadening, the volume or the width of the band would be exactly the same at the point of detection. Unfortunately, this is not the case. In all chromatographic systems, there is band broadening (Figure 1.2), caused by different physical processes.

In the columns, the following processes can occur:

- Eddy diffusion
- Longitudinal diffusion in the mobile phase
- Resistance to mass transfer: in the mobile phase, stationary phase, and stagnant mobile phase

If the distribution of each band is assumed to be a Gaussian distribution, the extent of band broadening can be expressed by the column efficiency N:

$$N = (t_R/\sigma)^2,$$

where t_R is the retention time and σ^2 is the band variance in time units (σ is the standard deviation of the Gaussian distribution).

Another expression for the band broadening in a column with length L is the plate height H:

$$H = L/N,$$

where H is measured in micrometer.

Since H is a function of the variance, individual contributions to band broadening can be expressed as individual contributions to the plate height.

1.3.1 Eddy Diffusion

Eddy diffusion occurs due to the presence of multiple channels of different widths and lengths in porous structures. Large inhomogeneous particles cause large contributions to band broadening of eddy diffusion. In a packed column, the size of the eddy diffusion is proportional to the particle size. A wide range of particle size also increases the eddy diffusion.

The main contribution of eddy diffusion to the plate height is

$$H = C_e d_p,$$

where d_p is the particle diameter of one-size particles and C_e is a constant.

In open tubular columns, there is no eddy diffusion.

Info-box 1.2

In liquid chromatography, eddy diffusion is responsible for a major part of the band broadening in the column. Since eddy diffusion is a combination of diffusion and convection, the term eddy dispersion might be more correct than eddy diffusion. Contributions to eddy dispersion come from column internal diameter, column length, and column packing efficiency besides particle size and homogeneity [2].

1.3.2 Longitudinal Diffusion

Longitudinal diffusion in the mobile phase is due to the natural tendency of a compound in a concentrated band to diffuse into less concentrated zones. The contribution of longitudinal band broadening is proportional to the diffusion constant. Since the diffusion velocity in gases is about 10^4 times higher than the diffusion in liquids, this contribution to band broadening is much more important in GC than in HPLC.

The contribution of the longitudinal diffusion to the plate height is

$$H_l = c_l D_m / u,$$

where D_m is the diffusion coefficient in the mobile phase, c_l is a constant, and u is the linear mobile phase flow rate.

1.3.3 Resistance to Mass Transfer

Resistance to mass transfer describes the band broadening caused by transporting the analytes by diffusion and convection from one phase to the other.

Resistance to mass transfer is, in general, inversely proportional to the diffusion constants in either phase.

In the mobile phase, there is an additional link to eddy diffusion. The contribution to the plate height can be described by band broadening taking place in the mobile phase, stagnant mobile phase, and stationary phase.

Resistance to mass transfer in the mobile phase

a) *In an open tubular column*

$$H_m = c_m d_c^2 u / D_m,$$

where d_c is the column internal diameter, u is the linear flow rate, and

$$c_m = (1 + 6k + 11k^2)/96(1 + k)^2.$$

b) *In a packed column*

$$H_m = c_{mp} d_p^2 u / D_m,$$

where d_p is the particle diameter and u is the linear flow rate (measured in mm s^{-1}).

In packed columns, H_m should be coupled with the eddy diffusion and the coupled term $H_{me} = 1/(1/H_e + 1/H_m)$.

Note: The plate height in a packed column is independent of the column inner diameter.

Resistance to mass transfer in the stagnant mobile phase (in a packed column)

$$H_{stm} = c_{stm} d_p^2 u / D_m,$$

where c_{stm} is a constant and the other parameters are as before.

Resistance to mass transfer in the stationary phase

$$H_s = c_s d_f^2 u / D_s,$$

where d_f is the film thickness, c_s is a constant, and the other parameters are as before.With thin films, H_s is small and can be neglected. In gas chromatography, this is the case for columns with a film thickness of 0.25 μm or less.