Summary: Demand for vitamin D testing has been on a constant rise worldwide, partially due to mounting evidence linking vitamin D status to overall health and well-being. Currently available assays measure 25-hydroxy vitamin D (25-OHD), a major circulating form of vitamin D. Available methodologies include immunoassays and mass spectrometry based methods (LC-MS/MS). Until recently, the only immunoassays available for diagnostic use in the US have been DiaSorin radioimmunoassay (RIA) and an automated immunoassay on a LIAISON® platform. Within the last year, Siemens and Abbott successfully launched immunoassays for determination of total vitamin D on their respective automated platforms, Centaur® and ARCHITECT®. Development of robust and precise Vitamin D immunoassays has historically been plagued with difficulty. One of the major challenges is development of specific antibodies against such a small antigen. Vitamin D is also highly hydrophobic molecule predominantly bound to vitamin D binding protein (DBP). It is likely, therefore, that immunoassays might be affected to varying extent by the DBP concentration. Adoption of LC-MS/MS into clinical laboratories has enabled development of accurate and almost fully automated methods that could handle increasing volume demands, especially in large volume reference laboratories. Smaller to mid-size hospital laboratories as well as physician offices have neither funds nor technical expertise to implement LC-MS/MS based testing. Our laboratory at the University of Chicago Medical Center has also seen increase in vitamin D volume and currently performs close to 20,000 25-OHD assays per year. We have recently developed an LC-MS/MS method for quantification of 25-OHD$_2$ (obtained from plant sources) and 25-OHD$_3$ (endogenous and animal sources). Prior to acquisition of LC-MS/MS


Address for correspondence:
Nikolina Babić
University of Chicago, Pritzker School of Medicine
Department of Pathology, Chicago, IL, USA
Introduction

The essential role of vitamin D in bone metabolism and calcium homeostasis is well established (1, 2). In addition, a number of research studies demonstrated the role of vitamin D in blood pressure regulation, autoimmunity, regulation of cell growth and metabolic diseases and malignancy (2–9). This has all led to increase in vitamin D testing requests, with many laboratories in the United States reporting annual increase rates of 50% or more (10). In the University of Chicago Medical Center, for instance, we have observed an increase of approximately 10 fold in vitamin D testing volumes since 2005.

Although the treatment for vitamin D deficiency or insufficiency is generally affordable and straightforward, the correct diagnosis is dependent not only on reliable and reproducible methods of analysis but also on the choice of the appropriate test. Confusion still exists among clinicians regarding the most suitable test to assess vitamin D status. To correctly determine vitamin D insufficiency, 25-hydroxyvitamin D (25-OHD) should be ordered rather than the active metabolite 1, 25-dihydroxyvitamin D (1,25-(OH)₂D). Measurement of 1,25-(OH)₂D should only be reserved for the cases of severe renal disease, and rare conditions such as vitamin D resistant rickets and granulomatous diseases (11–13).

Accuracy of 25-OHD Measurement

Accurate and precise measurement of vitamin D has been challenging. The methodology used to measure vitamin D includes immunoassays and liquid chromatography-tandem mass spectrometry (LC-MS/MS) and, is discussed in the next section. Recently, the US Centers for Disease and Control (CDC) have convened a roundtable to discuss the scientific challenges involved in the measurement of serum 25-OHD and the assessment of vitamin D status across several decades of US National Health and Nutrition Examination Survey (NHNES) (14). The panel of experts concluded that variability of serum 25-OHD measurements were likely the artifact caused by fluctuations in the assay performance over time rather than by true vitamin D status changes. This instance highlighted the need for robust methodology and accuracy-based standard. In 2009, the National Institute of Standards and Technology (NIST) developed Standard Reference Material (SRM) to assist accurate determination of 25-OHD in the serum or plasma (15, 16). This standard, SRM 972, consists of four pools of serum, each with different levels of vitamin D metabolites. Today, a number of clinical laboratories, mostly the LC-MS/MS users, participate in this standardization program. Unfortunately, due to matrix effects, only one SRM level could be used in immunoassay standardization. The other three levels are either spiked with exogenous vitamin D or diluted with horse serum and thus unsuitable for many immunoassays (17, 18). None of the commercial immunoassays are, therefore, aligned to SRM 972. Several candidate reference methods for accurate and sensitive 25-OHD measurement have also been published in the recent years (19–21).

Vitamin D Assays

Historically, gold standard methodology for Vitamin D measurement has been radioimmunoassay (RIA). With the increased adoption of the LC-MS/MS into the clinical laboratories, more laboratories are developing their own customized LC-MS/MS methods, using their own calibration preparations and value assignments. This, of course, initially introduced even more variability in vitamin D testing, a problem partially alleviated with the introduction of NIST SRM. Most of the clinical laboratories still lack either funds, expertise or both for mass spectrometry-based testing and are still relying on commercial immunoassays.
One source of variability for immunoassays are different, vendor specific, sample pretreatment protocols used to release vitamin D from vitamin D binding protein (DBP). Effects of variable recoveries and DBP concentration changes on different patient populations can have significant impact on assay accuracy and precision (22–25). Manufacturers have recognized increasing demands for vitamin D testing and are working on improving the existing kits to provide reliable and reproducible results. In the last year, two new total 25-OHD kits became available on the market, Abbott Architect and Siemens Centaur assays.

Radioimmunoassays (RIA)

Two RIA assays are currently available for measurement of total vitamin D: DiaSorin (DiaSorin, Stillwater, MN) based on the assay originally developed by Hollis et al. (26) and Immunodiagnostic Systems (IDS) assay (Immunodiagnostic Systems, Inc., Scottsdale, AZ). Only DiaSorin is approved for diagnostic use in the US. Both RIAs involve extraction of 25-OHD with acetonitrile followed by equilibrium RIA using 25-OHD specific antibody and 125I-labelled 25-OHD. As per their respective package inserts, DiaSorin assay claims 100% cross-reactivity with both 25-OHD2 and 25-OHD3, while IDS claims 100% cross-reactivity with 25-OHD3 and only 75% cross-reactivity with 25-OHD2.

Chemiluminescence Immunoassays

Both RIA manufacturers offer automated versions of their assays. The current version of DiaSorin assay was introduced in 2007 and is available on the Liaison automated platform. IDS introduced their version of automated immunoassay in 2009 to be used on iSYS™ automated analyzer (not available for sale in the US).

Two most recent immunoassays, Abbot Architect and Siemens Centaur, utilize 8-anilino-1-naphtalenesulfonic acid (ANSa), compound known to effectively displace hormones from binding proteins (27, 28). While both assays claim 100% cross-reactivity with 25-OHD3, Centaur package insert states 100% cross-reactivity with 25-OHD2 and Architect states only 82% cross-reactivity with vitamin D2. Only the Centaur immunoassay is traceable to LC-MS/MS, although it is not clear from documentation provided by manufacturer which LC-MS/MS methodology was used in calibrator value assignment.

Vitamin D assay is also available from Roche but this assay is only marketed for determination of 25-OHD3 and thus cannot be used in the US.

LC-MS/MS Assays

Mass spectrometry is a methodology of choice for the majority of large reference laboratories and academic centers in the US. LC-MS/MS methods are laboratory specific and could differ in aspects of sample preparation, chromatography, ionization source and fragmentation patterns detected. It appears that, compared to electrospray, APCI ionization source results in less variability in vitamin D measurements (29). Unlike immunoassays that measure total vitamin D, LC-MS/MS methods can separate 25-OHD3 and 25-OHD2 although most of the laboratories still report total 25-OHD to avoid confusion. Virtually all LC-MS/MS assays in the US are developed and validated by the individual testing laboratories. To date, there is only one kit for vitamin D analysis on the LC-MS/MS system available from ChromSystems (Munich, Germany). This kit is CE-marked and the company will likely seek FDA approval to market this kit in the US for diagnostic use (30).

Our laboratory has recently developed LC-MS/MS method for quantification of 25OH-D2 and 25OH-D3. During the transition period, we encountered several challenges, including the necessity to streamline sample preparation as well as the bias introduced by calibration differences. We chose to match the new LC-MS/MS method to our clinical RIA method, in order to make this transition transparent to the clinician.

Imunoassays versus LC-MS/MS: Head to head Comparison

Several investigators performed extensive side by side evaluation of commercial vitamin D assays (23, 31, 32). Ong et al. (31) evaluated accuracy and precision of three new automated immunoassays (Roche, Abbott and Siemens) and compared them to the existing RIA (DiaSorin) and in-house developed LC-MS/MS methods. These investigators found that all five assays had acceptable imprecision at vitamin D levels >40 nmol/L. At lower vitamin D values, only RIA and LC-MS/MS performed well. To assess agreement between these methods, a set of 200 patient samples were used. While the three automated assays and RIA correlated well with LC-MS/MS assay, Abbott and Roche assay demonstrated significant biases of 25% and 31%, respectively.

In March 2012 edition of Clinical Chemistry, two consecutive publications evaluated performance of essentially all 5 available automated immunoassays (ARCHITECT, Centaur, iSYS, LIAISON and Elecsys), and one RIA (DiaSorin) in comparison to the LC-MS/MS methods (23, 32). Farrell et al. (32) compared immunoassay performance against two independent, non-commercial LC-MS/MS assays aligned to the NIST SRM 972. A total of 170 serum samples from routine vitamin D assay requests were used. The
only immunoassay that matched the performance of mass spectrometry assays was RIA, most likely due to complete extraction of vitamin D from DBP. Among the automated immunoassays, only LIAISON and IDS demonstrated acceptable performance. ARCHITECT and Centaur showed excessive bias (>25%). In addition, ARCHITECT assay demonstrated unacceptable concordance with LC-MS/MS. Roche Elecsys assay had low bias but did not correlate well with LC-MS/MS assays. Farrell et al. (32) also observed an increased imprecision of the automated platforms at low end (vitamin D <20 nmol/L), which is in agreement with the observations reported by Ong et al. (31).

Heijboer assessed the accuracy of automated immunoassays by stratifying the patient populations based on their DBP levels. The authors found major differences in 25-OHD concentrations between different assays tested. This is the first study to demonstrate an inverse relationship between DBP concentrations and deviations of measured 25-OHD from LC-MS/MS method (aligned to Thienpont candidate reference method (21)). Significant biases observed were likely due to fact that, in automated assays, 25-OHD is not completely extracted from DBP in sera that have relatively high DBP concentration. For example, in critically ill patients who have lower DBP concentrations compared to healthy individuals, LIAISON significantly overestimated 25-OHD levels compared to LC-MS/MS. On the other hand, in pregnant women, who had higher DBP levels, Centaur and iSYS tended to underestimate vitamin D levels. Therefore, Heijnober’s data suggest that not all assays are suitable for 25-OHD assessment in all patient groups.

Choice of Method

Selection of the appropriate method is laboratory specific and depends on population tested, sample throughput and staff expertise (33).

In the US, for example, laboratories are required to measure both 25-OHD$_2$ and 25-OHD$_3$ as patients are still frequently supplemented with 25-OHD$_2$, unlike the laboratories in Europe, where there is no requirement to measure 25-OHD$_2$. Nonetheless, unless the laboratorians recognize limitations of their assay, significant confusion can arise. This was nicely illustrated in the case report from Belgium where physicians treated vitamin D deficient patient with vitamin D$_2$, while her serum vitamin D levels were measured using the vitamin D$_2$ assay (34). It is also important to recognize that none of the studies published on comparison of automated immunoassays with LC-MS/MS methodology recruited more than a few patients supplemented with vitamin D$_2$. This is important because, as mentioned earlier, not all immunoassays report 100% cross-reactivity with vitamin D$_2$. Further studies evaluating performance of these analyzers in 25-OHD$_2$ measurement are thus required. Finally, laboratories performing the significant volume of pediatric testing must evaluate potential cross-reactivity of their assay with vitamin D epimer (3-epi-25-OHD$_3$) present in significant amounts in neonates. This interference is only problematic for LC-MS/MS methodology, since the mass spectrometers cannot distinguish stereoisomers (35), and can potentially result in overestimation of 25-OHD$_3$. None of the main immunoassays in use today are susceptible to 3-epi-25-OHD$_3$ interference (14). Although the amounts of vitamin D epimer in adult serum are generally small, high concentrations have been reported in some individuals (36).

The use of mass spectrometry in the clinical laboratories has increased over the years due to its superior analytical characteristics and lack of interference from structurally related compounds. In addition, low LC-MS/MS reagent costs result in significant cost-savings compared with the immunoassays, provided the testing volumes are high enough to justify initial capital investment. However, different laboratories are encountering different challenges brought upon by continuous increases in vitamin D testing volumes. Smaller and mid-size hospital laboratories and academic centers typically employ classically trained laboratory technologists and are, therefore, lacking technical expertise required to sustain this high complexity testing. On the opposite end of the spectrum are large reference laboratories that receive hundreds to thousands of vitamin D requests daily. With such high volumes, the throughput of LC-MS/MS systems becomes the limiting factor. Until recently, the only strategy available to LC-MS/MS users to improve throughput has been multiplex LC systems using the technology such as Thermo Fisher TLX systems. This strategy is utilized in author’s own laboratory wherein up to 4 separate LC systems operate simultaneously in a staggered fashion. In 2011, a group at Mayo Clinic developed and implemented an elegant multiplexing method where up to 5 patient samples are multiplexed within one single LC-MS/MS injection, using the specifically designed mass tags. The throughput that can be achieved with this methodology is up to 300 specimens per hour or 7200 specimens per instrument per day, matching the throughput of automated immunoassays (37).

Conclusion

Considering superior precision and accuracy of the LC-MS/MS instrumentation, it is clear that, given the appropriate resources and technical expertise, it is the method of choice for vitamin D analysis. However, the reality is that many laboratories still possess neither financial resources nor technical know-how to adopt this technology and are still in the market for reliable automated immunoassay, a fact well recognized by
immunoassay manufacturers. Recent studies have found that automated immunoassay have suboptimal performance at measuring vitamin D levels below 20 nmol/L (31, 32). This might be acceptable to most laboratories considering that these levels are clearly deficient and it thus might be of little clinical significance. Finally, the laboratorians should be cognizant of the fact that accuracy of some immunoassays depends on patient population, especially if the patient condition might cause significant changes in DBP levels.

Conflict of interest statement
The authors stated that there are no conflicts of interest regarding the publication of this article.

References


Received: May 10, 2012
Accepted: June 8, 2012