

Official International Association for Therapeutic Drug Monitoring and Clinical Toxicology Guideline: Development and Validation of Dried Blood Spot–Based Methods for Therapeutic Drug Monitoring

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Abstract: Dried blood spot (DBS) analysis has been introduced more and more into clinical practice to facilitate Therapeutic Drug Monitoring (TDM). To assure the quality of bioanalytical methods, the design, development and validation needs to fit the intended use. Current validation requirements, described in guidelines for traditional matrices (blood, plasma, serum), do not cover all necessary aspects of method development, analytical- and clinical validation of DBS assays for TDM. Therefore, this guideline provides parameters required for the validation of quantitative determination of small molecule drugs in DBS using chromatographic methods, and to provide advice on how these can be assessed. In addition, guidance is given on the application of validated methods in a routine context. First, considerations for the method development stage are described covering sample collection procedure, type of filter paper and punch size, sample volume, drying and storage, internal standard incorporation, type of blood used, sample preparation and prevalidation. Second, common parameters regarding analytical validation are described in context of DBS analysis with the addition of DBS-specific parameters, such as volume-, volcano- and hematocrit effects. Third, clinical validation studies are described, including number of clinical samples and patients, comparison of DBS with venous blood, statistical methods and interpretation, spot quality, sampling procedure, duplicates, outliers, automated analysis meth-

ods and quality control programs. Lastly, cross-validation is discussed, covering changes made to existing sampling- and analysis methods. This guideline of the International Association of Therapeutic Drug Monitoring and Clinical Toxicology on the development, validation and evaluation of DBS-based methods for the purpose of TDM aims to contribute to high-quality micro sampling methods used in clinical practice.

Key Words: dried blood spots, guideline, validation, microsampling, VAMS

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INTRODUCTION

Dried blood spot (DBS) analysis has been introduced more and more into daily practice.¹ To assure the quality of bioanalytical methods and to assure that the results obtained with those methods are valid, it is of utmost importance that newly developed methods are fit for purpose. Those methods must have undergone adequate method validation and are monitored through a suitable quality control (QC) program. Absence of DBS-specific method validation guidelines results in DBS-based methods lacking essential validation aspects resulting into reduced credibility.^{1–4} Validation requirements described in guidelines for the quantitative analysis of

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traditional matrices (ie, liquid blood, plasma, or serum) are not always easily translated to analysis of DBS.^{5,6} Moreover, several additional parameters, such as volume and hematocrit (HT) effects, which are not part of traditional guidelines, are often overlooked or not adequately assessed.⁷

Therefore, this guideline aims at defining the parameters necessary for the validation of quantitative DBS-based methods and to provide advice on how these can be assessed. In addition, guidance is given on the application of validated methods in a routine context. The recommendations in this guideline are based on existing guidelines for traditional matrix analysis, in particular, the bioanalytical method validation guidelines issued by the European Medicines Agency (EMA) and the Food and Drug Administration (FDA),^{5,6} the guideline for measurement procedure comparison provided by the Clinical and Laboratory Standards Institute (CLSI),⁸ several white papers on dried matrix analysis,^{9–11} as well as other published work and the personal experience of the authors.

The focus of this guideline is the analysis of DBS for the quantitative determination of small molecule drugs and drug metabolites using chromatographic techniques for therapeutic drug monitoring (TDM) purposes. However, many elements of this guideline are also relevant for the analysis of samples obtained through volumetric absorptive microsampling (VAMS) and for dried plasma spot (DPS) analysis, as well as for the analysis of DBS for purposes other than TDM.

As the successful validation of a DBS-based analytical method starts with method development, this guideline commences by outlining the potential pitfalls encountered during that stage (see Considerations Regarding Sample Collection, Considerations Regarding Sample Preparation, and Other Important Considerations). Furthermore, the importance of prevalidation stress testing is highlighted (Prevalidation—Stress Testing). In a next section, the actual method validation is extensively discussed (see ANALYTICAL VALIDATION and CLINICAL VALIDATION). This validation section encompasses both the analytical validation (comprising both the classical and the DBS-specific validation parameters) and the clinical validation (ie, demonstration of equivalence between DBS-based results and results obtained in the classical matrix). Finally, QC is briefly discussed (see CROSS-VALIDATION). A summary of this guideline can be found in Supplemental Digital Content 1 (see Supplement S1, <http://links.lww.com/TDM/A342>).

METHOD DEVELOPMENT: CONSIDERATIONS FOR SUCCESSFUL VALIDATION

Before embarking on the set-up of a DBS-based procedure, it is essential to carefully think about the purpose of the method. Certain considerations need to be made to ensure the suitability of the method for a given application (ie, to ensure the method is fit for purpose) already in this early stage. These considerations are discussed below, and the different options are schematically summarized in Figure 1. Furthermore, stress testing of the method during method development will allow potential issues to be detected at an early stage, which will eventually increase the chances of a successful method validation and application.

Considerations Regarding Sample Collection Collection Procedure

Nowadays, the most frequently used dried blood sample collection method is the collection of a nonvolumetric drop of blood (DBS), free falling or by touching onto a filter paper (ie, directly from a finger prick or heel stick). Alternatively, the blood sample may be deposited volumetrically using a capillary or a pipette. Furthermore, several blood collection strategies exist in which a volumetric dried blood sample can be directly generated from a nonvolumetric drop of blood, without the use of pipettes or handheld capillaries. These strategies include, HemaXis,¹² hemaPEN,¹³ Capitainer-B,^{14–16} and VAMS.^{17–19} In addition, DPS may be collected rather than DBS. These DPS may be generated either by centrifugation of a liquid blood sample and subsequent application of an amount of plasma onto a filter paper or by using a device that allows in situ DPS generation.^{20–23}

Although some of the above-mentioned collection strategies may allow patient self-sampling (eg, nonvolumetric DBS collection,²⁴ VAMS,²⁵ and in situ generated DPS), other collection methods (eg, volumetric DBS collection using exact volume capillaries and DPS generation after centrifugation) require trained professionals and/or laboratory equipment. Although the latter strategies are not suitable for home sampling, they may still be valuable in another context. DPS generation through whole blood centrifugation and pipetting may, for example, be a suitable approach if DPS are prepared in a laboratory in a remote or resource-limited setting to allow more convenient transport to a centralized or reference laboratory.²⁶ In addition, other parameters such as required sample volume, automation capabilities, commercial availability, the cost of a given microsampling device, as well as overall costs may also play an important role in the selection of the sample collection method.

Selection of the Type of Filter Paper

If samples are to be collected on filter paper, the type of filter paper (card) that will be used needs to be carefully chosen. The type of filter paper may affect the occurrence of interferences, the blood's spreading behavior, sample homogeneity, as well as analyte stability and recovery.^{27–29} Commercially available filter paper can either be untreated (eg, Whatman 903, Ahlström 226, DMPK-C), or pretreated with for example, denaturing agents or enzyme inhibitors (eg, DMPK-A or DMPK-B).³⁰ Furthermore, in certain DBS-based methods, in-house pretreated filter paper has been used to increase analyte stability or recovery.^{31–34} Moreover, some types of collection devices have been reported to be less affected by the HT effect and may help to overcome this issue.^{35,36} In addition, chitosan and alginate foams have been proposed as collection substrates to help increase analyte recovery, as they dissolve during sample extraction.³⁷ Although most DBS-based bioanalytical methods use regular, cellulose-based, untreated filter paper (cards), for certain applications, it may be valuable to evaluate the use of pretreated or noncellulose-based alternatives. However, it needs to be kept in mind that the use of noncommercially available

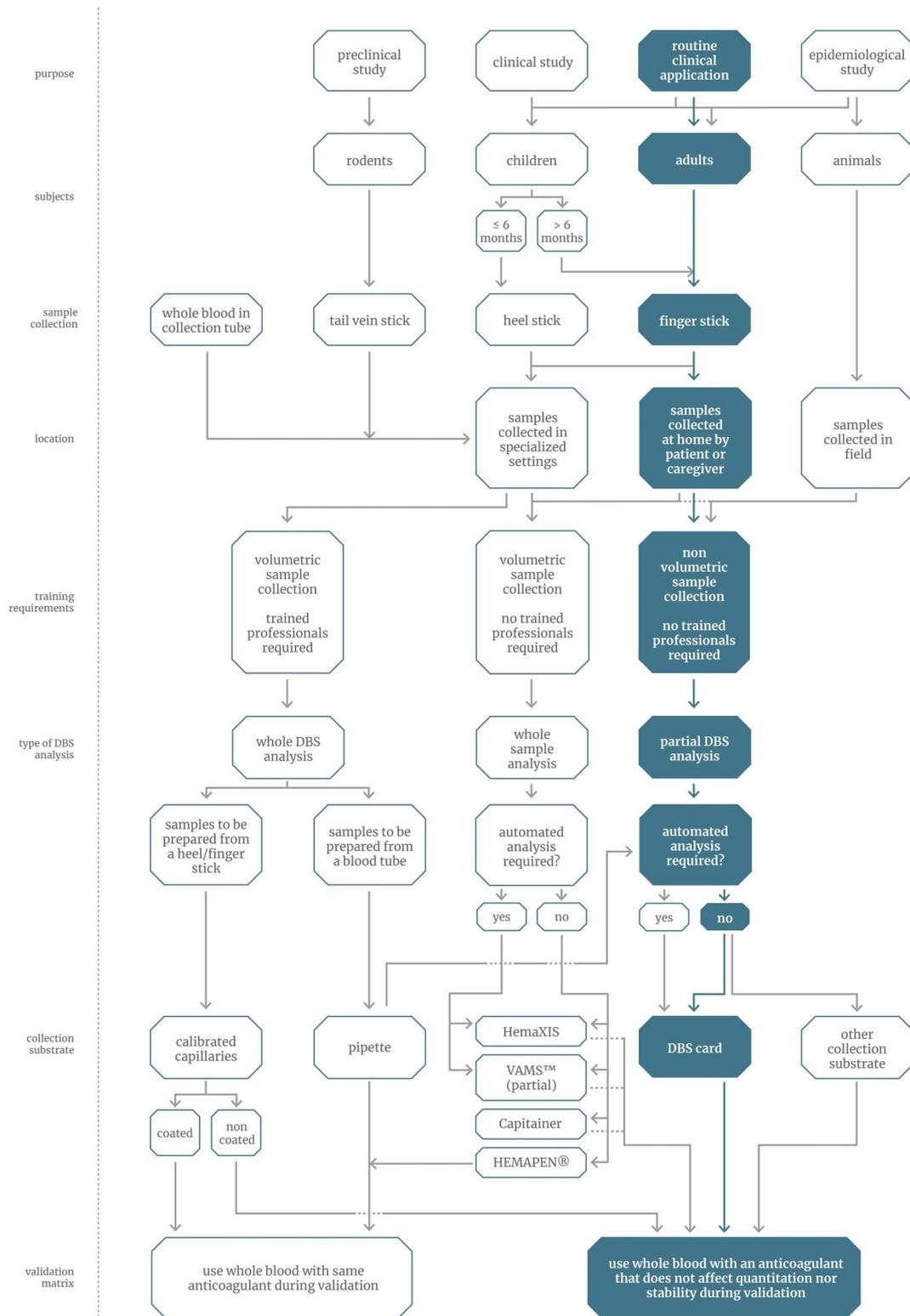


FIGURE 1. Flowchart depicting different options for the set-up of a dried blood spot-based method which can be used before setting up a dried blood spot-based procedure. The highlighted “flow path” shows the procedure for therapeutic drug monitoring of immunosuppressants following home sampling by adult patients and partial spot analysis of DBS cards sent to the laboratory. Reprinted with permission from Aniek Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

substrates may hinder a generalized application of the method and requires in-house assessment of batch to batch quality.³⁸

Interferences Originating From the Collection Substrate

It is advised to analyze some blank collection cards during early method development to assess whether the collection material itself is blank and whether there are any interferences present that need to be separated chromatographically from the target compound(s).²⁸ If one of these issues occurs, it might also be valuable to evaluate different collection substrates.

Sample Volume

The amount of sample that is required for a certain analysis will mainly depend on the envisaged lower limit of quantification (LLOQ) and is inherently linked to the available instrumentation. However, the minimally required volume should always relate to how the samples are collected. For the set-up and validation of the method, a sample volume representative of the sample volume of the patient samples needs to be used. Most people will typically generate DBS of 20–70 μL if free falling drops of blood are collected, whereas somewhat smaller DBS typically 15–50 μL will be obtained if a hanging blood drop is collected by bringing it into contact with the filter paper. With the latter approach, it is essential that only the blood drop and not the fingertip touches the filter paper. If a DBS is smaller than what is typically expected, this may be an indication that the fingertip came into contact with the filter paper. On the other hand, if a DBS is larger than expected, multiple drops were likely collected. Obviously, whenever samples are collected volumetrically, the sample volume will be determined by the used device. If a larger volume of blood is required to reach the LLOQ, sometimes punch stacking is used.³⁹ Nonetheless, the number of punches required for a single analysis should remain as small as possible, to limit the amount of good quality samples that needs to be collected and to allow incurred sample reanalysis (ISR).

Drying and Storage Process

A parameter that is often neglected in DBS-based methods is the impact of drying time. If the sample is not completely dry before putting it in a zip-locked bag for storage, microbiological growth may occur and compromise sample quality.⁴⁰ Furthermore, improper drying might also affect analyte stability and recovery.^{41,42} Therefore, it is advised to dry samples at least 3 hours under ambient conditions (preferably without direct sunlight) and to store them with a desiccant, which will remove an additional 5% of water from the dried samples.^{40,43} In certain settings, however, the required drying time may be longer because this depends on the ambient temperature and humidity, the sample volume, and the type of filter paper.⁴² In other settings, shorter drying times may suffice. Therefore, it is relevant to evaluate during early method development whether the drying time is adequate under the conditions likely to be encountered during the collection of the patient samples. This evaluation is preferably performed using DBS with an HT in the upper range of the HT of the target population and, if applicable, a large sample volume, as these

will dry the slowest.²⁷ Furthermore, the ambient temperature and humidity during drying have been suggested to affect DBS homogeneity (although this effect also depends on the type of filter paper that is used).⁴⁴ Similarly, also the storage conditions should mimic the ambient conditions encountered during patient sample transport/storage.⁴⁵

Considerations Regarding Sample Preparation

Punch Size

For volumetric DBS applications, the punch size needs to be large enough to punch out the entire DBS, independent of the HT of the sample. Hence, it is advised to select the required punch size based on samples with an HT of approximately 0.15, since this HT level will be lower than the lowest HT level of the patient population and will therefore yield DBS that are (slightly) larger than the largest expected patient DBS. The punches can either be made after application of the blood spot to the substrate or in advance.^{46–48} For nonvolumetric DBS applications, partial DBS punches are made that exclude the outer edge of the sample. If relatively small punches are made (≤ 4 mm or approximately 5.7 μL), most patients should be able to generate multiple DBS that are large enough to analyze. However, larger punch sizes may be required to obtain the desired LLOQ to increase method accuracy and imprecision or to exclude DBS homogeneity issues. Although generating larger DBS will be somewhat more difficult for a patient, when properly educated and trained, most patients will be able to provide at least 1 or 2 samples that are large enough to make punches up to 8 mm (± 20 μL). The latter will also be easier if falling-drop-collection is used rather than hanging-drop-collection.

Internal Standard Incorporation

Ideally, an internal standard (IS) is mixed homogeneously with the biological sample before sample preparation to compensate for any variability throughout the entire analytical process. Unfortunately, this is difficult to achieve with a DBS. For DBS analysis, the closest alternative is to spray the IS evenly onto the sample before extraction.⁴⁹ However, this requires the availability of a validated dedicated spraying system, which is not available in most laboratories. Another option is to precoat the filter paper with the IS.⁵⁰ However, in that case, the IS needs to be applied to a larger surface, as it is not known where exactly the sample will be deposited. Furthermore, the IS should be stable for a sufficiently long period (ie, during sample collection, transport, storage, and analysis). In addition, the same batch of IS solution should be used for calibrators, QCs, and patient sample collection cards, which is not feasible on a large scale. Another potential side-effect of precoating filter paper with IS (in the absence of matrix) is that the IS may show different recovery than the target analyte. To the best of the authors' knowledge, such strategies have not yet been evaluated for other dried blood samples nor has a successful application of IS-precoated microcapillaries been described. Again, such an approach would require the availability of tailor-made devices, which will be at the expense of additional costs. In most

DBS-based methods, the IS is added to the extraction solution or directly to the DBS punch before extraction and will hence not compensate for variability in analyte recovery.^{9,51} Therefore, analyte recovery must be investigated extensively under different conditions (see Evaluation of the Robustness of the Extraction Procedure and Short-Term Stability) during method development and validation.

Other Important Considerations

Type of Blood Used

For the set-up of calibration curves and internal QCs, it is from a practical point of view impossible to use capillary blood samples derived from a finger prick. Instead, spiked samples generated from venous whole blood containing an anticoagulant are used. Which type of blood is best suited for this purpose largely depends on how patient samples will be collected. If the DBS collection device that is used to generate the patient DBS contains a certain anticoagulant, the venous whole blood also needs to contain that same anticoagulant. On the other hand, if no anticoagulant is used during the collection of the patient samples, theoretically, the blood used to set up the calibration curves and QCs also has to be non-anticoagulated. Unfortunately, it is very impractical to prepare spiked samples from non-anticoagulated blood because blood will start coagulating almost immediately after collection. Therefore, in most cases, a suitable anticoagulant will have to be selected. It is essential that the use of this anticoagulant does not impact the obtained results, and that the stability of calibrators and QCs reflects that of real samples. Hence, we strongly advise to compare in an early stage results obtained from a non-anticoagulated sample with results from patient samples anticoagulated with different anticoagulants.⁵² These blood samples should all be obtained venously from the same volunteer or patient at (approximately) the same time and should be analyzed in quintuplicate. Based on the knowledge about the (lack of) impact of certain anticoagulants in liquid blood, some anticoagulants may readily be excluded. For example, if analytes are, for example, stabilized by oxalate/NaF, this type of blood should preferentially not be used to assess the analyte's stability in DBS (which in practice would not contain that stabilizing anticoagulant). On the other hand, if the anticoagulant stabilizes the analyte, and anticoagulant-containing DBS are commutable in any other way with DBS without anticoagulant, the former could be used for the set-up of calibrators and QCs as the prolonged analyte stability could help ensure consistent calibration.

Preparation of Spiked Samples

A first step in the preparation of spiked samples is to adjust the HT or erythrocyte volume fraction of the whole blood to the desired HT value. For most experiments, the latter will correspond to the mean or median HT value of the target population.⁵³ Although there are several ways of preparing samples with a certain HT, the preferred procedure is to measure the HT of the original blood sample with a hematology analyzer and to calculate how much plasma needs to be added or removed to obtain the desired HT value.⁵⁴ After the addition or removal of the plasma, it is important to

measure the HT again, to ensure the sample was prepared correctly.

In a next step, the analyte needs to be spiked into the blood. It is important to only spike a limited volume of analyte solution to the blood (ie, <5% of the sample and preferably even less) to not change the nature of the sample.⁵ Moreover, the addition of a larger volume of solvent would also change the sample's viscosity and/or cause cell lysis, thereby affecting its spreading behavior through the DBS filter paper. Furthermore, organic solvents may denature proteins. To further minimize the effect of the spiking volume on the sample's spreading behavior, stock solutions can be diluted with plasma, rather than with water or another solvent, if solubility allows for it. After spiking the blood with the target analyte, the samples should equilibrate for a sufficient amount of time at a suitable temperature to mimic the analytes' in vivo RBC/plasma distribution.⁵⁵

Prevalidation—Stress Testing

Exploratory Tests

As with a traditional bioanalytical method, several exploratory tests need to be performed to assess whether a developed method is good enough to proceed toward validation. As with any chromatographic method, several technical aspects should be checked early on during method development, for example, the absence of carryover and the influence of the sample matrix on the chromatographic method. Furthermore, the stability of the stock solutions used for the spiking of the calibrators and QCs should be guaranteed. Particular points of attention during prevalidation for DBS-based methods are short-term stability and extraction efficiency.

Although DBS generally tend to improve analyte stability, this is not always the case. Enzymatic analyte degradation may readily occur during the drying process.⁵⁶ Furthermore, oxidation sensitive analytes are likely to suffer from stability issues, since DBS are exposed to air during drying and/or storage.³⁰ If low signals are obtained from fresh samples (eg, compared with a standard solution with the same concentration), this might be due to stability issues during the drying process. In addition, these low signals may also be caused by matrix effects (MEs), poor extraction efficiency, or a combination of the above.

When using liquid chromatography tandem mass spectrometry (LC-MS/MS), the presence of MEs can be evaluated using postcolumn infusion. If present, these MEs may be eliminated by further optimization of the sample preparation and/or the chromatography. Poor extraction efficiency may be due to the analyte's interaction with the carrier or with endogenous matrix compounds.^{29,57,58} However, the differentiation between extraction efficiency issues and actual analyte instability may not be so straightforward.³⁴ To get an idea about potential stability issues, existing literature about the stability of the analyte in whole blood or about the chemical and physical properties of the analyte may be a good starting point. If degradation during sample drying is anticipated (eg, for compounds with a very short in vitro half-life), flash heating may improve the

analyte's stability (at least if the analyte is thermostable) because this inactivates the enzymes.⁵⁶ Unfortunately, this strategy is not suitable for home sampling. Nonetheless, it may help to figure out the cause of the poor method outcome. Other strategies to help improve the analyte stability may include preimpregnating the collection substrate with antioxidants or buffers.^{34,59} However, these strategies may hamper generalized application of the method. For some analytes, instability issues remain unsolved, even when taking into account a restrictive time frame for transportation of DBS. In those cases, it should be decided that dried blood sampling for that analyte is not feasible. In specific situations, a volumetrically obtained sample could be brought into a stabilizing sampling buffer shortly after.⁶⁰ When poor extraction efficiency is suspected, further optimization of the extraction procedure may be required (ie, the evaluation of different extraction solvents, additives and extraction temperatures, as well as more rigorous extraction techniques (such as sonication). Furthermore, the use of different (pre-treated) collection cards/devices may also help to improve the extraction efficiency.

At this stage, it should also be evaluated whether the obtained results are affected by the time between sample collection and analysis. More particularly, the results from samples analyzed at T_0 (typically between 30 minutes and 3 hours after sample generation, depending on the required drying time) should be compared with results obtained at later time points, preferably up to 48 or 72 hours. This experiment is important since time-dependent extraction issues have been described.⁶¹ More specifically, if the recovery decreases for the first (couple of) time points, but remains stable afterward, it may still be possible to obtain good analytical results. In such a case only samples older than a specified time point should be analyzed. Obviously, this strategy should not only be implemented for the patient samples, but also for the calibrators and QCs.

Evaluation of the Robustness of the Extraction Procedure and Short-Term Stability

In a next step, the robustness of the extraction procedure should be thoroughly investigated. This is a crucial experiment because in most DBS applications, the IS is not

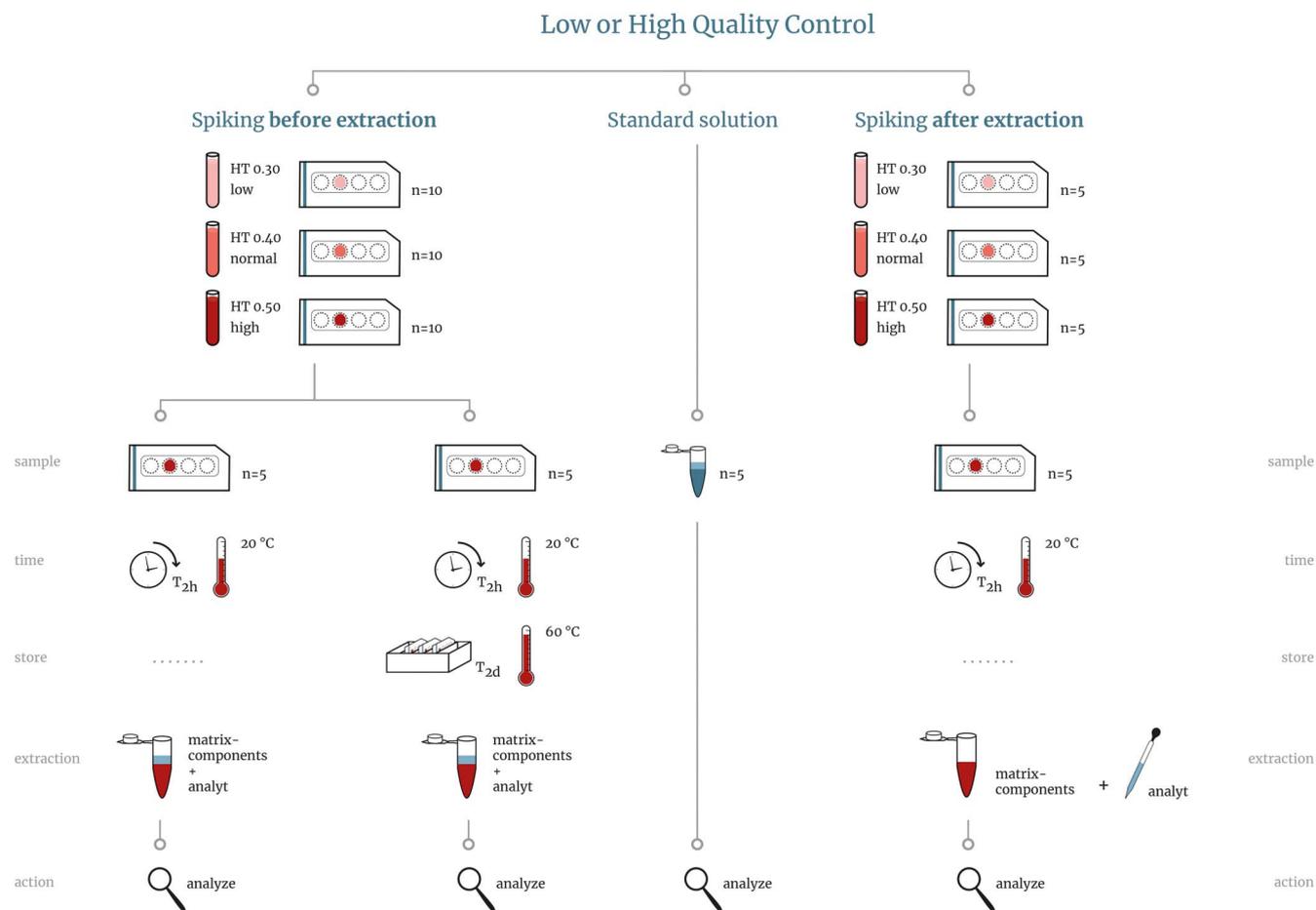


FIGURE 2. Schematic set-up of the experiments needed to assess the robustness of the extraction procedure and short-term stability. The total amount of samples to be analyzed for this experiment is 100 (plus calibrators and QC samples). Reprinted with permission from Aniek Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

capable of correcting for variability in extraction efficiency. The extraction efficiency may be concentration, HT, and time-dependent, and importantly, these parameters may also affect each other.^{41,62–64} HT-dependent extraction efficiency may be present or more pronounced at one concentration level compared with another.⁶⁴ Similarly, time-dependent extraction efficiency issues may occur earlier at a more extreme HT level.

For nonthermolabile compounds, the occurrence of HT- and time-dependent extraction issues can be evaluated by comparing the results from fresh DBS at low, medium, and high HT levels (with these HT levels encompassing the HT range of the target population; eg, 0.20, 0.40, and 0.60) with a second set of samples stored at 50–60°C for at least 2 days. This second set mimics thoroughly dried (aged) samples. This experiment should be performed at both the low and high QC levels (Fig. 2). Furthermore, to simultaneously determine the actual extraction efficiency at both QC levels, and to evaluate the presence of MEs, also samples spiked after extraction and standard solutions should be included in this experiment. Moreover, each of these samples should be analyzed in quintuplicate. In addition, along with these samples, a calibration curve and QCs have to be analyzed. Importantly, in case of partial DBS analysis, these samples should be prepared by the accurate pipetting of a fixed amount of blood onto prepunched filter paper disks to rule out any influence of the HT spreading effect on the amount of sample being analyzed.

When no relevant differences (ie, $\leq 15\%$) can be observed between the results obtained from fresh DBS and those stored at 50–60°C, it is unlikely storage will have an impact on extraction efficiency. A good outcome in this set-up may also readily indicate good stability under ambient conditions, although this needs to be formally evaluated during method validation. However, it needs to be mentioned that the latter can also be affected by other parameters such as humidity and exposure to sunlight. Furthermore, by comparing the results of the samples at the 3 different HT levels (both for the fresh and the stored samples), the occurrence of HT-dependent extraction efficiency issues can be evaluated. Moreover, using the Matuszewski approach, recovery and ME can be evaluated at both concentration levels and at 3 HT levels.⁶⁵ While performing this experiment may seem fairly elaborate at first, it may prevent serious problems at a later stage, which may require a complete revalidation (eg, if the extraction needs to be adapted). Moreover, if successful, the evaluation of ME and recovery may not have to be repeated at different HT levels during the actual method validation, as long as the method remains unchanged. Also, the evaluation of short-term stability at fairly extreme storage conditions (ie, 50–60°C) is already incorporated in this experiment (see Classical Validation Parameters to Be Evaluated).

For more thermolabile compounds, a similar experiment can be performed with samples stored at room temperature for 2 weeks instead of at 60°C for 2 days. Although this is a less harsh experiment than the previously described one, it does cover a time span in which most clinical samples in a laboratory will have been analyzed.

Alternatively, even lower storage temperatures may be used. However, if the analyte is not stable at room temperature for at least a couple of days, the method will not be suitable for routine use. Obviously, if satisfactory, these data can also be used as part of the stability data required for method validation.

To minimize the number of samples that has to be analyzed at this stage, a simplified experimental set-up is suggested in Figure 3. In particular, this set-up does not include “spiked after extraction” samples or standard solutions, and all samples are only analyzed in triplicate. This simplified set-up offers the advantage that if the extraction procedure has to be adjusted (and consequently, this evaluation has to be repeated), the number of samples that needs to be analyzed will not increase drastically. However, with this experiment, recovery and ME will still need to be evaluated at different HT levels in a separate experiment during method validation.

If the results of the above-mentioned experiments are nonsatisfactory, this may be due to instability of the target analyte or to extraction efficiency issues. If the results for the different HT levels differ significantly and/or substantially (ie, $>15\%$), this is due to an HT-dependent extraction efficiency issue, and the extraction procedure needs further optimization. In this context, heated extraction and the use of a mixture of organic solvents rather than a single organic solvent may be helpful.^{62,63,66,67} Furthermore, the use of a different collection card may also help to resolve this problem. Possibly, depending on the target population, the procedure can be repeated with less extreme low and high HT values, to evaluate whether acceptable results are obtained for a more limited HT span.

A difference between the fresh and the stored samples, on the other hand, might be due both to a time-dependent extraction efficiency issue and to actual instability of the target analyte.⁶⁸ However, if this difference is not observed at all HT levels, it is unlikely that analyte instability is the culprit. If the difference is observed at all HT levels, it may be worthwhile to repeat the experiment at a lower storage temperature, as this may indicate analyte instability.

DBS Homogeneity

In case of partial DBS analysis, it is essential to evaluate DBS homogeneity, that is, to assess whether results from central punches are equivalent to peripheral (or decentral) ones.⁶⁹ By already evaluating this parameter during prevalidation, one knows whether, during the next experiments, it is required to make a central punch or whether a peripheral punch or multiple punches can be made from a single DBS.

This evaluation must be performed at 2 concentration levels (low QC and high QC), at different HT levels (low, medium, and high) and at sample volumes representative of the anticipated patient sample volumes. Each of the evaluated conditions should be analyzed in quintuplicate. All samples should be compared with a calibration curve prepared with samples of medium HT level and average volume, of which a central punch was extracted. When both central and peripheral punches yield results within the standard

Low or High Quality Control

Spiking before extraction

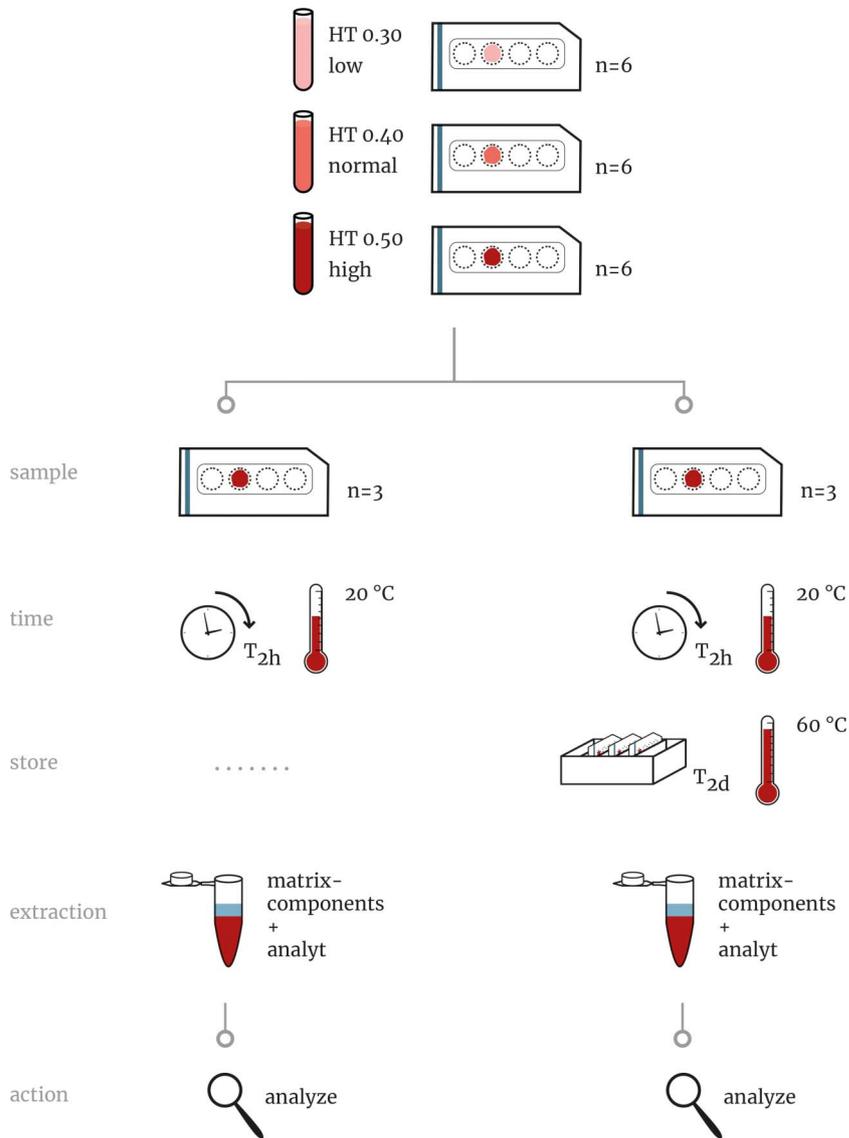


FIGURE 3. A simplified schematic set-up of an experiment to assess the robustness of the extraction procedure and short-term stability, requiring a minimum number of samples. The total number of samples to be analyzed for this experiment is 36 (plus calibrators and QC samples). Reprinted with permission from Anoeck Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

bioanalytical acceptance criteria (typically, within 15% of their target value), the use of both types of DBS punches is considered acceptable.⁶⁹

Obviously, this experiment only needs to be conducted if a central and a more peripheral punch can be made from a sample, which in turn will depend on the used punch size. When making peripheral punches, the very outer edge of the DBS should be excluded because this has a different composition than the rest of the DBS (eg, a higher amount of red blood cells, when using conventional Whatman 903 filter paper). In addition, the back of the filter paper should always be checked to ensure that the peripheral punch is made in a part of the DBS in which the filter paper is saturated. Importantly, the samples should be prepared under similar

conditions as the patient samples because the drying process is known to influence DBS homogeneity.^{27,70} Other parameters that may influence the equivalence between central and peripheral punches include the filter paper type, the position of the DBS card during drying, and the punch size (with larger punches being less affected by inhomogeneities within the DBS sample). The presence of an anticoagulant, on the other hand, does not seem to influence DBS homogeneity.²⁷

ANALYTICAL VALIDATION

None of the currently existing bioanalytical validation guidelines have been set up for dried blood sample-based methods. Certain experiments described in these guidelines

TABLE 1. Overview of the Analytical Validation Parameters That Require Additional Evaluation in Dried Blood Spot–Based Methods, and How to Assess Them

Validation Parameter	Evaluation	Statistical Test/Acceptance Criterion
Recovery, matrix effect, and process efficiency	Evaluate at both high and low QC levels using 6 different donors (with one donor evaluated at minimally 3 HT levels) with each condition determined in quintuplicate*.	Should be reproducible, both between matrices and HT values (%RSD $\leq 15\%$).
Volume effect	Evaluate at both high and low QC levels and at least at 3 HT levels and 3 volumes*.	One-way ANOVA with Bonferroni post hoc analysis ($P \leq 0.05$). Back calculated values deviate $\leq 15\%$ of medium volume.
Hematocrit effect	Evaluate at both high and low QC levels and at least at 3 HT levels*.	One-way ANOVA with Bonferroni post hoc analysis ($P \leq 0.05$). Back calculated values deviate $\leq 15\%$ of medium HT values.
Volcano effect	Compare central and peripheral measurements. Evaluate at both high and low QC levels and at least at 3 HT levels and one volume (typically, the highest)*.	Paired <i>t</i> test ($P \leq 0.05$) Back calculated “peripheral” values deviate $\leq 15\%$ of “central” values

*HT levels should cover the entire HT range of the target population, and the volumes should be representative of the sample volumes that will be generated by the patient. ANOVA, analysis of variance.

may not be applicable (eg, freeze-thaw stability, depending on the storage and transport conditions), whereas others may require some refinement (see Classical Validation Parameters to Be Evaluated). Moreover, some additional parameters will have to be evaluated (see DBS-Specific Validation Parameters).^{9,71} An overview of the required additional investigations can be found in Table 1. These will result in a slightly larger number of samples that will have to be analyzed during method validation (Table 2). Before starting any analytical validation, it is essential to contemplate what the desired quality of the method should be. Although the analytical performance requirements described in, for example, the FDA or EMA guidelines are widely applied and accepted, they may not always be suitable for DBS methodology. Depending on the analyte and the purpose of the method, these requirements can be set either more or less strict based on scientific evidence. In this context, some have suggested to use acceptance criteria based on biological variation, as is common practice in other areas of clinical chemistry.⁷²

Classical Validation Parameters to Be Evaluated

Most of the validation parameters described in traditional bioanalytical method validation guidelines will have to be assessed for DBS-based methods as well.^{5,6} Therefore, those documents will need to be consulted too when performing a DBS method validation. However, the particular points of attention when evaluating those classical validation parameters in the context of a DBS method are given below. Furthermore, to assist the reader, a brief overview of these classical validation parameters is given in Table 3.

Selectivity

To assess the selectivity of the method, blank matrices of at least 6 different individuals should be

analyzed without IS, as well as 2 zero samples (blank DBS extracted with extraction solvent containing IS). These blank samples should be obtained using the same sampling approach as the one that will be used to collect the patient samples. In addition, DBS prepared from blank blood spiked with common comedications, metabolites, and other potential interferences could be tested. At this stage, it may also be worthwhile to run a few authentic patient samples to ascertain there is no nonanticipated coelution of a metabolite that may not be available as a standard.

Calibration Model, Accuracy and Precision, Measurement Range

For the evaluation of the calibration model, the LLOQ and upper limit of quantitation (ULOQ), accuracy, and precision, all experiments should be performed in accordance with existing guidelines.^{5,6} The only difference is that all calibrators, blank, zero, and QC samples should be prepared in blood with the median HT of the target population and should have a volume representative of the patient samples.^{5,3} As with any bioanalytical method, the measurement range should be representative of the concentration range in patient samples. For the purpose of TDM, a calibration range minimally spanning from half of the lower end of the therapeutic interval to twice the upper end of the therapeutic interval should suffice. Furthermore, intracard and intercard variability do not need to be evaluated separately, as these variables will be inherently included throughout the method validation.⁹ For a method to be applied in a routine context, interbatch variability should be assessed. The latter can be performed by including cards from multiple batches in the validation experiments. However, if noncertified filter paper is used, a more elaborate evaluation of the filter paper may be warranted.

TABLE 2. An Overview of the Minimally Required Amount of Analyses for the Analytical Validation of Dried Blood Spots Versus Whole Blood

Validation Parameter	Amount of Samples (Dried Blood Spot–Based)	Amount of Samples (Liquid Whole Blood)
Selectivity	$n = (6 + 6) \times 1 \times 1 = 12$ 6 blank matrices, 6 LLOQs, 1 day, in singulo	$n = (6 + 6) \times 1 \times 1 = 12$ 6 blank matrices, 6 LLOQs, 1 day, in singulo
Calibration model	$n = 6 \times 5 \times 1 = 30$ 6 calibrators, 5 days, in singulo	$n = 6 \times 5 \times 1 = 30$ 6 calibrators, 5 days, in singulo
Accuracy and precision	$n = 4 \times 3 \times 2 = 24$ 4 QC levels (LLOQ, low, mid, and high), 3 days, in duplicate	$n = 4 \times 3 \times 2 = 24$ 4 QC levels (LLOQ, low, mid, and high), 3 days, in duplicate
Dilution integrity	$n = 1 \times 3 \times 2 = 6$ 1 QC level (dilution QC), 3 days, in duplicate	$n = 1 \times 3 \times 2 = 6$ 1 QC level (dilution QC), 3 days, in duplicate
Carryover	$n = (1 + 1) \times 5 \times 1 = 10$ a blank and zero sample, 5 days, in singulo	$n = (1 + 1) \times 5 \times 1 = 10$ a blank and zero sample, 5 days, in singulo
Recovery, matrix effect, and process efficiency	$n = 2x(2 \times 5 \times 1 \times 1 \times 5) + 2x(2 \times 1 \times 3 \times 1 \times 5) + (2 \times 1 \times 5) = 170$ 2 QC levels, 6 donors, of which 1 donor at 3 HT levels, 1 day, in quintuplicate (spiked before/after) 2 QC levels, 1 day, quintuplicate (standard solutions)	$n = 2x(2 \times 6 \times 1 \times 1 \times 5) + (2 \times 1 \times 5) = 130$ 2 QC levels, 6 donors, 1 HT level, 1 day, in quintuplicate (spiked before/after) 2 QC levels, 1 day, quintuplicate (standard solutions)
Stability	$n = 2 \times 1 \times 4 \times 5 = 40$ 2 QC levels, 1 HT level, 4 points: T_0 , T_{1w} , T_{2w} at RT, T_{2d} at 60°C, in quintuplicate	$n = 2 \times 1 \times 7 \times 5 = 70$ 2 QC levels, 1 HT level, 7 points, in quintuplicate Bench-top stability: T_0 and T_{24h} at RT Storage stability: T_{1w} and T_{2w} at 4°C/–20°C Freeze-thaw stability: min. 3 cycles N.A.
Volume effect, hematocrit effect, and volcano effect	$n = 2 \times 3 \times 4 \times 5 = 120$ 2 QC levels, 3 HT levels, low-, medium-, and high-volume central punch + high-volume peripheral punch, all in quintuplicate	
Total	412	282

RT = room temperature, T = time point, T_0 = starting point = at the minimum drying time (eg, 2 hours) = at the minimum drying time (eg, 2 hours).
Samples are prepared in blood of median HT, unless mentioned otherwise.

Dilution Integrity

Contrary to traditional liquid blood samples, DBS cannot be diluted directly. Hence, to analyze samples with a concentration above the measurement range, DBS extracts are typically diluted with blank DBS extracts or extraction solvent. Furthermore, IS-tracked dilution can be performed.^{6,73} With this approach, a higher concentration of IS is added to the extraction solvent, with the exact amount of IS depending on the envisaged dilution factor. This approach renders the dilution a volume-noncritical step. In addition, for DBS, the donut punch approach can be used.⁷⁴ With this approach, a small central punch (ie, smaller than the regular punch size for a given DBS method) is made from a DBS sample and is extracted simultaneously with a donut punch prepared from a blank DBS sample. This donut punch is a regular sized DBS punch from

which a small central punch (with the same punch size as used for the actual DBS sample) has been removed. However, to use the latter approach successfully, DBS homogeneity should be adequate for the small punch size, and the extraction efficiency should not depend on the punch size.

Carryover

Aside from classical carryover, in a DBS workflow, the punching step could be considered a potential source of contamination. Hence, we propose to include in the method validation, the processing of one or more blanks after the processing of the highest calibrator.⁹ To the authors' knowledge, however, no punch-mediated carryover has been described for (therapeutic) drugs, although it has been observed for PCR-based methods.⁷⁵ In addition, physical carryover between cards

TABLE 3. An Overview of the Classical Validation Parameters and How to Assess Them

Validation Parameter	Evaluation	Statistical Test/Acceptance Criterion
Selectivity	6 individual blank matrices	≤20% of LLOQ (analyte) ≤5% (IS)
Calibration model	Use min. 6 calibrators + zero + blank. Zero and blank samples should not be included in the calibration curve.	Back calculated concentrations ≤15% of nominal value (≤20% at LLOQ). ≥75% of all calibrators and ≥50% per calibration level should comply.
Accuracy and precision	Evaluate at 4 QC levels: LLOQ Low = ≤ 3 × LLOQ Medium = 30%–50% of range High = ≥75% of highest calibrator	≤20% for LLOQ ≤15% for other QC levels
Dilution integrity	Evaluate a dilution factor (eg, 1:9) applicable to the patient samples.	Accuracy and precision ≤15%
Carryover	The analysis of (zero and) blank samples after the highest calibrator	≤20% of LLOQ (analyte) ≤5% (IS)
Recovery, matrix effect, and process efficiency	Evaluate at both low and high QC, using 6 different blank matrices. Recovery: Spiked before/spiked after. Matrix effect: Spiked after/standard solutions Process efficiency: Spiked before/standard solutions	CV ≤ 15%
Stability	Evaluate at both low and high QC levels. Store stability QCs under representative conditions for a representative time frame and measure against fresh calibrators.	≤15% of nominal value (or ≤15% of value at T ₀)

T₀ = starting point, when samples were fresh.

should be avoided by storing the cards separately. However, if multiple cards will be stored together, potential carryover between cards requires evaluation.⁹ The same acceptance criteria as for classical carryover should be applied.^{5,6}

Matrix Effect, Recovery, and Process Efficiency

ME, recovery, and process efficiency should be evaluated in line with the set-up proposed by Matuszewski et al⁶⁵ (also see METHOD DEVELOPMENT: CONSIDERATIONS FOR SUCCESSFUL VALIDATION). For this experiment, blood from at least 6 different donors should be used, and 2 concentration levels should be evaluated (ie, low and high QC levels). In addition, since it is known that the HT may strongly impact the recovery—and possibly also the ME—it is essential to evaluate recovery and ME at different HT levels, prepared from the blood of at least one donor. These HT levels should encompass the anticipated HT range of the target population. Alternatively, this experiment could also be performed using 5 HT levels (0.20, 0.30, 0.40, 0.50, and 0.60). The latter set-up has the advantage that whenever the most extreme HT values do not yield acceptable results, a narrower, acceptable HT range (regarding recovery and ME) may still be determined, without having to repeat the experiment. This set-up is schematically depicted in Figure 4. As mentioned before, to accurately perform this experiment, a fixed volume of blank or spiked blood needs to be applied on pre-punched filter paper discs.

Although MEs are preferably as small as possible, recovery and process efficiency as high as possible, the exact values are not that relevant. It is essential, however, that they are reproducible (ie, relative SD or %RSD within 15% after IS normalization). It is relevant to note that observations by Abu-Rabie et al⁴⁹ suggest that extraction procedures with lower recoveries may be more subject to an impact of HT (see DBS-Specific Validation Parameters).

Stability

The stability assessments performed during method validation should be representative of the ambient conditions encountered during sample transport, storage, and processing. Therefore, stability should be evaluated at room temperature (the exact temperature depending on where the method will be applied) and the investigated time frame should cover the maximum expected time frame between sample collection, analysis, and potential reanalysis. Furthermore, because temperatures may be significantly higher during transport (eg, in a mail box in the sun during summer time), short-term stability at elevated temperatures (ie, 2 or 3 days at 50–60°C, or higher temperatures depending on the country) should also be tested.^{45,76} If stability under ambient conditions is only sufficient for a couple of days (but long enough to allow transport to the laboratory), it may be

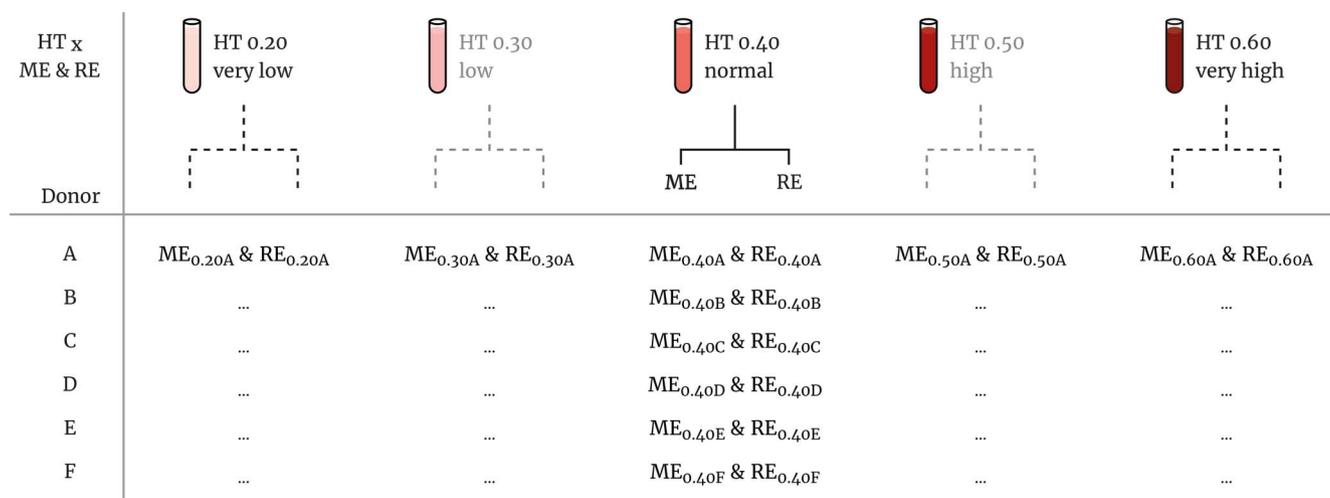


FIGURE 4. A schematic set-up for the evaluation of ME and recovery (RE). The experiment can either be performed at 5 HT levels or at 3 (ie, without the gray samples). This experiment allows to evaluate whether ME and RE are constant for different matrices and for different HT levels. Each condition is analyzed in quintuplicate. Reprinted with permission from Aniek Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

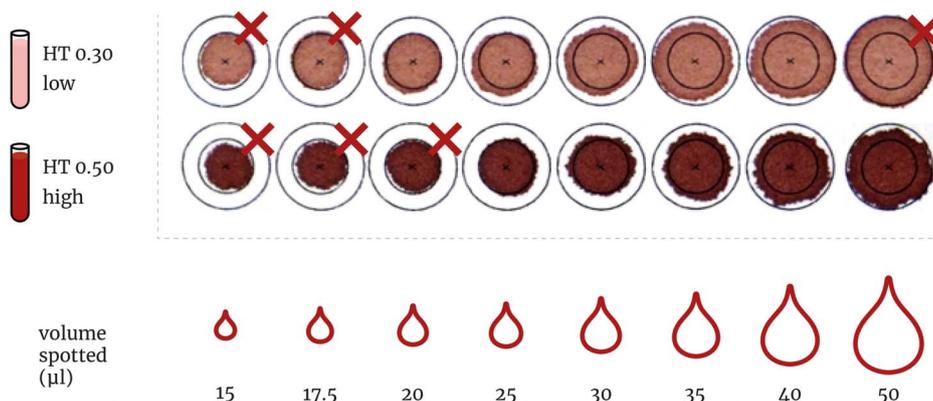
evaluated if storage at lower temperatures in the laboratory may help stabilize the DBS until (re)analysis.

Importantly, stability may also be affected by other parameters such as humidity and exposure to (sun)light, conditions which are harder to replicate in the laboratory. To evaluate the effect of actual sample transport, samples which are generated in the laboratory can be analyzed immediately after drying, after storage for a certain time under controlled conditions, and after sending them to the laboratory through mail service. Preferably, the samples are deposited in a mail box that is relatively far from the laboratory. Furthermore, it may be relevant to repeat this experiment under different weather conditions, to rule out any seasonal effects on the stability of the samples. Although stability is typically evaluated using spiked samples, it may be worthwhile to also evaluate the stability of incurred samples, as spiked samples may not always display the same stability profile as actual samples.⁷⁷ In addition, postoperative stability should be assessed.

DBS-Specific Validation Parameters

The analytical validation of DBS methods requires the evaluation of several additional parameters (Table 2): that is, the volume effect, the volcano effect (ie, DBS homogeneity), and the HT effect.^{1,9,71} It is essential that these parameters are assessed simultaneously because they may affect one another. These parameters can be evaluated in a single day experiment in which the obtained results are compared with those obtained from the reference condition (ie, central DBS punches generated from DBS of average or median volume and HT). Alternatively, this evaluation can be combined with the accuracy and precision experiments (ie, by measuring 2 series of DBS samples with different volumes, different HT levels, etc., on each of 3 days). The latter approach has the advantage that accuracy profiles can be established.^{78,79} Importantly, if a certain effect is observed (ie, a relevant volume, HT, or volcano effect), appropriate measures need to be taken to ensure patient samples are within the validated limits and patient results are reliable. Obviously, it should also be demonstrated that these measures are indeed adequate.

FIGURE 5. Example of filter paper with 2 concentric samples corresponding to the minimally required volume (eg, 20 µL) and the maximally allowed volume (eg, 50 µL), also taking into account different HT levels. Figure adapted from Capiou et al.⁸⁰ Reprinted with permission from Aniek Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.



Volume Effect

The volume range in which DBS-based results are still acceptable should be defined during method validation. Typical volume ranges to be evaluated are 10–50 µL for hanging-drop-collection and 20–70 µL for falling-drop-collection. The volume effect should also be evaluated at low (0.30), medium (0.40), and high (0.50) HT and at both the low and high QC level as shown in Figure 5. Whether a sufficient volume is collected from a patient should always be evaluated in the laboratory before DBS analysis. This evaluation should be performed based on the diameter of the DBS. More particularly, the diameter of the patient DBS should be between the diameter of the DBS prepared from the smallest validated volume at low HT and the diameter of the DBS prepared from the largest validated volume at high HT. To help patients to collect DBS of adequate volume, filter paper with 2 concentric circles may be used (Fig. 5).⁸⁰ These circles should correspond to the minimally required volume and the maximally allowed volume (also taking into account different HT levels, as described above).⁸⁰ It should be noted, however, that this type of filter paper is not commercially available. Furthermore, although these circles may be printed onto commercially available filter paper, it should be considered that the printing itself may affect the analysis (interferences from ink or toner, potential effect on blood flow, eg, caused by paper compression or wax-like materials present in toner). Therefore, the printed filter paper should be

used during the entire method validation. Alternatively, equivalence between the in-house printed filter paper and the filter paper used during validation should be demonstrated at both low and high QC levels, and at low, medium, and high volume and HT. In addition, the volcano effect might have to be re-evaluated, depending on the DBS punch size. Another option is to use a phone app to assess whether the generated DBS are within the validated volume ranges.⁸¹ Again, correct performance of the app should be verified during method validation using samples of known volume, covering the entire validated volume and HT range.

Volcano Effect

Spot homogeneity should be evaluated when embarking upon partial spot analysis (also see part 2, prevalidation). If a relevant volcano effect is observed (eg, punches from the central part of the spot yield different analytical results than punches from edges of the spot), only central punches should be analyzed.

HT Effect

As mentioned before, it is important to actually determine the HT of the calibrators and the samples used during method validation. This will ensure the exact HT value and, consequently, the validated HT range. At least 3 HT levels should be evaluated, more particularly, a QC generated with blood that has the same HT as the blood that was used to

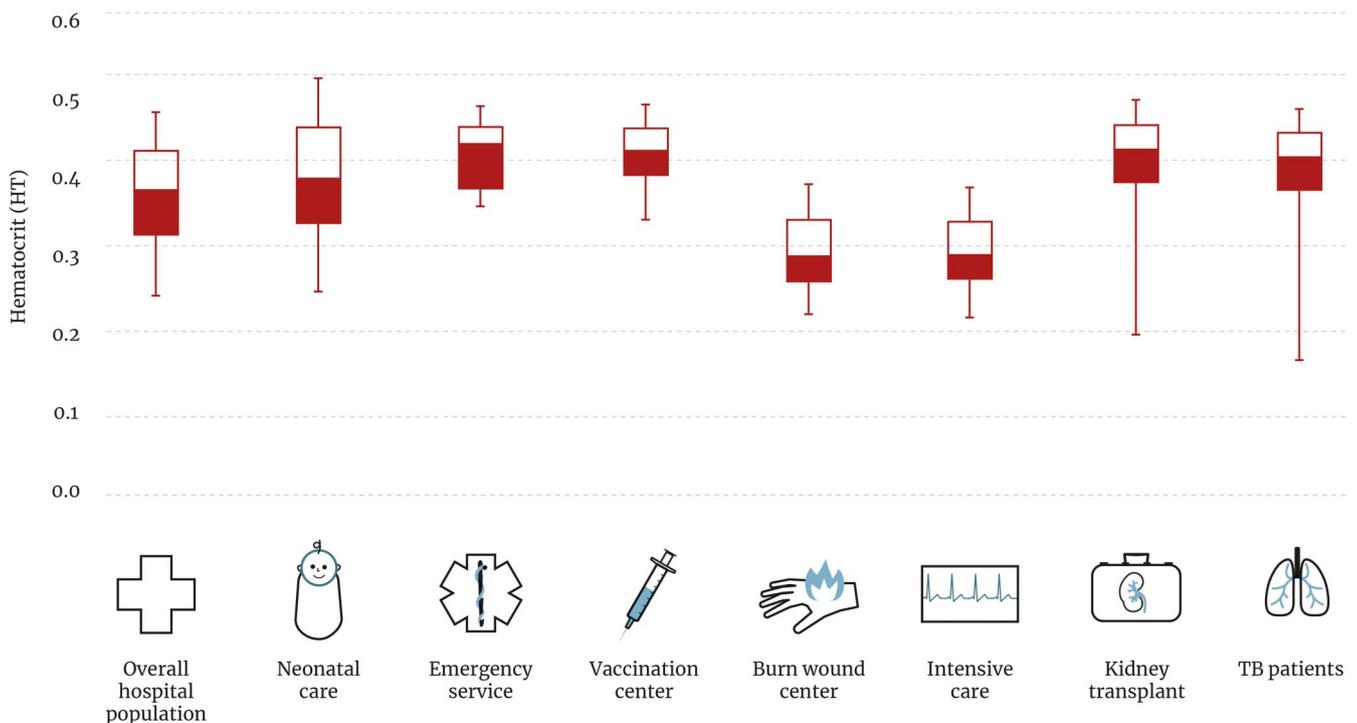


FIGURE 6. Overview of the expected hematocrit (HT) range in different patient populations. The boxplots depict the distribution of HT values per patient population. The boxes show the HT values between the 25th and 75th percentile, as well as the median HT value. The flags show the 2.5% and 97.5% percentiles. Adapted from De Kesel et al.⁵³ Reprinted with permission from Anোক Houben. Copyright 2018. Adaptations are themselves works protected by copyright. So to publish this adaptation, authorization must be obtained both from the owner of the copyright in the original work and from the owner of copyright in the translation or adaptation.

generate the calibrators, bracketed by HT values that encompass the expected patient HT range. At each HT level, 2 concentrations should be tested. The HT range that needs to be evaluated depends on the target population (Fig. 6). For a quasiuniversal method, the range should span from 0.20 to 0.65, although a narrower range will suffice for most applications.⁸⁰ The exact range will depend on the target population and should encompass at least 95% of the target population.⁵³

Unless no relevant HT effect is observed over the entire HT range (both during analytical and clinical validation, see CLINICAL VALIDATION) or unless it is reasonable to assume that all patient HT values will be within the validated HT range, a method should be used to assess the HT of the patient samples. Besides confirming that the HT of the patient sample effectively lies within the validated HT range, this may also allow to perform an HT correction, to alleviate the HT bias.^{82,83} Other options are to use volumetric dried blood samples (if there is no HT effect on recovery or ME) or DPS (if there is no HT effect on DPS generation).³⁶

Validation of Online DBS Analysis

Whether the sample preparation and analysis are performed online or not does not affect the validation parameters that need to be evaluated. The way in which certain parameters (more particularly, recovery, ME, and process efficiency) are evaluated, however, will need to be adapted.^{84–87}

Recovery is typically evaluated by comparing the peak areas from blank matrix samples spiked before extraction with the peak areas from blank matrix samples spiked after extraction. However, with an online sample preparation procedure, there is no option to spike the samples after extraction. Instead, the analytes are introduced to the system during the extraction step. Depending on the type of system used, this can be performed through the IS loop or by spiking the extraction solvent. The results of the samples spiked during extraction are then compared with those of DBS samples containing the same absolute amount of analyte. This requires the entire DBS to be analyzed. When adding the analyte during extraction, the analyte passes through the filter paper and dried blank blood matrix, during which, theoretically, some analyte adsorption may occur. If such adsorption occurs, this will yield a falsely lowered “100% extracted” reference value, which in turn will result in an overestimation of the analyte’s recovery. Alternatively, recovery may be evaluated by comparing the peak area resulting from a single extraction with the sum of peak areas resulting from, for example, 10 consecutive extractions. It needs to be considered that even after 10 extractions, not all the analyte may be extracted, again leading to an overestimation of the recovery. Moreover, these multiple extractions may technically not be possible because of filter paper deterioration (depending on the type of filter paper used).

For the evaluation of the ME, the peak areas resulting from the analysis of blank DBS samples and blank DBS cards can be compared. In both cases, the analyte will be introduced during extraction.

CLINICAL VALIDATION

It is generally accepted that a DBS sampling method can only be implemented in the routine care for the purpose of TDM—and thereby (partly) replacing the standard venous whole blood sampling with blood, serum, or plasma analysis—after it has been successfully validated in a clinical validation study.^{1,88–91} In a clinical validation study, paired DBS and venous blood, plasma, and/or serum samples are obtained and analyzed. The analytical results are compared and statistically evaluated. The purpose of a clinical validation is to demonstrate that results from DBS are interchangeable with those obtained with the standard method used for TDM, that is, a blood, serum, or plasma analysis. The aim of this part of the guideline is to provide recommendations on how to clinically validate a DBS assay for TDM in daily practice. Current recommendations regarding clinical validation are largely based on published clinical validation studies that used genuine finger prick blood-derived DBS, paired DBS and traditional matrix samples from at least 20 patients, and appropriate statistical analysis to compare both methods.^{90–102}

Concentration Range, Number of Clinical Samples, and Patients

The concentration range that needs to be covered during clinical validation depends on the sampling time points of interest (ie, trough and peak) and the shape of the pharmacokinetic time curve of a particular drug and the intra-individual and/or interindividual variability.² The CLSI guideline states that at least 40 patient samples should be analyzed for a clinical validation, ideally covering the entire measuring interval of the measurement procedures.⁸ This sample size is based on linear regression described by Linnet et al.¹⁰³ The sample size that is necessary mostly depends on the coefficient of variation (CV%) of the method and the range ratio (maximum value divided by minimum value). Because most DBS methods have a CV% >5% and a range ratio >25, the number of samples needed after Linnet’s calculation will always be 36 or 45. Therefore, using fewer than 40 samples is only possible if the CV% of the method is <5% and/or the range ratio <25. Depending on the situation, these 40 samples could either be paired capillary DBS venous blood samples from at least 40 different patients collected at a single time point (ie, trough or peak), or paired samples taken at 2–3 time points and from a smaller cohort, covering the whole concentration range of interest.^{8,103} Ideally, a total of 80 samples obtained from at least 40 different patients should be acquired for validation. This allows using one set of 40 randomly selected samples for fitting a line between DBS and blood (or serum or plasma) concentrations using appropriate statistical tests (see next paragraphs). If required, this will derive a conversion formula or factor to convert, for example, capillary DBS concentrations into venous plasma concentrations. The other set of 40 samples can be used to validate this conversion.¹⁰⁴ Despite the limitation of collecting multiple samples from the same patient, this approach does not require a new cohort of 40 subjects. If the amount of patients is limited and multiple samples from the same patient (eg, trough and peak) are acquired, it is our recommendation to have

a minimum of 40 samples from at least 25 different patients to account for variation in MEs. In those cases where there is only a limited number of paired samples available, the conversion of a concentration in one matrix to that of another can also be checked for by a jackknife method. In this approach, the original set of n samples is resampled n times by systematically creating all possible subsets of n-1 samples. Each of these subsets is then used to set up a conversion equation, which is subsequently applied to the nth sample (ie, that sample which was not included in the subset that was used to set up the conversion equation).¹⁰⁵ To assess the predictive performance of the conversion equation, the median percentage predictive error (MPPE) = median (corrected [analyte]_{test matrix} - [analyte]_{reference matrix}) / [analyte]_{reference matrix} × 100% and median absolute percentage predictive error (MAPE) = median (|corrected [analyte]_{test matrix} - [analyte]_{reference matrix}| / [analyte]_{reference matrix}) × 100% can be calculated. These provide a measure of bias and imprecision, respectively.^{106,107}

Comparing DBS Concentrations With Plasma or Whole Blood Concentrations and Effects of HT

Peripherally, collected blood consists of a mixture of venous and arterial blood and interstitial fluids. Therefore, the drug concentration in peripherally collected blood may differ from venously collected blood. This effect is mostly present during the distribution phase of the drug. Although drugs are usually rapidly distributed throughout the body, this process sometimes can take up to several hours, leading to unreliable results when samples are collected during the distribution phase.^{2,108–110} To detect a potential capillary-venous difference (Fig. 7), the results obtained from a DBS collected from a finger prick (sample A) can be compared with those from a DBS prepared from venously collected blood (sample B). This venous blood (sample C) can be used to generate plasma (sample D). Both sample C and D can be compared with blood collected by finger prick

(sample A). Alternatively, another blood sample needs to be collected at the same time point if serum (sample E) is to be prepared. Serum or plasma is typically used for routine TDM. It is essential that samples B and C should give the same result. If they do not, this points to an effect of the DBS approach in se.

In vivo, drugs can bind to components of plasma or accumulate in red blood cells, leading to differences between observed concentrations in whole blood (and hence DBS) and in plasma (or serum, depending on the matrix that is routinely used for an analyte).^{98,108} The difference in drug concentration between blood (DBS) and plasma can be explained by the fraction of drug in plasma relative to whole blood, the HT, and the drug's affinity for red blood cells. The study design may allow for the generation of this blood-plasma relationship. If a blood concentration has to be expressed as a plasma or serum concentration for easy interpretation by the clinician, HT values should ideally be measured, known, or calculated for each blood (DBS) sample. Furthermore, when acceptance limits for the HT have been set based on the analytical validation, one should actually know whether the HT of a given sample effectively lies within these limits. When comparing capillary DBS values with reference whole blood values, correction factors (sometimes based on HT) can be necessary and should be derived from clinical validation studies comparing whole blood values to finger prick (capillary) DBS values.^{89,91,92,95,97,111–115}

If, for a specified HT range, the analytical validation has demonstrated that a DBS analytical method is independent of HT (or dependency is within acceptable analytical limits, see above), confirmation is required in a clinical validation study by plotting the differences between DBS results and reference method results versus the HT. The slope of the resulting curve should not be significantly different from zero.⁸⁰ When this has been confirmed, plasma or serum concentrations can be calculated based on the equation derived from the Passing-Bablok or weighted Deming regression line.^{91,101,116–120} If an analytical method has

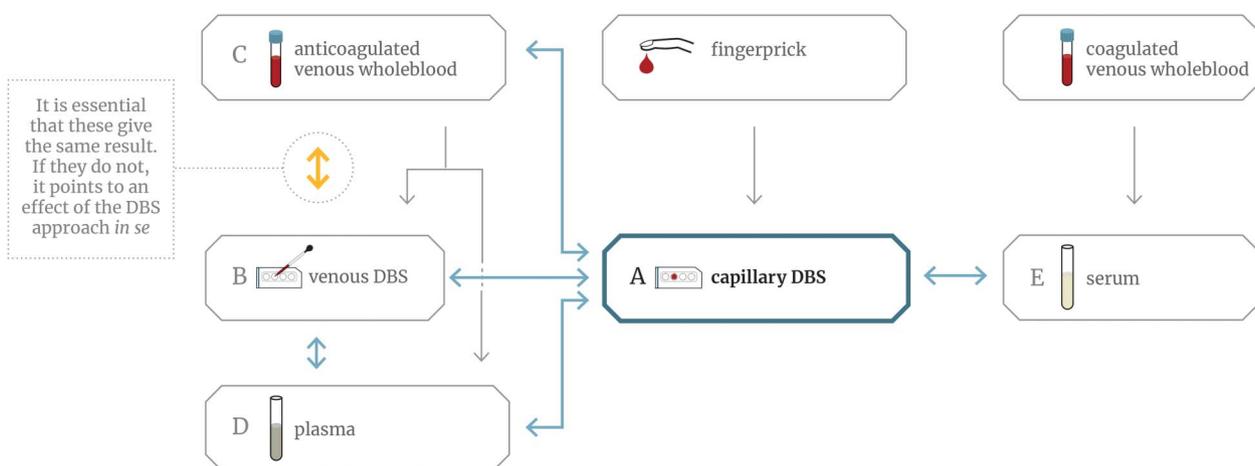


FIGURE 7. A schematic overview of the samples that could be collected during a clinical validation study. The bold blue lines depict which samples could be compared with one another. The gray lines show which samples can be generated from which sampling method. Reprinted with permission from Anoeck Houben. Copyright 2018.

proven to be dependent on HT values during analytical and clinical validation using appropriate statistical tests, a conversion formula should include a correction for HT.^{121,122} An example is the estimation of plasma values from DBS concentrations using the formula $1 - \left(\frac{HT}{100}\right)$.¹²² This will only be possible if there is a systematic effect from HT on estimated venous blood concentrations, which is fixed within the relevant clinical range.¹²³ If this is not the case, the method might not be suitable for clinical application. If an HT-dependent method is to be used in routine care, the HT of the DBS should ideally be known. Procedures to derive HT from a DBS card include potassium measurements,⁸⁰ noncontact diffuse reflectance spectroscopy,^{52,83} near-infrared spectroscopy,¹²⁴ or the use of sulfolyser reagent.¹²⁵ If, for an HT-dependent method, it is—because of technical or other reasons—not possible to know the HT of a DBS, clinical validation can be performed for a specific patient population, provided the HT range in that specific population is narrow and lies within the method's acceptance limits (Fig. 6).^{94,98} In many instances, the mean or median HT and range for a given patient population can be calculated from historical patient data.⁵³ For a different patient population, it should be determined whether a new clinical validation should be performed.^{10,98,122} Another approach to cope with the HT effect is whole blood spot analysis using a fixed spot volume. A volumetric capillary or pipet can be used to apply a fixed volume of finger prick blood to the filter paper.^{14,126,127} In this situation, no conversion formula to correct for HT is needed. However, it should be clear from the analytical validation that the HT has no impact on recovery or MEs.^{89,91,95,97,115} Moreover, this can be at the expense of the simplicity of sampling and/or bring along additional costs.

Statistical Methods and Interpretation

Technically, a DBS clinical validation is a cross-validation study because a candidate method (DBS-based) is compared with a reference method (blood-, serum- or plasma-based). Although guidelines from the EMA, FDA, and CLSI include cross-validation and subsequent statistical analysis of results, this paragraph provides additional recommendations and guidance for the interpretation of results.^{1,5,6,8}

As part of a clinical validation, the results obtained from DBS and the reference method should be compared using appropriate statistical tests. To compare 2 methods, regression analysis should be performed to measure the correlation, followed by an agreement and bias estimation test.⁸ As both the reference and the DBS method have some inherent variability, so that either Passing–Bablok or weighted Deming regression should be used instead of standard linear regression.^{8,128–130} Both approaches have been used in various clinical validation studies.^{91–102,131} Deming regression takes variability of both *x* and *y* into account; Passing–Bablok regression makes no assumptions about the distribution of data points and is more resistant toward outliers.^{8,129,132} Various clinical validation studies have shown that the absolute difference between results from a reference

and a DBS method is proportional to the concentration, at least at higher concentrations. However, in these studies, sometimes only a few high concentration samples were available.^{91,96,120} Theoretically, an outlier in this region would impose an inflated or deflated estimate of proportional difference. In this case, a Passing–Bablok regression analysis is the preferred statistical method.^{8,133} After regression analysis, a Bland–Altman difference plot should be made to assess the agreement between both methods and estimate the bias.⁸ When using a (HT-dependent) conversion formula obtained from Passing–Bablok or weighted Deming regression, the Bland–Altman difference plot should be made using the (blood, plasma, or serum) concentrations that were calculated from the DBS concentrations.^{1,91}

Most clinical validation studies show some level of bias when performing a Bland–Altman test. Although it may seem obvious that Bland–Altman graphs should be generated and interpreted in a correct manner, this is not always the case.¹³³ Several things can be deduced from a Bland–Altman difference plot. First, it can be observed whether there is an average bias between both methods and whether the 95% CI of this bias contains zero. Importantly, if the latter is not the case, it should have been formally decided beforehand what a clinically relevant or acceptable bias and corresponding limits of agreement (LoA) should maximally be. For instance, for tacrolimus, where trough concentrations in blood are usually between 5 and 20 mcg/L, a bias of 0.28 mcg/L (LoA –0.45 to –0.12 mcg/L), which is at most a bias of 5.6% (LoA 9.0%–2.4%) would not impact clinical decision making, whereas a higher bias or LoA might.¹³⁴ Second, the LoAs can be derived from the Bland–Altman plot. Here, the same holds true: preset criteria are needed to define what concentration or %difference span between the LoAs is still considered acceptable. This is a critical point that, in many instances, is lacking: for example, although, on average, there may be no bias between a DBS- and blood-based procedure, the span of the LoA's may be too wide (implying there is too much variation) to be acceptable. What is considered acceptable in terms of bias or LoA will largely depend on the clinical setting, the laboratory's internal policy, the availability of guidelines (eg, RCPA criteria)¹³⁵ and the drug of interest. Acceptance criteria should be decided by a multidisciplinary team of experts based on both clinical and analytical acceptance criteria. In addition, during a clinical validation, it can be investigated for each measured pair of samples whether the clinical decision by the health care provider would differ, based on the DBS concentration versus the concentration in the reference sample.^{92,93,99,136} Again, acceptance criteria should be stated beforehand in the study protocol. The EMA guideline states for cross-validation study samples, “the difference between the 2 values obtained should be within 20% of the mean for at least 67% of the repeats.”⁵ It has been suggested that this guideline could also be applied to assess agreement between DBS-based analytical results and reference results.¹ For example, a study, in which for 30% of the samples, a difference of more than 20% of the mean is observed, would theoretically fulfill the criteria put forward by the EMA guideline. However, this would likely be clinically unacceptable, and in this case, stricter LoA would be

preferred. It is also possible that, at lower concentrations, a maximum absolute deviation may be tolerated, while at higher concentrations, a maximum allowable percentage deviation may be set.

Type of Card/Paper Used

In a clinical validation study, it should be stated which type of paper or DBS card is used. This type of paper should be the same as the one that was used during analytical validation.²⁹

Sampling Method and Spot Quality

A major problem during clinical validation is that the provided DBS may be of insufficient quality for analysis due to incorrect sampling.^{42,137} Therefore, during clinical validation, the method of sampling and spot quality assessment by either an analyst or an automated quality assessment method should be mentioned in the study protocol.^{138,139} As drug concentrations are dynamic, it is important to collect all paired samples within 5–10 minutes of each other.^{91,116} Time-dependent changes in drug concentration are determined by pharmacokinetics and should be taken into account for the preparation of a sampling scheme. This is particularly relevant for drugs with a very short half-life or during the absorption and distribution phase of the drug.

The sampling method that is used during clinical validation should be the same as the sampling method that will be used in daily practice. For example, if the method is intended for home sampling by patient finger prick, the DBS samples obtained for clinical validation should also be obtained by finger prick. Spotting of venous blood on a DBS card is only appropriate if in clinical practice venous blood will be spotted on DBS cards. For instance, this may be the case when transport of tubes of whole blood is not possible due to instability of the compound or because of logistic difficulties (eg, in remote areas or in resource-limited settings).⁵⁸ This is highly relevant as for some analytes venous capillary differences may, or are known to, be present.

If a method is designed for home sampling, patients should ideally perform a finger prick to collect a DBS sample themselves during clinical validation. However, in most clinical validation studies, a trained phlebotomist collects or helps to collect samples, to rule out variability due to inexperienced sampling by the patient.^{91,95,97,99,116,123} Alternatively, both approaches can be used successively during clinical validation.

Proper finger prick DBS sampling technique has been described earlier by the WHO, CLSI, and in several studies^{11,42,131,138,140,141} and is also shown in Supplemental Digital Content 1 (see Figure S-2, <http://links.lww.com/TDM/A342>). In short, sampling should be performed after disinfecting the finger without excessive “milking” or squeezing of the puncture site to avoid hemolysis or dilution by tissue fluid. When possible, finger prick blood should fall on the sampling paper instead of applying the droplet of blood to the sampling paper with the finger (without touching the sampling paper with the finger). Both patient and phlebotomist should be trained before samples can be obtained. This training should include practicing the whole

sampling procedure under supervision of someone experienced in DBS sampling using either a test kit or a real finger prick aided by educational material such as a movie or a written instruction.^{25,131,137,138,140}

All spots provided in a clinical validation study should be checked for quality by an experienced analyst or through a validated automated quality assessment method. Some requirements for a good quality spot depend on the analytical method and should be stated on beforehand, such as minimum spot size imposed by punching size. Other requirements are independent of the analytical method. Criteria are stated in Supplemental Digital Content 1 (see Figure S-3, <http://links.lww.com/TDM/A342>). In short, all spots should be round, dried, consisting of one droplet of blood, and not touching other droplets.

ISR, Duplicates, and Outliers

In their guideline, the FDA mentions ISR as a validation parameter for DBS methods.⁶ In a clinical validation, ideally at least 2 replicate spots are available for analysis, to allow ISR and/or duplo analysis. However, reanalysis of the same spot (through a second punch) will not be possible when the protocol involves the use of larger punching sizes (eg, 6 or 8 mm).⁶⁴ During clinical validation, it is recommended to analyze 2 different spots per sample, when possible, to evaluate within-card precision, which can be calculated as the percentage difference $\% \text{difference} = \frac{\text{repeat value} - \text{initial value}}{\text{mean value}} \times 100$.^{5,24} The %difference between duplicates should not be greater than 20% of their mean for at least 67% of the samples.^{5,6} In addition, ISR of the same spot is recommended when decentral punches may be used, provided spot homogeneity is supported by the analytical validation, and small punch sizes (eg, 3 mm) are used.²⁷

The presence of an outlier may be explained by several reasons such as contamination of the sample, errors in sampling, extreme drying, or storage conditions during transport or analytical errors.⁴² In a clinical validation study, most of the possible errors can be accounted for by, for instance, checking of spot quality of the sample upon arrival in the laboratory or checking and logging the drying time. When an outlier cannot be explained by such errors, the extreme studentized deviate technique⁸ or a standardized score test can be used to exclude outliers.¹²¹ However, outliers should be discussed in the context of clinical application of the DBS method. Therefore, outliers require an argued discussion considering clinical setting and the aforementioned statistics tests.⁸

Clinical Validation of Automated Analysis Methods

Automation of a DBS assay could improve DBS sample and workflow efficiency and reproducibility. Several examples exist of automated (online or offline) DBS assays using techniques such as online extraction and solid phase extraction.^{87,142,143} If an automated method is designed without a previous manual DBS method, the same recommendations for clinical validation apply. If a manual DBS

assay used in clinical practice is replaced by an automated DBS method which is fully analytically validated, it is recommended to perform a cross-validation including sample size of 40 samples from at least 25 different patients.^{5,6,8} Because of the nature of DBS, it will most likely be challenging in real practice to measure the same spot using both an online and offline method. Therefore, if during the clinical validation the within-card precision is found to be acceptable and 2 spots per finger prick DBS sample are provided, it is recommended to analyze one spot using the automated method and one spot using the manual method. Evaluation of agreement can again be performed by Passing–Bablok or Deming analysis and through a Bland–Altman plot, as described earlier.

QC

Laboratories should participate in external QC programs if a DBS assay is implemented in routine care or provide objective evidence for determining the reliability of their results.^{2,38} Apart from a proficiency test pilot for the immunosuppressant tacrolimus, no external QC programs are currently available for DBS assays for drugs.¹⁴⁴ There is an urgent need for DBS proficiency testing programs to facilitate the uptake of DBS in routine care. Although external QC materials developed for the evaluation of liquid blood-based methods may be used to evaluate the quality of a DBS-based method, it should be taken into account that these materials typically have a different viscosity than true blood samples and will therefore yield DBS of deviating sizes. Therefore, when using these materials, they should always be analyzed using a full-spot approach.¹⁴⁵ Furthermore, the extraction efficiency of an artificial matrix may always differ from the extraction efficiency of an actual sample. Since most external QC materials are only available for plasma analysis and not for whole blood analysis, another option might be to remove part of the plasma of a blank whole blood sample and to replace it with the external QC material. The resulting blood can then be used to generate DBS, as was successfully applied for, for example, conventional antiepileptics.⁶⁷

CROSS-VALIDATION

Once a DBS assay has been successfully applied in clinical practice, it is possible that changes have to be made to the sampling method, filter paper, or analytical method. For some of these changes, the standard guidelines for cross-validation are applicable.^{5,6} This part will focus on additional recommendations when DBS assays or sampling methods are altered.

Different Punch Size

As stated before (see METHOD DEVELOPMENT: CONSIDERATIONS FOR SUCCESSFUL VALIDATION), a punch size is preferably less than 4 mm because punching the sample in the laboratory will be easier, and patients do not need to produce large blood spots. When the desired LLOQ, accuracy, and precision can be met with a different punch (eg, smaller or “donut” punch)⁷⁴ than currently used in practice,

a cross-validation study should be performed. If during the clinical validation the within-card precision is within analytical limits and 2 spots per sample are provided, it is recommended to analyze 1 spot with the new punch size and 1 with the old punch size. In total, 40 samples of at least 25 different patients should be analyzed. In addition, extraction efficiency and DBS homogeneity should be re-evaluated. The extraction volume used with smaller punches can be downscaled accordingly. Although theoretically possible, we do not recommend to use a surface-based formula to convert a result from a small (eg, 3 mm) DBS punch to a theoretical bigger (eg, 6 mm) DBS equivalent.

Different Type of Filter Paper

In routine practice, several types of DBS filter paper are used such as the Whatman 903, Whatman FTA DMPK cards (type, A, B and C) (GE Healthcare, Chicago, IL), and Perkin Elmer 226 cards (Ahlstrom, Helsinki, Finland).²⁹ Although performance of the FDA-approved Whatman 903 (GE Healthcare) and Perkin Elmer 226 paper is consistent and comparable in newborn screening,¹⁴⁶ the influence of drug concentration and HT can lead to a difference in recovery of up to 20% between cards.^{29,147} This may be caused by the drugs’ ability to form hydrogen bonds with the cellulose paper, leading to decreased recoveries,⁵⁷ differences in spot homogeneity, or differences in background signal.²⁷ Not only the recovery of the analyte may be altered, also matrix, volcano, volume, and HT effects may have changed, as well as the analyte’s stability. These parameters should all be re-evaluated as discussed before. Furthermore, QC samples for the new filter paper should be made using the same method as was performed for the old filter paper.⁵⁴ Both old and new QC samples should be analyzed, and the obtained mean accuracy should be within 15%.⁵ The equivalence between both filter papers should be confirmed using a minimum of 40 samples obtained from at least 25 different patients. If not all parameters prove to be similar for both types of filter paper, full analytical validation and clinical validation are required.

Different Sampling Method

Switching the sampling method will, most likely, be accompanied by some change in the method. For instance, it is likely that whole spot analysis rather than partial-punch analysis will be performed when a fixed volume of finger prick blood is deposited on a card instead of direct application of blood from the fingertip to the card. Moreover, it is possible that DBS-based assays are replaced by newer alternatives such as the earlier discussed VAMS technique because of the convenience of sampling and/or automation possibilities.²⁵ Importantly, as stated earlier, volumetric sampling does not necessarily eliminate the effect of HT or aging on recovery, so this remains an important parameter to be studied.^{7,29,57,62,148} In addition, a new sampling technique might influence spot homogeneity, thereby introducing a possible unknown error in analytical results.²⁷ Therefore, when changing sampling technique, sample vehicle, or changing to whole spot analysis, it is recommended to perform a full clinical validation study, comparing the new method to the reference method, provided this change has been appropriately analytically validated.²⁵

CONCLUSION

To successfully incorporate DBS-based methods in routine practice, good quality methods are a prerequisite. Since the quality of a method starts with its design, a sound method set-up not only ensures the method is suitable for a given application, it also increases the chances of a successful method validation. The quality of a method needs to be assessed both during analytical and clinical validation and should be compared with preset acceptance criteria. This is the first guidance document discussing how to evaluate the quality of a DBS-based method. This guideline outlines which traditional and nontraditional validation parameters should be assessed for this type of method and provides suggestions on how to do this. Most importantly, each parameter should be evaluated in a way that reflects the real-life situation in which the method will eventually be applied. Furthermore, to ensure the method's quality on a day-to-day basis, the first QC programs for quantitative DBS-based methods have been established recently. It is important to keep in mind that DBS for TDM applications only has a future if the quality of the result can be guaranteed. A proper analytical validation and clinical validation are essential to achieve this.

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