

Expert system for ion chromatographic methods using dynamically coated ion-interaction separation

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ABSTRACT

The development of an expert system is described for ion chromatographic methods which use ion-interaction chromatography as the separation technique. The object of the system is to help define appropriate starting conditions for the analysis of a desired group of ions. The system is implemented in a rule-based expert system development tool, Xi-Plus. Rules are used which act on certain properties of the sample and on the availability of instrumentation and accessories. With this information the method conditions can be defined for the column, detector and mobile phase. The expert system incorporates a module which allows the user to modify some of the rules in order to avoid problems which arise with expert systems which are too rigid. Many laboratories have their own preferences for columns, etc., which would be difficult for an expert system to predict. The rule change module therefore allows users to customise the system to their own requirements. Two approaches to the knowledge engineering process were employed. The first used the conventional approach of interrogation of an expert (in this case, P. R. Haddad). In the second approach, statistical analyses were applied to a previously compiled database of published ion chromatographic methods. The conclusions from these searches were then examined by the expert to define rules for the expert system. This paper describes this process of knowledge acquisition and some preliminary results on the use of the expert system.

INTRODUCTION

Expert systems technology is now relatively mature and several systems have been built for analytical chemistry applications [1–5]. Most of these systems have been applied to problems in high-performance liquid chromatographic method development. Systems exist which offer advice on selecting the best starting conditions, and for optimising and validating the chosen method. Some of these systems have also been integrated to form larger systems capable of tackling a number of these problems simultaneously [6,7]. However, no expert system has yet attempted to resolve the unique problems associated with ion chromatography (IC). In this paper we describe such an application of expert systems technology and the approach taken is novel

in two respects. First, an extensive library of previously published IC methods is used to assist in the knowledge acquisition process. Second, a module is implemented which allows the user to modify the rules and thus to customise the system to include specific preferences.

The application of IC has grown rapidly since the technique was introduced as an ion-exchange method coupled with conductivity detection for the assay of a series of anions and cations [8]. IC offers reliable methodology for the simultaneous determination of mixtures of ions and has found use in many industrial and environmental applications. Although IC is used widely, expertise in the subject is relatively rare, and this makes it an ideal application for expert systems. Some work has been published on the application of computers to method development for IC [9,10], but this work has not included the application of artificial intelligence.

Knowledge acquisition and engineering is the

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most time-consuming stage and is often considered the bottle-neck in the development of expert systems. This stage can require an inordinate amount of time from the domain expert, who is usually a very busy person. It is therefore beneficial if the knowledge engineer can employ techniques which can reduce the involvement of the expert. For this project we were fortunate to have available an extensive database of previously published IC methods, covering the literature up to 1990 [11]. This database was searched systematically and the results were analysed statistically to find the most commonly used method conditions for different applications. These conclusions were then examined by the expert and rules were generated for the expert system.

A failing of some previously developed expert systems has been the inability of the final user to interact with or modify the rule base without compromising the validity of the whole system. To investigate a solution to this problem, a small rule base was programmed which allows the user to alter the conclusions of some of the rules. In this way, the user can interact with the rule base in a controlled

manner without altering the overall philosophy of the expert system.

EXPERIMENTAL

The expert system was implemented in Xi-Plus, which is a rule-based expert system development tool (Expertech, UK). The database was implemented in Reflex (Borland International, CA, USA). These software packages require approximately 10 megabytes of memory, including storage of the database files. An IBM compatible computer with a 486 CPU was employed; however, the system was tested on a 286 and showed satisfactory performance.

RESULTS AND DISCUSSION

Definition of the chemical domain

Definition of the chemical domain is important to ensure the final success of an expert system. The knowledge for IC can be defined in terms of the following boundaries: (1) separation mechanism; (2) application area; (3) stages in the method devel-

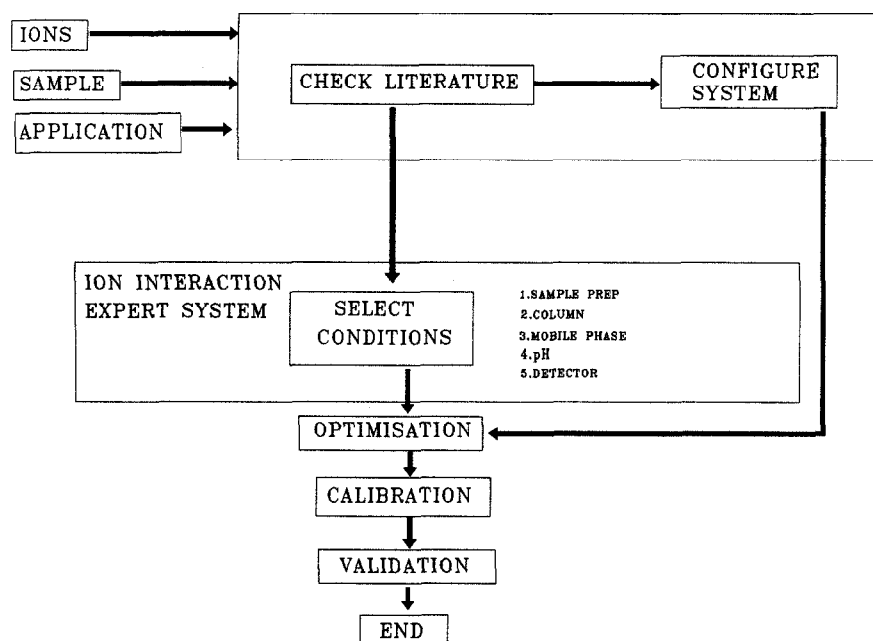


Fig. 1. Stages of method development in IC.

opment process. There are various mechanisms, or separation modes, which can be applied to the analysis of ions. These mechanisms employ different chromatographic conditions to influence different chemistries of the separation process and include ion-exchange chromatography, ion-interaction chromatography (IIC) (also known as ion-pair chromatography), ion-exclusion chromatography and miscellaneous separation methods, such as reversed-phase liquid chromatography, the use of chelating stationary phases, etc.

IC can be applied to a diverse range of application areas, including environmental, industrial, foods and plants, clinical and pharmaceutical, metals and metallurgical solutions, and treated waters. The sample may be simple and require little or no sample preparation, or can be very complex and require extensive pre-treatment.

The actual development of a method for IC involves several stages, as depicted in Fig. 1. The first stage is to collect any available information on the number and type of ions, the complexity of the sample matrix and the requirements of the application. A check is usually made of the literature in an attempt to locate a previously developed method. If such a method is available it can be configured to a complete method description. Alternatively, the method may require some further optimization. If a method is not available then a first guess must be made for a suitable sample preparation, column, eluent (including pH) and detector. The selected method must now be further optimized for retention, selectivity and instrumental conditions. Finally validation of the method must be performed and a suitable calibration procedure defined. Selection of the calibration method is often an integral part of the validation study.

Quite clearly IC is a very large subject domain and needs to be divided into smaller parts which can be tackled in sufficient depth without requiring excessive computer memory or consultation times. In this project the subject domain has been divided into two stages: the first involves the searching for and configuration of previously published methods, whilst the second involves the development of IC methods using the major retention mechanisms (namely ion-exchange, ion-exclusion and ion-interaction).

This paper describes an expert system which has

been built to develop methods which use IIC as the retention mechanism. IIC involves the use of apolar stationary phases with eluents containing a hydrophobic ion (called the ion-interaction reagent, IIR) of opposite charge sign to that of the analyte ions. Two operational alternatives exist. The first (or "permanent coating" method) requires that the column is first equilibrated with the IIR, which is then absent from the eluent during the analysis step. The second (or "dynamic coating" method) uses an eluent containing IIR for both the column conditioning and analysis steps. IIC was selected for expert system development for two reasons. First, the number of literature citations in this area is relatively small (approximately 10% of the total for IC), so that IIC forms an ideal subset for the study of expert systems in IC. Second, IIC has a larger number of experimental variables than any other retention mechanism used in IC and therefore offers the greatest challenge for method development.

Defining the influencing factors

In order to define method conditions for the assay of ions by IIC, certain information is required. This information usually encompasses characteristics of the analytes (*e.g.*, whether the solute ion is an anion or a cation and is hydrophobic or hydrophilic), the sample matrix (*e.g.*, the number of ions to be determined and their concentrations, the presence of likely interferences, etc.) and the application (*e.g.*, the need for automation, the detection limits and precision required, etc.). It is also important to recognise that the value of one chromatographic variable can affect decisions on another; for instance some eluents are incompatible with some detection modes. These influences need to be established such that the conditions are selected in an appropriate order.

Searching the database for relationships

In order to find any trends or interdependences of chromatographic conditions for published IIC methods, selective searches were made of the previously compiled database of applications. Since there are 343 IIC methods in the database (compared to a total of about 4000 for all separation modes), it was feasible to perform manual searches and subsequent statistical analyses for this number of applications.

TABLE I
CLASSES OF IONS

| Anions | Cations | Organics |
|---------------------|-------------------------|------------------|
| Halides | Ammonium, alkali metals | Carboxylic acids |
| Nitrate, nitrite | Alkaline earth metals | Amines |
| Sulfate | Transition metals | Alkylsulfonates |
| Other | Lanthanides | Other |
| | Other | |

To determine whether the database would reveal preferred conditions for certain classes of ions, it was necessary to clearly classify the ion types. Table I shows the initial classification groups. The database of applications was first searched to find which classes had IIC as the preferred mechanism and the following conclusions were made: (1) all ion classes could be analysed successfully using IIC; (2) IIC appears to be the preferred mechanism for the determination of lanthanides and, to a lesser extent, transition metals; (3) IIC is applied infrequently to the determination of alkali metals, alkaline earth metals and ammonium. The database was then analysed to find the distribution of IIC methods be-

tween the two operational modes of dynamic and permanent coating. It was found that permanent coating represented less than 20% of IIC applications and it was therefore decided to concentrate on the dynamic coating procedure. A further factor influencing this decision was that the permanent coating method results in the formation of an ion-exchange stationary phase, so that this method can be correctly classified as ion-exchange chromatography which will be dealt with at a later stage of the project. Initial searches revealed that silica-based columns represented almost 65% of IIC applications. Trends in IIC column usage over the time period 1975–1989 were then examined, which revealed that there has been a trend away from the use of polymer-based columns. This can be explained by the fact that silica columns generally offer better chromatographic efficiency, are widely available and are more rugged than columns packed with polymeric stationary phases. Further searches on column usage for the individual ion classes revealed a similar trend to the overall usage, with the only preference for polymer columns being evident for samples of extreme pH. Over 40 similar searches were performed to ascertain trends in eluent and detector uses and from this a rule base was built for IIC.

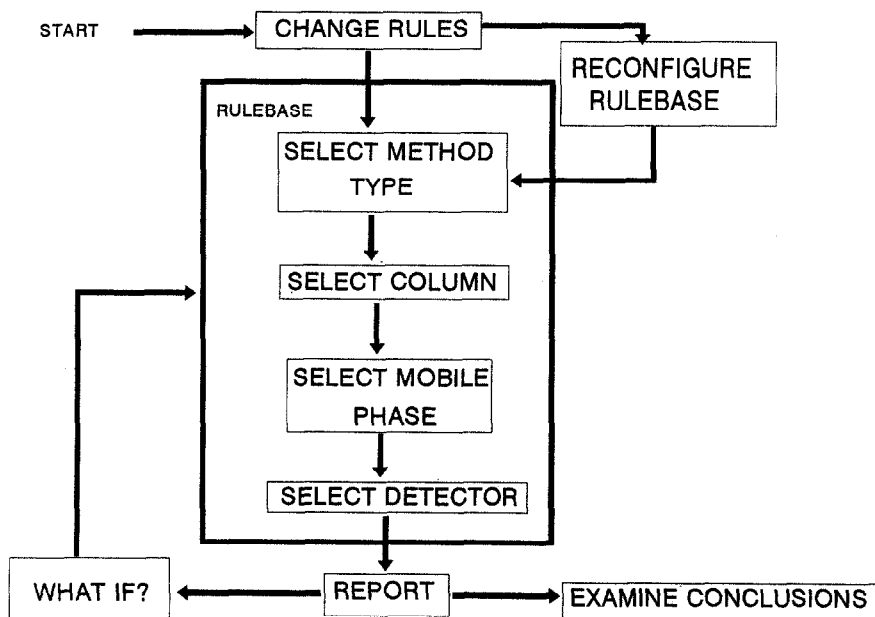


Fig. 2. The IIC expert system.

Implementation of the expert system

The knowledge acquired by searching the database was transcribed into rules. An example of such a rule is:

If the ion class is anions
and anions include UV-absorbing species
and anions do not include non-UV-absorbing species
and detectors include ultraviolet spectrophotometer
and sample matrix has an extreme pH
then method is one

This rule selects an outline method for anions which are UV-absorbing and are in a sample matrix with an extreme pH. The way in which these rules are implemented is shown in Fig. 2. This figure also shows how the rule base interacts with the other facilities offered by the development tool. The first module allows the user to change the conditions for activating some of the rules and the conclusions made by these rules. If any modifications are made then the rule base is reconfigured to account for these changes. The actual rules for defining the method conditions are divided into four stages: (1) selection of the method type: this part ascertains the class of ion to be analysed and selects a suitable

preliminary method; (2) selection of the column: the column is selected by examining the nature of the sample and its matrix; (3) selection of the eluent: the eluent is determined chiefly by the class of ions for analysis; (4) selection of the detector: the detector is chosen on the basis of the properties of the solute ions and the availability of detector types.

A report is then shown which summarises the chosen method conditions. As an example of the application of the developed expert system, a consultation was made to find a suitable method for the determination of transition metals in a strongly acidic sample. Fig. 3 shows the method printout obtained. The suggested method is workable, but it would be more usual to employ a silica-based C₁₈ column, despite the low sample pH. The conclusions reached should therefore be examined by looking at the rules which generated each conclusion and, if necessary, modifying these rules. For example, the rule for selection of a polymer column is based on the sample having an extreme pH value and a polymer column being available, so that some refinement of this rule could be desired by the user. Throughout the consultation, help is available for each query which is made of the user. These help files include hints on the best responses to queries in

ION INTERACTION EXPERT SYSTEM

Print report

A polymer-based column is chosen as the most suitable type for this application. There are several columns commercially available, for instance

PS-DVB - Hamilton PRP-1
XAD-2
Dionex MPIC

The column length is 30 cm
The particle size is 10 µm
The internal diameter is 4 to 7 mm

The mobile phase recommended for this application is as follows:
2 mM sodium octanesulfonate, 50 mM tartaric acid, adjusted to pH 3.5 with sodium hydroxide. Flow-rate of 1 ml/min
The octanesulfonate acts as the ion interaction reagent and tartaric acid as the mobile phase ligand.

The detection method recommended is spectrophotometry at 530 nm after post-column reaction with PAR

Fig. 3. Typical method report generated by the expert system.

situations where the information requested is not critical to the specific application under study and the user wishes to maximize the options available to the expert system.

Once the conclusions have been examined it is possible for the user to reconsider answers to any of the queries by using the "What if?" facility. This allows the user to modify any answers and examine the new conclusions. The question "Why?" can also be asked at any stage in the consultation.

CONCLUSIONS

The method of knowledge acquisition which was employed in this paper, namely the use of a database of literature methods in IC to compile a rule base, enabled us to successfully create an expert system for IIC. The expert agreed with the majority of conclusions which were reached by statistical analysis of the database. This method considerably reduced the amount of time required from the expert, but still resulted in the development of a competent expert system. However, this process proved to be very time-consuming for the knowledge engineer. There are a number of artificial intelligence techniques under development which can generate relationships within databases of examples. These include neural networks and the Quinlan rule generating system. The next stage of this project will be to investigate the potential of these techniques for knowledge acquisition. They will be used to compile rule bases for the mechanisms of ion exclusion and ion exchange. These mechanisms are used more frequently than IIC and thus the number of applications in the database would make it extremely diffi-

cult to perform the statistical analyses manually and to ensure that the statistics are free of bias. Furthermore these learning techniques should reduce subsequent validation requirements because they are well defined procedures.

Xi-Plus proved to be a competent expert system development tool, however, it is limited in some respects. It provides few facilities for integration of the expert system with a database and the user interfacing is not extensive. It is therefore likely that other newer expert system tools will be employed for the implementation of the final integrated system.

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