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Clinical Chemistry Education for Medical Students

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ABSTRACT

Clinical chemistry plays an important role in medical practice. Approximately 60% to 70% of medical decisions rely on laboratory test results, justifying the need for physicians to have sufficient knowledge of clinical chemistry. However, recent studies have shown that medical students' knowledge of clinical chemistry is inadequate, and many are unable to interpret the meaning of laboratory parameter results. This implies that the study of clinical chemistry in the curriculum is currently insufficient. There are several related problems, namely a lack of a formal or structured clinical chemistry curriculum, limited time allocated for these studies, a lack of teaching experts and the failure of stakeholders to acknowledge the importance of clinical chemistry. This review discusses problems in the current clinical chemistry education of medical students and provides solutions. A structured search strategy in PubMed and Google Scholar for publications in English was applied using the search terms "clinical chemistry", "clinical pathology", "laboratory" and "laboratory medicine" in combination with one of the following keywords: "education", "medical student", "curriculum", "guideline", "undergraduate", "medical school" and "training". The extracted literature focused on research studies, review articles and meta-analyses. Background information and details about the current status of clinical chemistry/laboratory medicine education were extracted from review articles, while research articles were used to analyse and evaluate the current conditions in the medical schools regarding clinical chemistry/laboratory medicine education.

Keywords: *Clinical chemistry, Laboratory medicine, Curriculum, Education, Medical student*

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INTRODUCTION

Clinical chemistry is a branch of medical science that deals with the analysis of biological materials (mainly body fluids) to obtain diagnostic information related to the human body (1). Compared with other medical specialties, clinical chemistry as a specialty is relatively recent. Its first foundations emerged mainly in Germany in the 19th century nearly 200 years ago (2). However, it was not until the 1930s that clinical chemistry began to be established as a separate and independent branch of medical science (3). It was in this era that alternative terms for clinical chemistry arose including laboratory medicine, clinical pathology and clinical laboratory. The field is now placed under the umbrella of pathology studies, together with anatomical

pathology. Throughout this article, these alternative terms for clinical chemistry may be used interchangeably (1).

Importance of Clinical Chemistry in Medical Care

Clinical chemistry has come to play a crucial role in daily medical practice. Approximately 60% to 70% of medical decisions rely on laboratory test results (4). This indicates the need for doctors to have sufficient knowledge of laboratory medicine. Laboratory results provide objective data that help the treating physician to assess and analyse a patient's condition, decide and select the appropriate management strategy, and track the progression of the patient's disease (5). Together with other diagnostic results (e.g. anatomical pathology, radiology), the value of laboratory test results is expected to increase and further contribute to optimising and improving patient care (5–6). Furthermore, many diseases rely on laboratory results to establish the final diagnosis and track disease progression. For instance, a diagnosis of diabetes mellitus can only be made after a blood glucose level test. The course of heart disease can only be determined after a laboratory investigation of cardiac biomarkers. Thyroid problems must be confirmed by assessing the thyroid hormone levels, which necessitates laboratory blood tests. Prostate and liver disease progression can be respectively monitored through prostate-specific antigen and aspartate/alanine aminotransferase enzyme levels in the blood (7). Determining the correct type of thrombocytopenia for a pregnant patient with pregnancy-associated thrombocytopenia can only be accomplished through hematology testing (8). A suspected infectious disease may be presumed based on anamnesis, but certainty can only be achieved after identifying the expected organism through specimen examination.

The trend towards personalised medicine has been underway as part of standard care. Personalised medicine acknowledges the uniqueness of a patient's physiology and pathology, which can differ from those of other patients. Management strategies can thus be tailored based on each patient's profile. Personalised medicine centres on genetic data as the main driving force to develop precise and individualised treatments for diseases to achieve better treatment outcomes. The success of the human genome sequencing project in 2003 and the subsequent Encyclopedia of DNA Elements (ENCODE) project in 2012 has enabled a deeper understanding of the complex mechanisms behind numerous human diseases, which can be influenced by gene expression, gene regulation and their interaction (8). Applying the knowledge of such networks to the patient context has helped to improve patient care. This feat has highlighted the importance of pathology (including laboratory medicine) as an important subject that can contribute to medical practice.

The concept of point-of-care testing (POCT) was introduced in 1994. The advent of POCT has made it possible to conduct blood testing in hospital wards and outpatient clinics. In their 2010 review article, Zaninotto and Plebani stated that POCT will be a commonplace testing method in the future because it can rapidly provide laboratory results on site and thereby expedite the administration of suitable treatments for the patient (9). POCT is expected to be established as a standard procedure in patient examinations.

In summary, the contribution of clinical chemistry is paramount to aid in the diagnosis and management of disease. It can also help to predict a patient's vulnerability to certain diseases. In these cases, suitable interventions to hinder or even prevent the predicted disease can be initiated. Therefore, doctors must acquire sufficient knowledge in clinical chemistry to ensure optimal patient care. Consequently, as future doctors, medical students must have a solid foundation in clinical chemistry.

Literature Search Methods

This review aims to address the current shortcomings of clinical chemistry education for medical students and how to improve medical schools' curriculums to better incorporate clinical chemistry. The papers included in this review were related to the current state of medical students' knowledge of clinical chemistry, reviews and analyses of the problems related to the clinical chemistry curriculum and pilot/trial projects for improving clinical chemistry education for medical students. The proposed solutions described in this review were synthesised based on these papers.

The articles were obtained from PubMed and Google Scholar using a structured search strategy and all extracted articles were in English. The following search terms were used: "clinical chemistry", "clinical pathology", "laboratory" and "laboratory medicine" in combination with one of the following keywords: "education", "medical student", "curriculum", "guideline", "undergraduate", "medical school" and "training". The articles focused on research trials and reviews, as well as meta-analyses, if available. Articles published in the last 10 years were included, but article(s) beyond the established time range were expected to be incorporated if there were only a few related publications available in the last 10 years. Background information and details regarding the current status of clinical chemistry/laboratory medicine education were obtained from review articles, while research articles were used to analyse and evaluate the current conditions in medical schools regarding clinical chemistry/laboratory medicine education.

CURRENT KNOWLEDGE OF MEDICAL STUDENTS

Unfortunately, despite the importance of clinical chemistry in the diagnosis and management of diseases, medical students do not adequately understand and apply this knowledge in clinical care settings. A 2018 survey report of medical students in Hong Kong described students' inability to interpret the iron profiles of a clinical scenario constructed by the surveying researchers. This was reflected by the fact that only one-third of the recruited students answered the given questions correctly (10). They acknowledged some common biochemical tests that are often ordered in daily practice such as renal and liver function, endocrine gland function, blood gas and electrolyte tests, but they were not aware of other tests that are often used, particularly in oncology, geriatrics and paediatrics.

Another survey assessing the clinical chemistry knowledge of medical interns was conducted at two local hospitals in Cape Town, South Africa (11). The students were asked to complete a structured questionnaire designed to measure their confidence in ordering and interpreting clinical chemistry tests. Similar to the Hong Kong study, 23% of students were not sufficiently confident in interpreting the results of the tests they ordered. The students were confident (>50% sure) when interpreting liver function, lipid profile, thyroid-stimulating hormone, troponin, creatine kinase, urea, electrolytes and protein tests, but they felt less confident (<50% sure) when interpreting urinalysis, parathyroid hormone and iron profile tests. Meanwhile, 67% of the students surveyed in a hospital in Britain admitted a lack of understanding of clinical pathology, which made them feel unprepared for a future postgraduate career as a doctor (12). Similarly, a survey study in Iran assessing medical students' current knowledge in clinical chemistry also reported inadequate understanding (13). The study employed basic and objective questions that focused on various stages of test ordering (pre-analytical, analytical and post-analytical). Almost half of the students' surveyed showed poor performance in all three phases, with the worst performance in the pre-analytical phase (55% of students

achieved a "weak" grade) compared to analytical (40.7%) and post-analytical (48.2%) phases.

PROBLEMS WITH THE CLINICAL CHEMISTRY CURRICULUM

In the United States, a national survey examining the current state of laboratory medicine education was conducted in 2013 to 2014 across 131 medical schools (14). Relevant education directors filled out questionnaires that assessed the status of clinical chemistry education in their respective school. Several parameters were measured, namely required and elective courses in laboratory medicine, competency assessments implemented, the availability of formal laboratory medicine clinical consultation to support the education and perceived barriers to optimising laboratory medicine education. The analysis identified several problems. Although most schools (78%) included laboratory medicine in their compulsory medicine coursework, the majority (>50%) of the surveyed directors admitted a lack of formal routine review for the laboratory medicine curriculum. Moreover, only 10% reported having a well-structured assessment method to observe student competence in laboratory medicine.

Regarding the barriers to optimising laboratory medicine education, the most significant concern was the limited time spent teaching and a lack of standard guidelines outlining competency levels in laboratory medicine, which are needed to ensure good clinical practice. According to Laposata's 2016 commentary of "Insufficient teaching of laboratory medicine in the United States medical schools", the average dedicated time for laboratory medicine courses in the medical curriculum is a mere eight hours; this is in significant contrast to the time spent on anatomic pathology (61 to 302 hours) (15). Combined with the absence of a standardised assessment in the medical curriculum to determine student's laboratory medicine knowledge, insufficient teaching hours leads to students being unskilled in laboratory medicine because of their low exposure to the field. All these barriers likely contribute to the high rate (63%) of respondents reporting a lack of student interest as another substantial barrier to improving laboratory medicine education. The obscurity of the discipline's curriculum has hindered teaching in this area, leading to the assumption that laboratory medicine courses are unclear and that it is an unimportant subject to learn (14).

Wilson's 2010 editorial "Educating medical students in laboratory medicine" also elaborated on problems in clinical chemistry curriculum implementation (6). Unlike other disciplines in medicine, the majority of medical schools have no separate clinical chemistry/laboratory medicine rotation in the clinical curriculum. Even if they have such rotation, it is usually non-mandatory for students (i.e. it is considered as an elective) (16). The field tends to be treated like an "auxiliary" proficiency, thus placing it into the context of individual patient cases. Because patients are directly treated by clinical physicians, these physicians are often in charge of teaching laboratory medicine to students (6). In addition to resulting in poor standardisation, the auxiliary education mindset can lead to students having only a cursory knowledge of laboratory medicine. They cannot achieve a deeper understanding of the discipline because they do not receive formal training (i.e. a distinct rotation) in laboratory medicine. Students may understand the appropriate laboratory testing suited for patients with common, daily encountered diseases, but they face difficulties when treating less common, rarely seen diseases in practice. Furthermore, Wilson stated that most of the treating doctors who teach laboratory medicine to students have no formal education or training in the field (6). Therefore, it is possible that students are not receiving comprehensive knowledge about clinical chemistry due to the teaching clinician's background.

The 2010 publication "Educating medical students in laboratory medicine: A proposed curriculum" by Smith et al. described extensive laboratory medicine learning goals and objectives for medical students to achieve by the time they graduate from medical school (17). This report was the result of reviews conducted by members from the Academy of Clinical Laboratory Physicians and Scientists (ACLPS). The curriculum proposed in the report covers most of the relevant courses in the laboratory medicine specialty (chemical pathology, microbiology and immunology, molecular diagnostics, hematology and transfusion medicine), including the overall vision and foundations of laboratory medicine itself to explain the core competencies for medical students to achieve in clinical chemistry. The report provides a detailed list of goals and objectives for each included subject. The list contains specific technical terms and competencies that students need to comprehend during their bachelor's degree studies. The proposed ACLPS curriculum was published in 2010; thus a reliable, thorough and standardised reference to establish a curriculum matrix for laboratory medicine courses in medical school has existed for some time. However, several studies of the recent status of students' laboratory medicine competencies show contradictory results (10–13). This indicates that the implementation of the proposed curriculum has not been well executed. There are several reasons for the delay in implementation.

Wilson stated that the accrediting agencies are reluctant to mandate the curriculum enforcement effort. In his view, this is perhaps because of the dearth of systematic studies that have investigated or reviewed the current state of clinical chemistry education across medical schools (6). Such a claim appears to be valid. In the current review, few reports about the current (poor) clinical chemistry understanding of medical students in only one or few institutions in a handful of countries were identified (10–13). Although the United States has fairly good institution coverage, with over 100 medical school institutions nationwide, the evidence points to insufficient clinical chemistry education among these medical school institutions (18). Thus, the struggle to implement the ACLPS curriculum continues. Similar results were found in a 1993 study that investigated laboratory medicine education in the United States medical schools (19). The study reported that nearly 50% of the United States medical schools did not have a firmly established laboratory medicine curriculum. In addition, one-third of the surveyed schools did not offer elective courses to study laboratory medicine. The report also identified a lack of allocated teaching time as a problem. Therefore, there has been relatively little change in improving laboratory medicine education.

There is still a tendency in the United States to oppose changing the curriculum to include clinical chemistry in medical education, as described in the Flexner report (20). The long tradition of the hyperrational system in Western medicine is thought to be a cause for the aversion to clinical chemistry inclusion in the medical curriculum (20). This can also be inferred from the historical assumptions of clinical chemistry as pseudoscience and a superstitious discipline in the early period of its establishment over a century ago; this was described in the Flexner report. This historical context combined with a paucity of studies that have evaluated clinical chemistry education (nationwide and worldwide) has appeared to ingrain a hesitancy to change the curriculum in the minds of relevant stakeholders. Similarly, this situation is occurring at a national medical school in India, where the scarcity of clinical chemistry investigations to be offered as evidence for revising the curriculum has led to doubts about making such changes (21).

It is thought that implementing changes to incorporate laboratory medicine studies into the medical curriculum (either as mandatory or elective courses) would finally solve this problem. However, a 2012 article by Magid

and Cambor reported an interesting finding (18). This study evaluated the progression of pathology (including clinical chemistry) curriculum integration into existing medical curricula across medical schools in the United States and Canada. Some challenges were still found, such as no time slots left for the courses, a lack of practicing experts to teach the students and a failure to acknowledge clinical chemistry as a clinical discipline. A 2017 editorial article discussing the current pathology rotation of most medical schools stated that the concept of passive learning is still applied. The students attended classes and engaged in discussions or tutorials with attending physicians or residents (16). The laboratory findings were prepared in advance by the department, and the students were not involved in the process of making and analysing the laboratory specimens, leaving most students with a lack of interest and satisfaction (16). In addition to the limited exposure to clinical chemistry due to inadequate time allocation, it may be that the negative perceptions of this field contribute to the low performance of medical students in this area. However, at present, there are no published studies or reviews that can directly confirm this relationship.

SOLUTIONS TO THE PROBLEMS

How can we improve the study of clinical chemistry in medical schools? The stakeholders must recognise and appreciate the role of clinical chemistry as an important diagnostic tool in patient diagnosis and management (6). The increasing contribution of laboratory results in establishing a correct diagnosis, tracking disease progression and guiding treatment management must be acknowledged. This recognition is an important first step because it can initiate an interest in (re) thinking the clinical chemistry curriculum as a crucial matter for medical schools and institutions.

THE EXPOSURE OF MEDICAL STUDENTS TO CLINICAL CHEMISTRY

An interesting article by Minhas et al. in 2017 proposed an innovative approach to improving student interest in learning clinical chemistry (16). The main goal was to engage students in direct and active patient management. The physicians or residents acted as mentors to the students in guiding patient case analysis. The students were divided into groups and then visited the laboratory to gather the data needed to interpret and understand the given case. The students were also encouraged to do the necessary examination themselves in order to build their interest and sense of engagement in managing the case. For example, the students could conduct a blood check under the microscope to view and analyse the blood cells in order to type and screen the patient's blood. To further assess and solve a given case, the students were also encouraged to visit other relevant departments if needed, such as pathology (e.g. cutting or sectioning tissue specimens) and microbiology (e.g. performing culturing). A wrap-up session was held at the end to discuss and conclude the case. Later, all groups prepared their respective report and presented the case to the other groups in a plenary session; the meeting was supervised by the mentors. These types of training may improve the quality of students' experience in clinical chemistry and subsequently lead to a better understanding of this clinical area.

A 2012 study at Harvard Medical School assessed student satisfaction after completing clinical chemistry courses that were part of an integrated pathology curriculum for students within a clerkship timeframe (22). The curriculum consisted of mandatory and elective classes and was designed to take one year to complete. The mandatory courses included transition courses and case conferences. The transition courses provided an introduction to the

field of clinical chemistry and familiarised students with diagnostic testing and laboratory procedures. The case conferences were designed to enable students to observe the role of clinical chemistry in patient care. The elective portion was designed for interested students to delve deeper into clinical chemistry-related activities during the clerkship rotations. The students also participated in direct hands-on laboratory procedures. After completion, the students were asked about their experience of the courses. Most students reported that they were satisfied because they had learned a lot about clinical chemistry. They had seen the relevance of this field in helping to appropriately manage patients. The courses made clinical chemistry's role visible to them.

The Harvard study implies that Minhas et al.'s suggestion for a direct and active patient management approach is useful for educating medical students about clinical chemistry. A well-planned curriculum design is key for successful student learning and outcomes. The study also showed that it was possible to integrate clinical chemistry into the existing medical curriculum without extending the timeframe for completing medical school. This is in accordance with Chu et al.'s suggestion in their 2015 editorial, which encouraged the involvement of clinical pathologists in all currently established clerkship rotations in the curriculum and the requirement for students to participate in case conferences to help them see the role of clinical chemistry in team-based medical decision-making (23).

To the best of the author's knowledge, there are no published studies about clinical chemistry courses that are conducted in a separate rotation. Nevertheless, it may be ideal for clinical chemistry to have a separate rotation as a mandatory course for students to take in addition to integrating it into the existing curriculum. It may be even better when combined with other diagnostic fields such as anatomic pathology and radiology in a single pathology rotation entity; this would enable the students to have an even more holistic understanding of this clinical realm. Chu et al.'s article suggested such an approach to improve learning; this was based on a study that found that more than 80% of students believed a combined field would be valuable (23). More studies are needed to verify whether these approaches will result in better learning outcomes for the students.

Molinaro et al. evaluated students who underwent a clinical laboratory course for 1.5 days (5). The course began with a pretest of laboratory medicine knowledge to obtain the students' baseline scores. Next, a 1.5 hour panel discussion introduced the field of laboratory medicine. The panel was composed of an internal medicine resident, an infectious disease doctor, the director of laboratory medicine, a medical technologist and the patient. The panellists related their respective stories about the role of laboratory medicine in the patient's disease management. The students could then ask the panellists' questions.

The next day, the students were divided into groups and went to an assigned medical case they had been matched to. Many clinical specialties were involved in the cases, such as internal medicine, neurology, surgery, obstetrics, paediatrics and emergency medicine. The included cases covered laboratory medicine aspects in chemistry, cytology, hematology, microbiology and transfusion medicine. Facilitators were also provided for each group to guide the case discussion. On the second day, the student groups met up to present and discuss their case with the other groups. The conference was led by the assigned facilitators. Pre-analytical, analytical and post-analytical issues of concern related to laboratory testing were emphasised to inform the students how these issues may affect the results and interpretation and, consequently, the diagnosis and management of the respective cases. After summarising and concluding the conference session, the same pretest questions were given to the students to reassess their laboratory medicine knowledge (i.e. as a posttest). The results

showed an improvement in knowledge. However, the investigators posited several caveats to their 1.5 day course approach:

a. The pretest and posttest quizzes only measured a portion of knowledge that was recently acquired.

b. No incentive was given for completion of the course or quizzes (which may have affected the pretest and posttest results for some students).

c. The course was conducted with fourth-year medical students in their last month of training; this was a concern for a possible lower level of attentiveness among the students.

Although the study had positive results, the researchers acknowledged that the 1.5 day course was insufficient to address the vast and diverse subject of laboratory medicine. Furthermore, there is no evidence that the students would retain what they had learned in the course for their future practice. Nonetheless, the investigators stated that it was a better approach, particularly for medical schools that already have a full curriculum.

Another experiment was conducted in Iran by Omidifar et al. (24). A 1.5 day short crash course on laboratory medicine was offered to interested third-, fourth- and fifth-year students. The students were also instructed to complete a pretest and posttest, as well as a satisfaction questionnaire. In this study, the students were given an introduction to laboratory medicine. This was not through clinical case analysis, but directly through visiting different sections of the laboratory (hematology and blood bank, biochemistry, immunology-serology and urine analysis). The investigators stated that the main goal of the study was to familiarise the students with clinical chemistry, since the participating students were thought to have little exposure to the field due to a lack of sessions in the already overloaded curriculum. Similar to Molinaro et al.'s study, the posttest results found that the students' knowledge had improved after the course. Student satisfaction with the crash course was also confirmed.

Molinaro et al. (5) and Omidifar's et al. (24) study indicates that even without integrating clinical chemistry into the existing curriculum, an effort to improve students' exposure to laboratory medicine could still be useful. The 1.5-day course showed that even for such a short course, improvement could be expected. Omidifar et al. also provided recommendations to medical schools for introducing clinical chemistry studies to their institution. They strongly suggested implementing a laboratory medicine course in the clinical clerkship phase to ensure that students understand the practicality of the discipline in disease management. The course should include sessions for general information and protocols, laboratory tours, performing test procedures under the supervision of a clinical pathologist, an introduction to quality control, laboratory informatics and economy, and test result interpretation (24). Supporting the current low status of clinical chemistry education for medical students, the authors also stated that more research about clinical chemistry education is needed to gain more evidence in this area.

A unique approach for introducing clinical chemistry was implemented in Azer et al.'s study in Saudi Arabia (25). The authors did not design a long-term integrated curriculum or a crash course; instead, they implemented clinical chemistry study as part of the existing problem-based learning (PBL) classes that were already scheduled in each block or module system. Several blocks were chosen for this study, namely the nervous, gastrointestinal, hematology and endocrine systems. The participating pre-clinical students were divided into groups in these blocks' PBL classes. Several different clinical chemistry study topics related to the chosen blocks were established, viz. cerebrospinal fluid infection (in the nervous system block), small intestine, pancreas and liver function tests (in the

gastrointestinal and hematology blocks), and adrenal function (in the endocrine block). The PBL sessions were led by facilitators and laboratory assistants that had been briefed about the study. Students' pretest and posttest scores were compared to assess short-term retention of knowledge after the PBL session. Additionally, an objective structured practical examination (OSPE) test was given to the students at the end of each block or module system to examine long-term knowledge retention. Student satisfaction with the faculty's approach to learning clinical chemistry was also assessed through a questionnaire. Similar to the previous studies, the authors reported significantly better mean scores for the posttest compared with the pretest and similar mean OSPE scores for stations covering the studied topics and similar mean scores of those that did not cover the topics. The student feedback questionnaire following the PBL classes indicated overall satisfaction.

This study shows that even without additional modifications to the currently overwhelmed curriculum or allocating time for a new course, an introduction to clinical chemistry and related tutorials can still be implemented through the existing curriculum. Most medical schools have PBL sessions in their block or module system as part of the regular curriculum. The utilisation of PBL to introduce the field of clinical chemistry could be a good option for schools that have not included proper clinical chemistry studies in the curriculum and are unable to find an open timeslot or create a separate course. This notion is also supported by the aforementioned Hong Kong study that asked students to provide suggestions for improving clinical chemistry teaching; suggestions included increasing the number of lectures and teaching time, providing more PBL sessions and assigning clinical pathologists to teach clinical chemistry (10). The use of PBL sessions could provide a double benefit, i.e. there is no need to remodel the curriculum and it increases students' exposure to clinical chemistry.

From the studies described above, several key points can be highlighted for stakeholders to consider:

a. There are several ways to incorporate clinical chemistry into the medical curriculum. Studies have used different approaches for this—modifying the existing curriculum, designing a crash course and using existing PBL classes. All these approaches were successful in improving students' knowledge of clinical chemistry. Therefore, reasons such as limited time and difficulties in finding a timeslot are no longer acceptable.

b. The active engagement of students and innovative teaching methods improve students' understanding and satisfaction when studying clinical chemistry. Active participation in the laboratory course enhances the learning process and mediates the transition of the newly acquired knowledge into memories; such engagement is associated with changes in learning-associated neural circuitry (29). The introduction to case discussions, touring laboratories and performing hands-on laboratory testing stimulates the student to actively learn by undertaking the analysis and interpretation themselves. These learning experiences may explain the good outcomes obtained in the studies.

c. The collaboration between medical specialties and clinical pathologists in building and designing an integrated curriculum or courses is of paramount importance. Most students in the studies expected that the clinical chemistry course would be relevant to clinical cases they will often face later in their practice. The curriculum or course design has to be thoroughly checked and reviewed so that it fulfills the needs of students. Medical students do not need to know

how to perform complicated and specialised testing procedures in the laboratory, but they do need to know how laboratory test results relate to a patient's diagnosis and management. Therefore, the input of clinicians must be considered when designing case studies for the clinical chemistry curriculum/courses. This is also in line with the principal recommendation mentioned by Laposata who stated that an accurate and quick diagnosis in medical practice is based on the collaborative involvement of treating clinicians and laboratory medicine doctors (15).

These key points are similar to the suggestions in the ACLPS guidelines regarding teaching methods. It encourages the use of PBL sessions, case discussions and a collaborative interdisciplinary approach in designing clinical chemistry courses. Additionally, the guidelines offer detailed suggestions for choosing the right time and the right way to teach clinical chemistry topics. Hence, it is essential for relevant stakeholders to first read and consider the syllabus proposed by ACLPS before designing a suitable course or approach for teaching clinical chemistry to medical students. To address the problem of insufficient knowledge of clinical chemistry among medical students, well-planned and appropriate exposure to clinical chemistry is required; otherwise, students may not be interested in acquiring a deeper understanding of the field and educational efforts could be futile.

Finally, more research in clinical chemistry education is urgently needed. Only sporadic research reports are available at present. Studies in multiple countries should be conducted to provide evidence for change and to make the suggestions described in this paper more generalisable, with the ultimate goal of establishing an international consensus about an ideal clinical chemistry curriculum for medical schools worldwide.

DESIGNING A CLINICAL CHEMISTRY CURRICULUM

In their 2014 article, Sadofsky et al. described three main competencies in all pathology-related medical fields (including clinical chemistry/laboratory medicine): understanding disease mechanisms, integrating the mechanisms into interorgan system pathology, and applying this knowledge for diagnosing (26). The proposed ACLPS syllabus fulfills Sadofsky's standards, making it an excellent curriculum reference for designing a clinical chemistry curriculum and related courses for medical schools. In support of the proposed ACLPS curriculum, a consensus guideline for practical competencies in laboratory medicine/clinical chemistry for undifferentiated graduating medical students was issued in 2015 by Magid et al. (27). This guideline provides key general laboratory medicine terms and competencies that undergraduate medical students should have by the time they complete their bachelor's degree—knowing the different test reference ranges for different demographics, inferring results that fall outside the reference range, being able to identify factors that may influence a test result and its interpretation, using correct techniques to acquire patient specimens, considering the critical value, sensitivity and specificity of a test when making clinical judgements, differentiating between a screening and a confirmatory test, and choosing the right test for a patient. Together, the ACLPS syllabus and the consensus guidelines provide a strong reference for developing a clinical chemistry education curriculum matrix.

All planned competencies in the clinical chemistry curriculum design should be relevant and applicable to the clinical context, especially for patient diagnosis and management. The courses should introduce and educate students about commonly encountered and necessary laboratory tests that are often used by physicians in their

practice (15). Therefore, the teaching of clinical chemistry must be directed such that it prepares students to implement the learning into their practice with real patients and helps them avoid errors in requesting inappropriate laboratory tests. Such errors could lead to multiple harms for the patient (e.g. physical injury, financial and psychological burden) (28), which may even initiate medico legal issues for the treating physician should the patient feel unsatisfied with the care provided (29). This predicament can be avoided through proper training in clinical chemistry during medical school.

An excellent concrete example of a competency-based curriculum matrix is found in Ford and Pambrun's 2015 paper (30). The report describes the competencies that medical students should have by the end of their studies (see Appendix). It was developed by the Canadian Association of Pathology Education Group. The matrix contains practical and point-by-point facets that the graduating students should know and retain. The targets are measurable (action-oriented competencies), clinically focused (directly relevant to patient care) and generalisable (applies to all medical school graduates, regardless of their future specialty preference). In addition, this matrix also promotes critical thinking and reasoning. It encourages students not to simply recall the knowledge but also to see the necessity and reason for requesting certain laboratory parameters for a given case. The list of competencies was created in such a way as to be integrated into the existing clinical rotations.

There is an additional problem with a lack of practicing experts to teach clinical chemistry. This matter could be overcome by medical schools hiring more clinical pathologists as permanent staff. If this is not possible, inviting additional (visiting) experts from other medical schools could also be appropriate. The latter consideration may be effective especially if the school has only a short amount of allocated time or a few courses for clinical chemistry studies in its curriculum. The need for experts should be adjusted according to the circumstances of each medical school.

CONCLUSION

Clinical chemistry plays a crucial role in disease diagnosis and patient management. However, the current clinical chemistry knowledge among medical students is insufficient, implying that the clinical chemistry curricula of medical schools are inadequate. There are several main problems: a lack of a formal or structured clinical chemistry curriculum, limited time allocated for studying this topic, a lack of teaching experts and a failure of stakeholders to acknowledge the importance of clinical chemistry. These problems must be overcome in order to improve clinical chemistry education and teaching, ultimately enhancing the students' competence in clinical chemistry.

Students expect the clinical chemistry lessons to be relevant to the management of cases that they will come across in daily practice. They also want the teaching to be interesting by engaging them in hands-on experience and active discussions. This approach should be considered because it stimulates students, thereby improving student satisfaction and enabling them to achieve a better understanding of clinical chemistry. This may help them to retain the knowledge after the sessions. Accordingly, the clinical chemistry courses should be designed so that they answer the students' need for active and applicative learning. Collaboration between the different specialties and clinical pathologist/laboratory medicine doctors is crucial to ensure appropriate curriculum and/or course design. The ACLPS guidelines and Magid et al.'s consensus of practical competencies can be used as a reference for developing a robust clinical chemistry curriculum.

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APPENDIX

The Canadian Association of Pathology Education Group exit competencies for graduating medical students

Practice	Competencies
Foundational	1. Order appropriate laboratory testing based on the patient's clinical presentation and the results of any previous investigations.
	2. Include clinically important information on the laboratory requisition (e.g. clinical differential diagnosis) for biopsies and other invasive tests.
	3. Ask a pathologist for assistance (urgently, if necessary) in selecting or interpreting the laboratory investigations for challenging or unusual clinical problems as well as when errors are suspected.
	4. Avoid ordering clinically irrelevant tests or unnecessarily repeating previous tests and appropriately counsel patients who request such testing.
	5. Provide appropriate clinical management in the case of a critical laboratory value.
	6. Manage a patient based on laboratory test information, demonstrating an understanding of test limitations including insufficient sensitivity or specificity, as well as the possibility of sampling and/or laboratory error. Take the appropriate action(s) for patient follow-up, including consultation with the pathologist if applicable.
	7. Explain to a patient or family how a potential malignancy or other serious condition is being diagnosed and staged as well as how long it will be before a final diagnosis is available.
	8. Explain to a patient the etiology and pathogenesis of his or her disease, in language appropriate for the patient.
	9. Describe a patient's diagnosis to the patient and to colleagues using the correct terminology: e.g. in situ, invasive, dysplastic, myelodysplasia, myeloproliferative, etc.
	10. When presented with a challenging clinical scenario where a diagnosis is not immediately apparent, use pathogenetic reasoning to develop a differential diagnosis.
	11. Teach medical students (and other trainees) key clinical concepts about common and important diseases, including etiology, pathogenesis and laboratory testing.

(*Continued on next page*)

Appendix: (*Continued*)

Practice	Competencies
Biopsy or cytology investigation	1. In a patient with an abnormal mass, provide initial management based on a differential diagnosis including both benign and malignant lesions (and if malignant, of either primary or secondary origin). 2. In a patient with an abnormal mass, work with senior members of the health care team to request excisional biopsy, incisional biopsy, core needle biopsy, fine needle aspiration cytology, or exfoliative cytology where it is appropriate to do so. When the best diagnostic procedure is unclear, obtain advice from the pathologist before the procedure is performed. 3. In patients who have undergone a biopsy or cytological investigation, including Pap smear, explain the pathologist's report to the patient as well as outlining any appropriate follow-up. 4. In patients with breast cancer and other malignancies, correlate the pathologist's report with the results of radiological investigations.
Hematology	1. In a patient with abnormal blood cell counts (e.g. anemia, polycythemia, neutropenia, thrombocytopenia, etc.), use the complete blood count along with history and physical exam findings to develop an appropriate initial diagnostic and management approach. 2. In a patient with a bleeding or thrombotic disorder, use screening and focused laboratory testing along with history and physical exam findings to develop an appropriate initial diagnostic and management approach. 3. In a patient with symptoms or signs of a hematologic malignancy, order the appropriate initial screening and/or diagnostic tests (e.g. complete blood count [CBC], serum/urine protein electrophoresis, bone marrow aspirate and biopsy, molecular and cytogenetic testing etc.).
Transfusion medicine	1. Obtain informed consent for a blood transfusion, including explaining to a patient the risks and benefits of blood product transfusion. 2. Order the appropriate blood product (e.g. red blood cells [RBCs], platelets, plasma, cryoprecipitate, etc.) based on the patient's clinical status and according to accepted national/state/provincial guidelines. 3. Write a complete order for a blood product transfusion, including product, volume, rate, etc. Consider product modification or special orders where appropriate (e.g. cytomegalovirus [CMV] negative, irradiated), for discussion with senior trainees or staff. 4. Do not transfuse a contraindicated blood product. 5. Recognise a patient experiencing a transfusion reaction, stop the transfusion, and seek appropriate clinical and laboratory support in the patient's management.

(*Continued on next page*)

Appendix: (*Continued*)

Practice	Competencies
Microbiology/ infectious disease	1. For a patient with symptoms or signs of an infectious disease, order the appropriate initial laboratory tests corresponding to the clinical infectious differential diagnosis (e.g. gram stain, acid fast stain, viral serology, blood or tissue cultures, etc.) to permit diagnosis of infections caused by bacteria, viruses, fungi, parasites, or prions. 2. Correctly interpret a microbiology lab report in the context of the patient's clinical presentation, to differentiate among infection, colonisation and contamination. 3. Use microbiology test results and the patient's clinical status to guide antimicrobial therapy. 4. Follow appropriate infection control guidelines for patients with infectious diseases, including hand-washing, isolation procedures and outbreak management. 5. When caring for a patient with an infectious disease which may be reportable, consult with senior members of the health care team regarding how and to whom the condition should be reported.
Biochemistry	1. Order specialised laboratory tests in a clinically appropriate sequence, demonstrating an understanding of the approximate relative cost and/or availability of individual tests. 2. Order special tests to be collected at appropriate times of day or at appropriate intervals (e.g. therapeutic drug monitoring). 3. Diagnose and manage patients using an evidence-based approach to biochemical testing, including patients with diabetes mellitus, lipid disorders, endocrinopathies and abnormalities of electrolytes and blood gases. 4. Interpret test results in the context of the laboratory's reference ranges, with specific attention to tests for which reference ranges may differ according to the patient's age, sex, pregnancy status, etc.
Genetic testing	1. In a patient with a personal and/or family history suggestive of a genetic disease, order appropriate genetic testing (including karyotype, comparative genomic hybridization, polymerase chain reaction [PCR], etc.) where such testing is clinically indicated. 2. Discuss with a pathologist the best approach to genetic testing for patients or families at risk for chromosomal imbalances (e.g. Down syndrome), single gene diseases (e.g. Huntington syndrome, thalassemia, sickle cell disease, inherited cancer syndromes), and multifactorial/complex diseases (e.g. familial melanoma clustering). 3. Obtain appropriate consent from the patient before ordering genetic testing, and consult with senior members of the health care team regarding any need for genetic counselling.
Post-mortem patient management	1. Request a medical autopsy for a patient dying a non-reportable death, where there are outstanding medical issues which may be relevant to the patient's family or to clinical care of other patients (e.g. for further characterisation of a new or poorly understood disease). 2. Obtain autopsy consent from a patient's family.