PLANNING EXPERIMENTS THAT INVOLVE MEASUREMENT AND ANALYZING THE EXPERIMENTAL DATA WITH THE CONSTRUCTION OF CALIBRATION CURVES OF THE ANALYTICAL INSTRUMENTS

A. G. Chunovkina

UDC 543.862.28:389.6

This article examines certain problems in the practical use of the least-squares method to construct linear calibration curves of measuring instruments on the basis of calibrating mixtures. Two methods of interpreting the errors of such mixtures are examined, and recommendations are made on choosing the parameters of the experiment and ensuring the necessary accuracy in the mixtures.

Quantitative analysis involves specific measurement procedures performed in several stages. The quality of the results obtained in quantitative analysis is determined by the efficiency with which these stages are carried out, with allowance for their interrelationship and interdependence. The problems of improving the accuracy of the results obtained from quantitative analysis and ensuring the necessary accuracy in the development of methods for such analysis are stimulating research into ways of efficiently organizing the analytical process and optimizing its individual stages and the analysis as a whole [1].

One of the most important stages in quantitative analysis is the construction of the calibration curves of the measuring instruments (MI CC). Construction of these curves entails planning of the measurements as part of development of the method to be used for quantitative chemical analysis (QCAM). Here, we are not speaking of the planning of a single measurement, but of a procedure that will be repeated multiple times during utilization of the QCAM. Any errors made at this planning stage cannot be eliminated during use of the QCAM and may have a significant effect on the accuracy of the measurements. In the process of constructing a calibration curve (CC), the planning of the measurements is preceded by the collection and analysis of experimental data. Information that makes it possible to concretize the problem and thus allows the planning to be done more efficiently is also needed before the actual planning is begun. The problem of constructing CCs in the course of developing a QCAM is of an exploratory nature and requires a large volume of experimental data. It is at this stage of development that an a priori evaluation is made of the measurement errors. Study of the calibration curve and planning of the measurements for its construction make it possible to establish procedures for the actual plotting of the curve during the analysis, as well as to establish procedures to check the error of the curve. The latter set of procedures includes suitable norms calculated on the basis of characteristics of the errors typically made in obtaining the plot. These norms are also used to check the standard specimens and the certified mixtures used in the calibration process.

Below, we examine aspects of measurement planning during the construction of linear calibration curves. Linearity is established as a requirement in order to simplify the discussion and avoid having to use complex formulas. The approach being taken here and the main results that are obtained can also be applied to nonlinear calibration curves.

The task of plotting linear calibration curves is the problem most often encountered in practice and remains of considerable interest. Nonlinear relations are often reduced to linear form by dividing the measurement range into subranges. The use of a linear model is justified by the fact that such models often give a good approximation for the given range of experimental data, while complicating the model by introducing nonlinearities fails to significantly improve the level of accuracy achieved relative to the level required for the accurate construction of calibration curves. In addition, increasing the number of parameters that can be evaluated by the model on the basis of experimental data also increases the error of the calibration curve. Finally, linear models are often more stable and make it possible to more easily check the results and perform the calibration under working conditions.

The problem of measurement planning in the construction of calibration curves involves the following steps:

- selection of an algorithm for analyzing the experimental data;
- selection of specimens for calibration;
- selection of a plan for performing measurements in the experiment. This plan includes the number of measurement points and their location along the range of measurement, as well as the number of parallel determinations.

Methods of planning measurements for the construction of empirical relations have been developed in mathematical statistics and regression analysis. In the case of the construction of calibration curves, the problem of measurement planning has an exact mathematical solution if certain conditions are observed. However, maintaining these conditions is difficult in practice. The direct use of mathematical methods is impeded by the existence of systematic errors, the inexact nature of the specified model of the CC, the deviation of the error distribution law from a normal law, and other factors. This situation makes having a priori information much more important, since such information makes it possible to narrow the range of possible solutions. The a priori information also needs to be analyzed in order to develop planning criteria. In the case being discussed, a priori information can be conditionally divided into two groups: the first group contains information on the measuring instruments used to certify the mixtures, etc.; the second group includes the accuracy requirements that must be satisfied in regard to the type of calibration curve and its construction.

The a priori information includes the following:

- characteristics of the errors of the measuring instruments and their dependence on the value of the quantity being measured;
- characteristics of the errors of the standard specimens and certified mixtures and estimates of the errors made in the preparation of the calibrating solutions;
- the accuracy required in the construction of the CC;
- possible limitations on the number of measurements that can be made in the calibration; the order in which experimental data is obtained;
- the results of calibration of similar instruments, previous calibrations of the same instrument, and previous experimental data;
- the form of the calibration curve (either the desired form or the physically substantiated form).

Let us take a closer look at the main problems that have to be solved when planning measurements as part of the construction of a calibration curve.

**Selection of the Algorithm for Analyzing the Experimental Data.** The least-squares method (LSM) occupies the dominant position in the analysis of experimental data. The preference shown this method is based on the quality of the estimates it yields (their accuracy, lack of bias, and efficiency). The estimates made of the parameters of functions by the LSM are of this quality as long as the following conditions are met:

a) the exact form of the function is known;

b) the exact values of the input variables are known;

c) the errors of measurement of the output variables have a normal distribution.

In practice, either it is difficult to check for the satisfaction of these conditions or they are known not to be satisfied. This situation has stimulated the development of stable (robust) nonparametric and confluent methods in mathematical statistics. However, these methods have not come into wide use as yet, which may be a reflection partly of the complexity of the computational procedures that are involved and partly due to researchers' hesitance to embrace new techniques. Given this, it is especially important that an attempt be made to analyze the consequences of failing to satisfy the above three conditions and to determine the actual range of validity of the LSM, i.e., the range in which use of the LSM is both feasible and expedient but does not offer the benefit of its exceptional properties (particularly its efficiency):

- violation of condition (a) essentially means having to change over from a "physical" model of the CC to a model that interprets experimental data. Such a change may result in an additional error caused by the inadequacy of the model, and the degree of its adequacy is quite difficult to evaluate. The adequacy of the model is substantiated indirectly, usually by checking for inconsistencies between the model and the experimental data after the calibration curve has been constructed;

- violation of condition (b) leads to bias in the resulting estimates and renders them invalid. However, when the calibration curve is constructed using standard specimens that have been certified and calibrated on the basis of mixtures, the experiment is considered an "active" experiment (the values of the input variable are established at chosen reference points). In an "active" experiment, LSM estimates remain valid and free of bias when the model used is linear, while these two properties are conserved only within the framework of a certain approximation when the model is nonlinear. Violation of condi-