Institute of Pharmacy[1], Humboldt University, Berlin and Institute of Informatics[2], Humboldt University, Berlin-Adlershof

Glass classification by linear discriminant analysis of LA-ICP-MS data

T. Schmidt[1], T. Vogt[1], J.-P. Surmann[1] and W. Kössler[2]

The classification of pharmaceutical and common glasses (ampoules, infusion bottles, cylinders, lead crystal and bottle glass) has been performed means by of chemometric methods. For this purpose intensity data of glass examinations received by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) were applied. A Nd : YAG laser with 10 Hz repetition rate in the Q-switch mode at its 4th harmonic (266 nm) was used to get mass spectrometric data of the glasses. 13 isotopes (= variables) were used for measurements (^{7}Li, ^{11}B, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{39}K, ^{42}Ca, ^{47}Ti, ^{57}Fe, ^{123}Sb, ^{137}Ba, ^{207}Pb). The glass samples represented four types of glasses: 1. borosilicate glass (type "Duran®") 2. borosilicate glass (type "Fiolax®") 3. soda-lime glass 4. lead glass. Calculations were made by using the SAS® statistical software. All results were obtained on the assumption that the underlying data are normally distributed. By applying linear discriminant data analysis a classification of all types of the glasses was possible (13 variables included). The use of the method of "stepwise discriminant analysis" reduced the minimal required number of variables to eight. All types of glasses could be distinguished faultlessly. Besides a graphic system consisting of the isotopes ^{24}Mg–^{47}Ti–^{137}Ba was developed. By means of this system optical distinction of glass classes was possible. The developed method allows to distinguish several types of pharmaceutical and common glasses on the basis of intensity data of mass spectrometric measurement without calibration experiments and linear regression.

1. Introduction

The application of glasses as package material in pharmaceutical industry or food industry is increasing [1]. The distinction of several types of glasses is of great concern for quality control in pharmaceutical production [2–4]. Fast and precise determination of glass composition is often time consuming or needs expensive analytical instrumention. In many cases glasses only have to be distinguished by their membership of a certain glass type [5].
Chemometric data analysis concentrates on structures in analytical data. Especially the classification of samples by means of analytical results is possible by linear discriminant analysis (LDA) [6]. This technique allows the best possible linear separation of given groups followed by their classification. According to principle component analysis (PCA) optimal linear combinations (= weight factors) have to be searched. In comparison to PCA it is not intended to maximize the variance, but to separate groups as good as possible [7].
The challenge of this work was the classification of different glasses on the basis of intensity measurements of laser ablation inductive coupled plasma mass spectrometry (LA-ICP-MS). Results of 13 isotopes (^{7}Li, ^{11}B, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{39}K, ^{42}Ca, ^{47}Ti, ^{57}Fe, ^{123}Sb, ^{137}Ba, ^{207}Pb) should be used for statistical calculation by statistical software (SAS®). Simultaneously with the development of a classification function a graphic system should be established to distinguish samples optically by means of intensity data. The outcome should be compared with the results received after calibration and linear regression.
The suitability of the method for the distinction of glass types should be proved for three classes (borosilicate glass, soda-lime glass, lead glass). Additionally the capability of the method should be tested concerning the differentiation of two similar borosilicate glasses (type Duran® and type Fiolax®). Finally the number of variables (measured isotopes) should be minimized that classification is possible without loss of precision.

2. Investigations, results and discussion

2.1. Linear discriminant analysis

For the classification of pharmaceutical and common glasses seven samples (ampoules, infusion bottles, cylinders, lead crystal and bottle glass) were used. The samples were analysed by LA-ICP-MS with a Nd : YAG laser, 10 Hz repetition rate in the Q-switch mode at its 4th harmonic (266 nm). 13 isotopes (= variables) were measured to get intensity data (^{7}Li, ^{11}B, ^{23}Na, ^{24}Mg, ^{27}Al, ^{28}Si, ^{39}K, ^{42}Ca, ^{47}Ti, ^{57}Fe, ^{123}Sb, ^{137}Ba, ^{207}Pb). The samples could be distinguished by their chemical composition into four glass classes: 1. borosilicate glass (type "Duran®"). 2. borosilicate glass (type "Fiolax®"). 3. soda-lime glass. 4. lead glass. Calculations were made by using the SAS® statistical software (version 6.12). All results were obtained on the assumption that the data are normally distributed. For the classification experiment a matrix was developed. The structure of the matrix is given in eq. (1).

$$X = \begin{pmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \end{pmatrix} \qquad X_g = \begin{pmatrix} x_{g;1;1} & x_{g;2;1} & \cdots & x_{g;j;1} \\ x_{g;1;2} & x_{g;2;2} & \cdots & x_{g;j;2} \\ \vdots & \vdots & \ddots & \vdots \\ x_{g;1;i} & x_{g;2;i} & \cdots & x_{g;j;i} \end{pmatrix} \tag{1}$$

matrix "X" for glass classification; "i" data sets (i = 1, 2, . . . , 23) in "g" groups (g = 1, . . . , 4) for "j" Isotopes (variables) (j = 1, . . . , 13).
This data matrix (X) joins 92 objects with 13 variables within four classes (X_1, X_2, X_3, X_4). The results of each class were weighted in the same way. The measure of distance between two groups (g = 1 and g = 2) is given by the Mahalanobis distance [7].

$$D^2(g = 1 \mid g = 2) = (\bar{X}_{g=1} - \bar{X}_{g=2})' \operatorname{cov}^{-1} (\bar{X}_{g=1} - \bar{X}_{g=2}) , \tag{2}$$

where cov is the common variance-covariance matrix of the two groups and $\bar{X}_g$ is the centroid of group "g".
By calculation of the so-called weight factors new artificial variables occur, which can be described as discriminant variables. The coefficients in the classification func-

Table 1: Classification of unknown samples: linear discriminant analysis, 13 variables

n = 28 Sample no.	Assigned glass type				
	G 1	G 2	G 3	G 4	trueness [%]
P 1	4	–	–	–	100
P 2	2	–	–	2	50
P 3	4	–	–	–	100
P 4	–	–	–	4	100
P 5	4	–	–	–	100
P 6	–	4	–	–	100
P 7	–	–	4	–	100

P 1 infusion bottle, white (borosilicate glass, type Duran®)
P 2 ampoule, brown (borosilicate glass, type Duran®)
P 3 laboratory glass, brown (borosilicate glass, type Duran®)
P 4 ampoule, white (borosilicate glass, type Fiolax®)
P 5 laboratory glass, white (borosilicate glass, type Duran®)
P 6 lead crystal, white (lead glass)
P 7 bottle glass, white (soda-lime-glass)
G 1 borosilicate glass, type Duran®
G 2 lead glass
G 3 soda-lime-glass
G 4 borosilicate glass, type Fiolax®

tion should be chosen in such a way to get maximal distinction. The term of distance between element "i" and group "g" is given by

$$D_{ig}^2 = (X_i - X_g)' \operatorname{cov}^{-1} (X_i - \bar{X}_g)$$

with

$$X_i' = [x_{1i}, x_{2i}, \ldots, x_{ji}]$$

$$\bar{X}_g' = [\bar{X}_{1g}, \bar{X}_{2g}, \ldots, \bar{X}_{jg}] \tag{3}$$

function of distance for glass classification.

The classification of unknown glass samples could be made by calculating posterior probabilities of membership in each group corresponding to eq. (4).

$$\Pr(g \mid i) = \frac{\exp\left(-\frac{1}{2} \cdot D_{ig}^2\right)}{\sum_{g=1}^{G} \exp\left(-\frac{1}{2} \cdot D_{ig}^2\right)} \tag{4}$$

function for classification of unknown glass sample "i" in group "g".

The results of the classification experiment are given in Table 1. All samples were classed to the right group. Sample no. 2 was correctly assigned to glass type "borosilicate glass", but could not be detected definitely as Fiolax®-glass. About half of the data matrix was classed as Duran®-glass (probability between 56.0–73.8%).

2.2. Reduction of variables

The classification using the whole data (13 isotopes = variables) includes some isotopes, which do not contribute to the separation of groups. These variables are not only abundant, but have a strong influence on the resulting error. Thus it is necessary to reduce the number of isotopes. The minimized number of variables should be suitable for a correct separation with low error rates.

The SAS®-software offers a "stepwise discriminance analysis" modul. In a first run the "backward elimination procedure" for the reduction of variables was used, where ^{29}Si and ^{47}Ti were defined as dependent variables and should not be eliminated. After having carried out the procedure for each glass type the isotopes ^{24}Mg, ^{47}Ti and ^{137}Ba were detected as being suitable for separation. The graphic system is shown in the Fig.

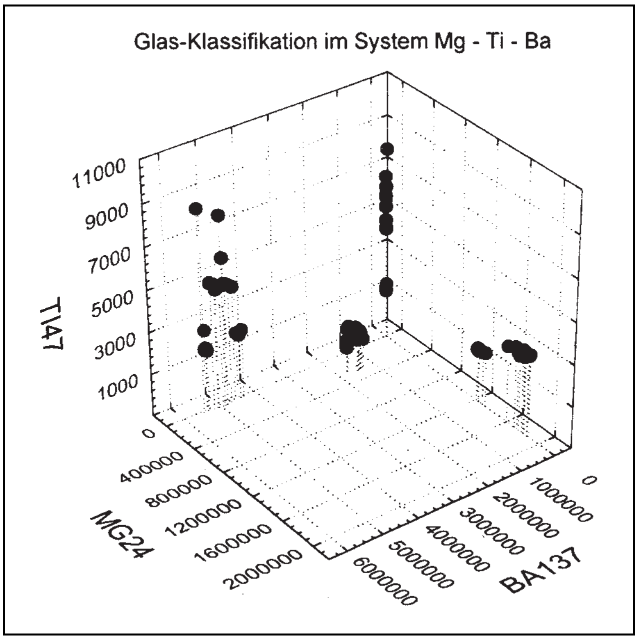

Fig.: Classification of glasses after backward elimination procedure, reduced number of variables (3): isotopes ^{24}Mg, ^{47}Ti and ^{137}Ba

The result of the classification experiment with a reduced number of variables (three isotopes) was not better in comparison with the former experiment (13 variables). Sample no. 4 was faultly classed as Duran®-glass (probability between 71.9–93.7%), but correctly detected as borosilicate glass.

In a second run the method of "stepwise elimination procedure" was used. In both procedures the F-statistics were used. The result of the reduction procedure was a minimized number of eight isotopes. In detail the following isotopes were isolated: ^{7}Li, ^{11}B, ^{23}Na, ^{24}Mg, ^{27}Al, ^{42}Ca, ^{47}Ti, ^{137}Ba. The resulting classification of the glass samples using the reduced number of these eight variables was correctly. Results are shown in Table 2.

Table 2: Classification of unknown samples: stepwise discriminant analysis, 8 variables

n = 28 Sample no.	Assigned glass type				
	G 1	G 2	G 3	G 4	trueness [%]
P 1	4	–	–	–	100
P 2	4	–	–	–	100
P 3	4	–	–	–	100
P 4	–	–	–	4	100
P 5	4	–	–	–	100
P 6	–	4	–	–	100
P 7	–	–	4	–	100

P 1 infusion bottle, white (borosilicate glass, type Duran®)
P 2 ampoule, brown (borosilicate glass, type Duran®)
P 3 laboratory glass, brown (borosilicate glass, type Duran®)
P 4 ampoule, white (borosilicate glass, type Fiolax®)
P 5 laboratory glass, white (borosilicate glass, type Duran®)
P 6 lead crystal, white (lead glass)
P 7 bottle glass, white (soda-lime-glass)
G 1 borosilicate glass, type Duran®
G 2 lead glass
G 3 soda-lime-glass
G 4 borosilicate glass, type Fiolax®

3. Experimental

3.1. Software

Statistical calculation was performed by SAS® statistical software, version 6.12. The module DISCRIM was used to perform the linear discriminant analysis. For the reduction of variables the options "backward elimination procedure" and "stepwise elimination procedure" of the module STEP-DISC were used.

3.2. Instrumentation

All measurements were carried out with the ICP-MS instrument ELAN 6000 from Perkin-Elmer-Sciex© coupled with a Laser Sampler Model 320. The Laser Sampler consisted of a Nd:YAG laser, ran at the 4th harmonic in the Q-switched mode (laser wavelength $\lambda = 266$ nm, pulse frequency 10 Hz, pulse energy 35 mJ), a sample stage with three software-controlled stepper motors for sample positioning in the μm-range and a CCD camera system. The ablation-cell purge rate was 1.0 l/min Ar, ablation was performed at atmospheric pressure.

Fiolax® and Duran® are trade marks of Schott-Rohrglas GmbH, Bayreuth, Germany.

References

1 Pfaender, H. G.: Schott Glaslexikon, 5. Auflage, mvg-Verlag Landsberg (1997)
2 USP 23 NF 18 supplementary 03/15/99, **661**: 1781–1783 (1995)
3 DAB 10: aktualisierte Ausgabe vom 28.03.2000, VI.2.1: 1–6 (1991)
4 EuAB: aktualisierter Nachtrag vom 26.04.1999 (1997)
5 Schmidt, T.; Surmann, J.-P.; Stephanowitz, H.; Hoffmann, E.: Pharmazie **56**, 852 (2001)
6 Fischbacher, C.: "Chemometrische Datenanalyse", in: Analytiker Taschenbuch 19, Springer Verlag Berlin (1995)
7 Henrion, R.; Henrion, G.: "Multivariate Datenanalyse", Springer-Verlag Berlin 1998

Received October 14, 2001
Accepted October 29, 2001

Prof. Dr. J.-P. Surmann
Institut für Pharmazie
Goethestraße 54
D-13086 Berlin