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Are Medical Technologists still needed in Medical Laboratories in a Technologically Advanced Future?

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Abstract
An emerging trend in modern medical laboratories is automation, and it is having a positive impact on the quality of service to patients and on the safety of medical laboratory staff. The use of automation in medical laboratories enable many tests by analytical instruments with minimal use of an analyst. These automated instruments result in increasing the capabilities of a laboratory to process more workload with minimum involvement of manpower. Total Laboratory Automation (TLA) has many advantages including workload reduction, less time spent per sample, increased number of tests done in less time, use of a smaller sample amount, decreased risks for human errors, and higher reproducibility and accuracy. With the future practice of medical technologists in a technologically advanced future in peril. What edge do medical technologists have over Artificial Intelligence and Robotics that would still make them essential in medical laboratories in a future that is technologically advanced?

Keywords: Laboratory Automation, Artificial Intelligence, Robotics, Medical Technologists, Medical Laboratory Scientists

1. Introduction

There has been rapid evolution of clinical laboratories since 1990s that is mainly driven by technological advances whose main focus is on automation(Burtis, 1995; Panteghini, 2004; Bajwa, 2014). Today, there is a consensus in the bioanalytical industry that automation in bioanalytical laboratories improves its function and productivity (Armbruster, Overcash and Reyes, 2014; Archetti *et al.*, 2017; Ellison *et al.*, 2018; Yeo and Ng, 2018; Lippi and Da Rin, 2019). Services of medical laboratories are an essential component of high-quality healthcare delivery and require adequate space and equipment so that high-quality work and safety of patients, visitors, customers, and staff are not compromised (Mosadeghrad, 2014; Carey *et al.*, 2018).

Medical laboratories are potentially dangerous places due to biological hazards. Introducing automation results in a reduction of manipulation of biological sample by the staff, in particular transport of samples, subsampling, analytical operations, and waste management (Aita *et al.*, 2017). In addition to reducing occupational hazards, automation reduces tedious labor, employee turnover, permits the reallocation of staff for expansion and growth, and generally improves productivity (Lippi & Da Rin, 2019).

There is already a technological revolution happening in medical laboratories wherein machines have made tasks and procedures safer and more efficient (Thimbleby, 2013; Shah *et al.*, 2019). With total automation of medical laboratories a distinct possibility in the near future and more and more tasks of medical technologists are being delegated to artificial intelligence and machines, the main question of this discussion paper is "would we still need medical technologists in medical laboratories in a technologically advanced future?"

2. The Medical Technologist

A medical technologist, also known as a clinical laboratory scientist or medical laboratory scientist, analyzes a variety of biological specimens (Tan and Ong, 2002; Ortiz and Hsiang, 2018). They are the third largest medical profession after doctors and nurses (Resources and Administration, 2016), their responsibility lies in the performance of scientific testing on samples and reporting the results to physicians. Medical laboratory scientists perform complex tests on samples from patients using sophisticated equipment like microscopes. The work of medical technologists play an important role in the identification and treatment of medical conditions (Hosogaya, 2015; Ortiz and Hsiang, 2018). This type of analysis requires extensive knowledge of abnormal and normal physiology, ability to correlate laboratory data to specific diseases as well as extensive knowledge of instrumentation and individual test principles. It has been estimated that 70-80% of all decisions with regard to a patient's diagnosis, hospital admission, treatment, and discharge are based on the results of the tests that are performed by the medical technologists (Ortiz and Hsiang, 2018).

Medical Technologists work closely with other healthcare professionals in the diagnosis, monitoring of disease processes, as well as the monitoring of the effectiveness of therapy. Areas of medical laboratory training include chemistry, immunology, microbiology, hematology, toxicology, transfusion medicine, and molecular diagnostics (Bayot and Naidoo, 2020). Medical technologists have a wide variety of duties and responsibilities that includes: Examining and analyzing body fluids, blood, cells, and tissues; identify microorganisms capable of infection; analyze the chemical constituents of body fluids; measuring the efficacy of specific treatments by testing; evaluating test results for accuracy and aid in the interpretation to help physicians; cross matching blood for blood transfusions; monitoring patient outcomes; and establishing quality assurance programs that monitor and ensure the accuracy of test results (Wood, 2002; Hosogaya, 2015).

3. Automation in Medical Laboratories

Automation has a strong contribution to revolutionizing a host of human activities that results in the provision of unquestionable benefits on system performance (Archetti *et al.*, 2017; Yeo and Ng, 2018). The multifaceted and abundant advancements of automation technologies have also resulted in a profound impact on the organization of medical laboratories, where many manual tasks have now been partially or completely replaced by labor-saving and automated instrumentation. Laboratory automation is commonly classified according to the sophistication of instruments integration (Da Rin, Zoppelletto and Lippi, 2016; Ellison *et al.*, 2018; McAdam, 2018), which ranges from "no automation" which means all analyzers exist as stand-alone machines, "partial laboratory automation" which means there is the development of "automation islets" where laboratory analyzers are interconnected and are partially integrated with pre-analytical workstations such as in the serum work area which integrates clinical chemistry and immunochemistry testing, and "total laboratory automation (TLA)" which means that most analyzers performing different types of tests (such as immunochemistry, clinical chemistry, hemostasis, hematology, and others) on different sample matrices (serum, whole blood, citrated or heparinized plasma) are integrated physically as modular systems or connected by assembly lines (e.g. conveyer belts) (Lippi & Da Rin, 2019). In TLA, various preanalytical and postanalytical steps (e.g. sample input, check-in, sorting, decapping, centrifugation, separation, aliquoting, sealing, and storage) are performed automatically in workstations that are physically connected with the analyzers and are managed efficiently by software programs.

4. Potential Advantages of Total Laboratory Automation

4.1. Lower costs in the long term

There is evidence that automation can successfully lower the costs of laboratory diagnostics (Archetti *et al.*, 2017). The return on investment (ROI) is more appreciated more in the long term after reaching the "break-even point" when the high initial cost will be offset. The major economic revenue of automation comes from the merging of many diagnostic platforms within a consolidated system resulting in reduction of manual workforce needed for the management of high-volume testing (Ellison *et al.*, 2018).

4.2. Decreased congestion in the laboratory

The decrease of personnel essential for the performance of tests would also result in lower staff congestion within the laboratory (Lippi & Da Rin, 2019). An optimized layout of integrated workstations would prevent the unnecessary movement from one workstation to another by staff resulting in minimizing the distance covered by personnel for the performance of multiple analyses on different instrumentation.

4.3. Improved efficiency

Other than benefits in cost-containment, automation also provides other advantages within the laboratory environment that is commonly attributable to the use of customizable assembly lines that can be organized to meet specific requirements and layouts of laboratories (Armbruster, Overcash and Reyes, 2014). Studies demonstrate that an efficiently designed automated laboratory may be variably effective in reducing turnaround time (TAT) and concomitantly improving laboratory productivity (Angeletti *et al.*, 2015; Chung *et al.*, 2018; Bhatt, Shrestha and Risal, 2019). These goals are achieved through workflow optimization.

4.4. Improved sample management

Information technology has drastically contributed to the improvement of medical laboratory organization and work (Carey *et al.*, 2018; Sutton *et al.*, 2020). Modern generation of laboratory instrumentation come equipped with advanced software programs (i.e. all samples can be stored within online stockyards that can be automatically retrieved and re-analyzed hours or days after initial testing) that allow better sample management (Lippi & Da Rin, 2019). Setting of decision rules that are based on a predefined criteria now permits auto verification of data, automatic re-analysis of samples with suspect or highly abnormal results, as well as a triggering reflex (reflective) and add-on testing that ultimately contributes to an improvement in the quality and safety of diagnostic testing (Rimac *et al.*, 2018; Wu *et al.*, 2018).

4.5. Enhanced standardization for certification/accreditation

The consolidation of different diagnostic areas within the same workspace would result in increased accuracy and repeatability throughout the entire testing process that has been enabled by automated operations. This in turn will grant paramount benefits in terms of standardization, thus resulting in the simplification of accreditation and certification procedures (Zima, 2017; Lippi and Da Rin, 2019).

4.6. Improved quality of testing

Automation allows delegating the bulk of manual ordinary activities such as specimen sorting, loading, centrifugation, decapping, aliquoting, and sealing from humans to machines (Zima, 2017; Yeo and Ng, 2018; Lippi and Da Rin, 2019). Improved process standardization will result in tangible benefits to the quality of the total testing process and also lowering the risk of diagnostic errors, especially errors that emerge from manually-intensive activities (Yeo and Ng, 2018).

4.7. Lower sample volume

One of the benefits of an automated medical laboratory is a reduction in the number of blood tubes needed for testing (David Hopper, 2016). The same serum tube can be used for multiple immunochemistry and clinical chemistry tests which allows to consistently reduce the total volume of blood required for testing. More importantly, a reduced sample volume will also result in a lower impact on biological waste disposal which results in additional economic savings (National Research Council, 2011).

4.8. More efficient integration of tests results

Consolidation of different diagnostic areas within the same space results in an improved ability to navigate and manage the flow of data from delivery, analytical, and archival systems (Tozzoli *et al.*, 2015; Lippi and Da Rin, 2019). Automation of medical laboratories enables the integration of a vast array of test results produced by different analyzers. This will not only enable the definition of a larger, more complex, and accurate auto-validation criteria, but would also enable laboratory personnel to gain a broader picture of the patient's results, thus resulting in an improved ability to detect potential errors or identify critical situations that need immediate communication to clinicians (Lippi & Da Rin, 2019).

4.9. Lower biological risk for operators

Worker safety is one of the most significant advantages of automation. Automated systems not only remove human operators from the workplace, but also defends them against the risks of performing biologically hazardous operations and handling of materials that are biohazardous (Armbruster et al., 2014; Lippi & Da Rin, 2019).

4.10. Staff Requalification and Job Satisfaction

One of the major advantages of automation in medical laboratories is the minimization of manually-intensive labor that results in net saving of staff needed for the management of the laboratory workflow (Lippi & Da Rin, 2019) This will enable the requalification of personnel, elimination of manpower, and the redefinition of job roles towards value-added tasks such as implementation of new tests like genomics, proteomics, theranostics, or quality assessment that would ultimately lead towards personalized (laboratory) medicine.

5. Potential Disadvantages of Total Laboratory Automation

5.1. Higher costs in the short-term

Association with an initial escalation of costs is inevitably related to the implementation of TLA because accommodating the project requires environmental modifications, heavy-duty air conditioners, and soundproofing for installation of the system and for the new hardware (Lippi & Da Rin, 2019)

5.2. Increased costs for supplies (i.e. maintenance, energy, and supplies)

The new hardware implementation that consists mainly of pre-analytical workstations, assembly lines, and sample storage units, carries subsidiary costs for system functioning (i.e. energy and water) and for supplies (e.g. caps for sealers and tips for aliquotters). TLA would require a higher level of maintenance compared with manually-operated instrumentation (Lippi and Da Rin, 2019).

5.3. Space requirement and infrastructure constraints

The accommodation of multiple analyzers and new hardware into a pre-existing environment may be difficult, especially when the environment is not purpose-built for this reason. But an advantage of TLA are flexible models that may be used when the environment does not allow developing an ideal solution, when renewing possibilities are limited, the configuration of the TLA system can be designed to fit in the local environment, so that the orientation of analyzers and access for repair or maintenance would be possible (Archetti *et al.*, 2017; Lippi and Da Rin, 2019).

5.4. Overcrowding of personnel

An unquestionable benefit of the implementation of TLA is a reduction in the need for staff to move many times from one analyzer to another. A drawback of this is the consolidation of many different analyzers within the same area may increase the risk of the generation of overcrowded work environments, where many technicians occupy the same space at the same time (Lippi and Da Rin, 2019). To avoid this from happening, there is a need to develop an efficient plan that is aimed at identifying a lean laboratory layout concept.

5.5. Increased generation of heat, noise, and vibrations

The consolidation of numerous analyzers in an area will concentrate heat, noise, and vibrations in a narrow environment. This may result in the perception of excessive warming and increased exposure to acoustical or electrical noise in the work environment (Lippi and Da Rin, 2019).

5.6. Increased risk of downtime

The higher is the sophistication of the system, the greater the risk of a system failure that would generate serious consequences on laboratory functioning (Archetti *et al.*, 2017; Lippi and Da Rin, 2019). Critical system failures that involve assembly lines would require restoring manual procedures for the management of samples (i.e. manual sorting, centrifugation, decapping, aliquoting, loading, and unloading). As a result, there is production of variably protracted downtimes, delaying analysis of specimens and prolonging the TAT (turnaround time).

5.7. Psychological dependence on automation

Replacement of manual activities with automation results in loss of locus-of-control in the staff, rapid deterioration of skills, and inefficient resumption of manual functioning when automation fails (Lippi and Da Rin, 2019).

5.8. Differential requirements for sample management

Different types of samples with different biological matrices (i.e. heparinized or citrated plasma, whole blood serum, etc.) can be introduced simultaneously into the system. This means that all samples may be managed the same way along their path to the analyzers but different biospecimens may need different preparations before being tested like EDTA-anticoagulated samples for hematologic testing that do not need centrifugation (Armbruster, Overcash and Reyes, 2014; Lippi and Da Rin, 2019).

5.9. Generation of potential bottlenecks

The optimal management of urgent testing is a critical issue in TLA. The larger the volume of routine testing, the higher the risk of the creation of bottlenecks that may reduce system productivity and TAT (Lippi and Da Rin, 2019).

5.10. Disruption of staff trained in specific technologies

The development of the "core lab," where a majority of laboratory staff will be committed, is a consequence of the consolidation of many different diagnostic areas. The larger the volume of knowledge requirement, the lower the competency of staff on specific technologies (Armbruster, Overcash and Reyes, 2014; Lippi and Da Rin, 2019). The enhancement of workforce flexibility may contribute to a decrease in competency and skills in specific tasks, most especially in laboratory services that are shifting towards TLA, where there is incorporation of several diagnostic lines (e.g. immunochemistry, clinical chemistry, coagulation, hematology, microbiology, and virology). Although automation and technology have made the performance of tasks much easier, some specific and practical skills may be lost over time. Overall, there is a limitation on the experience that laboratory specialists harvest on a daily basis due to automation and this would potentially lead to decreased skills and expertise in analytical procedures (Armbruster, Overcash and Reyes, 2014; Archetti *et al.*, 2017; Lippi and Da Rin, 2019).

5.11. Risk of transition toward a manufacturer's-driven laboratory

The establishment of a strategic relationship with manufacturers and suppliers is essential for the achievement of an efficient TLA. This implies that the technology should be more accurately defined according to the expected laboratory layout. Full commitment to a single supplier or manufacturer paves a way to manufacturer's-driven laboratory and this would substantially limit or even prevent laboratory professionals from organizing or managing their own laboratories (Lippi and Da Rin, 2019).

Automation is considered as one of the most significant breakthroughs that have taken place in laboratory diagnostics over the past decades (Archetti *et al.*, 2017; Yeo and Ng, 2018). The ability to connect multiple diagnostic specialties to one single track has been proven to enhance efficiency, organization, standardization, quality, and safety of laboratory testing, and also providing a substantial return of investment in the long term and enable the requalification of staff (Lippi and Da Rin, 2019). Technological breakthroughs happen at a growing rate and as a result, technology is revolutionizing human wellness and care. The structure and organization of the healthcare industry have been drastically changed by technological advancements (Thimbleby, 2013). But the ultimate question remains, are medical technologists still needed in medical laboratories in a technologically advanced future? Medical technologists should learn more about emerging technologies in the healthcare industry like what are the capabilities of these technologies, especially intelligent machines, and search for ways where they can use these technologies to complement the tasks they are performing daily.

There are ways medical technologists are irreplaceable in the healthcare industry

Healthcare will need humans in the future

Artificial Intelligence (AI) will become routine in healthcare practice during the next 10-15 years (Jiang *et al.*, 2017; Buch, Ahmed and Maruthappu, 2018; Davenport and Kalakota, 2019). AI will transform what it means to be a healthcare provider: some tasks will disappear, while there will be additional tasks to the work routine. AI systems use deep and machine learning to analyze enormous amounts of data to generate predictions and recommend interventions. The advances in computing power have enabled the creation and cost-effective analysis of enormous datasets (Dunjko and Briegel, 2018; Kersting, 2018; Vollmer *et al.*, 2020). Digital microscopy analysis influences machine-learning algorithms trained with the use of tens of thousands of specimen images. These algorithms can quickly, consistently, and accurately identify and classify cellular and particulate objects in serum, urine, or tissue samples and are able to handle high volumes of samples for analysis (Delahunt *et al.*, 2015; Xing *et al.*, 2018; Rai Dastidar and Ethirajan, 2020).

AI is wholly dependent on data in its computation. A problem with this dependence is that AI is unable to verify the accuracy of the underlying data they are given (Cresswell, Cunningham-Burley and Sheikh, 2018; Kim *et al.*, 2019; Yang *et al.*, 2020). AI assumes that the data they are given are perfectly accurate, reflect high quality, and are representative of excellent care and outcomes. An advantage of clinicians against AI is the capability of clinicians to make assumptions and care choices based on unstructured data (Dash *et al.*, 2019; Hong *et al.*, 2019; Palanisamy and Thirunavukarasu, 2019). Experienced medical technologists develop intuition that enables them to identify an abnormal finding even though the sample provided might look identical to normal findings. This gives experienced medical technologists an edge over AI because clinical judgment may not be well represented by data (Walton, 2018; Patel *et al.*, 2019).

Medical technologists also have a non-linear working method. Although data, measurements, and quantitative analytics are also important factors of a medical technologist's work, the development of a diagnosis and developing a proper treatment regimen for patients are not linear processes and would require creativity and problem solving skills that robots and algorithms may never have (Kaartemo and Helkkula, 2018; Kelly *et al.*, 2019). The lifestyles of people vary to the degree that people differ. This feature also applies to diseases, which means no case is the same.

Another reason why medical laboratories will still need medical technologists in the future is the fact that complex digital technologies will require competent professionals (Groenier, Pieters and Miedema, 2017). Take for example, IBM's Watson. It's a unique AI for oncologists that is capable of providing clinicians evidence-based options. But a limitation of this technology is it is not capable of providing the best treatment option available for the patient and can only come up with potential suggestions (Lee *et al.*, 2018; Liu *et al.*, 2018). No robot or algorithm may be capable of incontrovertibly interpreting the complex, multi-layered analysis needed in determining the best treatment intervention for patients. While these technologies may be able to provide the data, the interpretation will always remain a territory for humans (Bader and Kaiser, 2019; Dear, 2019; Araujo *et al.*, 2020).

And the final reason why medical technologists would still be needed in laboratories in the future is the fact that there will always be tasks that algorithms and robots can never complete (Ozawa *et al.*, 1992; Royakkers and van Est, 2015; Kaartemo and Helkkula, 2018). There are responsibilities and duties which technologies cannot perform and would need the procedural expertise of humans to complete. Clinical laboratory testing plays a crucial role in the detection, diagnosis, and treatment of diseases. The Medical Technologists who perform most of these laboratory tests, are involved in the examination and analysis of body fluids, tissues, and cells. They usually look for the presence of bacteria, parasites and other microorganisms in the body. They analyze the chemical contents of fluids, match blood transfusions, and test for drug levels in the blood to show a patient's response to a specific treatment. They also prepare specimens for examination, to count cells, and look for abnormal cells in the blood and other body fluids. Clinical laboratory scientists as they are called from other countries use microscopes, cell counters and other sophisticated laboratory equipment to confirm the findings of the machine. After testing and examining a specimen, laboratory scientists analyze the results and relay them to the attending physicians. In these instances, humans will always be faster, more reliable, or cheaper than technologies in these tasks.

Collaborating with technologies

It should not be humans vs. technologies since technological innovations will always serve to help people (Pohoryles and Tommasi, 2017; Edwards-Schachter, 2018; von Schomberg and Blok, 2019). It doesn't matter if it's AI or robotics, healthcare professionals must accept that these technologies have a massive influence on the way the healthcare system operates, and healthcare professionals must start utilizing their power. Collaboration between technology and humans should be the most suitable response (Thimbleby, 2013; Simoes, 2015; Mitchell and Kan, 2019).

Medical technology is designed to improve the detection, diagnosis, and treatment, and monitoring of diseases. As such, it has linkages with many other disciplines for specific diagnostic or therapeutic purposes. The use of sophisticated technology in medical laboratories isn't a question of replacing but it's a question of complementing. The role of AI in healthcare is to complement and not to replace people by delivering actionable intelligence to human experts (Kaartemo and Helkkula, 2018; Laï, Brian and Mamzer, 2020). AI could pave a way for the creation of a world where human abilities are amplified as technology processes, analyzes, and evaluates the abundance of data in the world today. This allows humans to spend more time engaged in creativity, high-level thinking, and decision-making (Loh, 2018; Reddy, 2018; Ahuja, 2019). The challenge now falls on how laboratories can successfully use sophisticated technologies in ways that enable their human workforce, aiding them to become faster, more efficient, and more productive.

6. Conclusion

Medical Technologists would still continue to be needed by growing as professionals, the more basic and routine tasks of laboratory testing will be delegated to machines and AI, while medical technologists attend to more complex issues that require creativity, high-level thinking, decision-making and tasks that require expert level procedural expertise. Essentially, as sophisticated technologies will not be able to replace medical technology practice, there is no need for medical technologists to feel anxious about the security of their employment. With the challenge of the increasing sophistication of technology, as long as medical technologists are willing to develop professionally and transform into more exceptional versions of the outstanding healthcare providers that they are today, human medical technologists will still prevail in a technologically advanced medical future.

References

Ahuja, A. S. (2019) 'The impact of artificial intelligence in medicine on the future role of the physician', *PeerJ*. PeerJ Inc., 2019(10). doi: 10.7717/peerj.7702.

Aita, A. *et al.* (2017) 'Patient safety and risk management in medical laboratories: theory and practical application', *Journal of Laboratory and Precision Medicine*. AME Publishing Company, 2, pp. 75–75. doi: 10.21037/jlpm.2017.08.14.

Angeletti, S. *et al.* (2015) 'Laboratory Automation and Intra-Laboratory Turnaround Time: Experience at the University Hospital Campus Bio-Medico of Rome', *Journal of Laboratory Automation*. SAGE Publications Inc., 20(6), pp. 652–658. doi: 10.1177/2211068214566458.

Araujo, T. *et al.* (2020) 'In AI we trust? Perceptions about automated decision-making by artificial intelligence', *AI and Society*. Springer, pp. 1–13. doi: 10.1007/s00146-019-00931-w.

Archetti, C. *et al.* (2017) 'Clinical laboratory automation: A case study', *Journal of Public Health Research*. Page Press Publications, 6(1), pp. 31–36. doi: 10.4081/jphr.2017.881.

Armbruster, D. A., Overcash, D. R. and Reyes, J. (2014) 'Clinical Chemistry Laboratory Automation in the 21st Century - Amat Victoria curam (Victory loves careful preparation).', *The Clinical biochemist. Reviews*. The Australian Association of Clinical Biochemists, 35(3), pp. 143–53. Available at: http://www.ncbi.nlm.nih.gov/pubmed/25336760 (Accessed: 29 June 2020).

Bader, V. and Kaiser, S. (2019) 'Algorithmic decision-making? The user interface and its role for human involvement in decisions supported by artificial intelligence', *Organization*. SAGE Publications Ltd, 26(5), pp. 655–672. doi: 10.1177/1350508419855714.

Bajwa, M. (2014) 'Emerging 21st century medical technologies', *Pakistan Journal of Medical Sciences*. Professional Medical Publications, 30(3), p. 649. doi: 10.12669/pjms.303.5211.

Bayot, M. L. and Naidoo, P. (2020) *Clinical Laboratory*, *StatPearls*. Available at: http://www.ncbi.nlm.nih.gov/pubmed/30570979 (Accessed: 29 June 2020).

Bhatt, R. D., Shrestha, C. and Risal, P. (2019) 'Factors Affecting Turnaround Time in the Clinical Laboratory of the Kathmandu University Hospital, Nepal.', *EJIFCC*. International Federation of Clinical Chemistry and Laboratory Medicine, 30(1), pp. 14–24. Available at: http://www.ncbi.nlm.nih.gov/pubmed/30881271 (Accessed: 29 June 2020).

Buch, V. H., Ahmed, I. and Maruthappu, M. (2018) 'Artificial intelligence in medicine: Current trends and future possibilities', *British Journal of General Practice*. Royal College of General Practitioners, pp. 143–144. doi: 10.3399/bjgp18X695213.

Burtis, C. A. (1995) 'Technological trends in clinical laboratory science', *Clinical Biochemistry*. Elsevier, pp. 213–219. doi: 10.1016/0009-9120(94)00075-7.

Carey, R. B. *et al.* (2018) 'Implementing a quality management system in the medical microbiology laboratory', *Clinical Microbiology Reviews*. American Society for Microbiology, 31(3). doi: 10.1128/CMR.00062-17.

Chung, H. J. *et al.* (2018) 'Experimental fusion of different versions of the total laboratory automation system and improvement of laboratory turnaround time', *Journal of Clinical Laboratory Analysis*. John Wiley and Sons Inc., 32(5). doi: 10.1002/jcla.22400.

Cresswell, K., Cunningham-Burley, S. and Sheikh, A. (2018) 'Health care robotics: Qualitative exploration of key challenges and future directions', *Journal of Medical Internet Research*. Journal of Medical Internet Research, 20(7). doi: 10.2196/10410.

Dash, S. *et al.* (2019) 'Big data in healthcare: management, analysis and future prospects', *Journal of Big Data*. SpringerOpen, 6(1), p. 54. doi: 10.1186/s40537-019-0217-0.

Davenport, T. and Kalakota, R. (2019) 'The potential for artificial intelligence in healthcare', *Future Healthcare Journal*. Royal College of Physicians, 6(2), pp. 94–98. doi: 10.7861/futurehosp.6-2-94.

David Hopper, L. (2016) 'Automated Microsampling Technologies and Enhancements in the 3Rs', *ILAR Journal*. Oxford Academic, 57(2), pp. 166–177. doi: 10.1093/ILAR/ILW020.

Dear, K. (2019) 'Artificial Intelligence and Decision-Making', *RUSI Journal*. Routledge, 164(5–6), pp. 18–25. doi: 10.1080/03071847.2019.1693801.

Delahunt, C. B. *et al.* (2015) 'Automated microscopy and machine learning for expert-level malaria field diagnosis', in *Proceedings of the 5th IEEE Global Humanitarian Technology Conference, GHTC 2015*. Institute of Electrical and Electronics Engineers Inc., pp. 393–399. doi: 10.1109/GHTC.2015.7344002.

Dunjko, V. and Briegel, H. J. (2018) 'Machine learning & artificial intelligence in the quantum domain: a review of recent progress', *Reports on Progress in Physics*. IOP Publishing, 81(7), p. 074001. doi: 10.1088/1361-6633/AAB406.

Edwards-Schachter, M. (2018) 'The nature and variety of innovation', *International Journal of Innovation Studies*. Elsevier BV, 2(2), pp. 65–79. doi: 10.1016/j.ijis.2018.08.004.

Ellison, T. L. *et al.* (2018) 'Implementation of total laboratory automation at a tertiary care hospital in Saudi Arabia: Effect on turnaround time and cost efficiency', *Annals of Saudi Medicine*. King Faisal Specialist Hospital and Research Centre, 38(5), pp. 352–357. doi: 10.5144/0256-4947.2018.352.

Groenier, M., Pieters, J. M. and Miedema, H. A. T. (2017) 'Technical Medicine: Designing Medical Technological Solutions for Improved Health Care', *Medical Science Educator*. Springer, 27(4), pp. 621–631. doi: 10.1007/s40670-017-0443-z.

Hong, L. *et al.* (2019) 'Big Data in Health Care: Applications and Challenges', *Data and Information Management*. Walter de Gruyter GmbH, 2(3), pp. 175–197. doi: 10.2478/dim-2018-0014.

Hosogaya, S. (2015) 'Role of Medical Technologists' Training in the Future', *Rinsho byori. The Japanese journal of clinical pathology*, 63(1), pp. 137–140. Available at: http://europepmc.org/article/med/26524891 (Accessed: 29 June 2020).

Jiang, F. *et al.* (2017) 'Artificial intelligence in healthcare: Past, present and future', *Stroke and Vascular Neurology*. BMJ Publishing Group, pp. 230–243. doi: 10.1136/svn-2017-000101.

Kaartemo, V. and Helkkula, A. (2018) 'A Systematic Review of Artificial Intelligence and Robots in Value Co-creation: Current Status and Future Research Avenues', *Journal of Creating Value*. SAGE Publications, 4(2), pp. 211–228. doi: 10.1177/2394964318805625.

Kelly, C. J. *et al.* (2019) 'Key challenges for delivering clinical impact with artificial intelligence', *BMC Medicine*. BioMed Central Ltd., p. 195. doi: 10.1186/s12916-019-1426-2.

Kersting, K. (2018) 'Machine Learning and Artificial Intelligence: Two Fellow Travelers on the Quest for Intelligent Behavior in Machines', *Frontiers in Big Data*. Frontiers Media SA, 1, p. 6. doi: 10.3389/fdata.2018.00006.

Kim, D. W. *et al.* (2019) 'Design characteristics of studies reporting the performance of artificial intelligence algorithms for diagnostic analysis of medical images: Results from recently published papers', *Korean Journal of Radiology*. Korean Radiological Society, 20(3), pp. 405–410. doi: 10.3348/kjr.2019.0025.

Laï, M. C., Brian, M. and Mamzer, M. F. (2020) 'Perceptions of artificial intelligence in healthcare: Findings from a qualitative survey study among actors in France', *Journal of Translational Medicine*. BioMed Central Ltd., 18(1), p. 14. doi: 10.1186/s12967-019-02204-y.

Lee, W.-S. *et al.* (2018) 'Assessing Concordance With Watson for Oncology, a Cognitive Computing Decision Support System for Colon Cancer Treatment in Korea', *JCO Clinical Cancer Informatics*. American Society of Clinical Oncology (ASCO), (2), pp. 1–8. doi: 10.1200/cci.17.00109.

Lippi, G. and Da Rin, G. (2019) 'Advantages and limitations of total laboratory automation: A personal overview', *Clinical Chemistry and Laboratory Medicine*. De Gruyter, pp. 802–811. doi: 10.1515/cclm-2018-1323.

Liu, C. *et al.* (2018) 'Using artificial intelligence (watson for oncology) for treatment recommendations amongst Chinese patients with lung cancer: Feasibility study', *Journal of Medical Internet Research*. Journal of Medical Internet Research, 20(9). doi: 10.2196/11087.

Loh, E. (2018) 'Medicine and the rise of the robots: A qualitative review of recent advances of artificial intelligence in health', *BMJ Leader*. BMJ Publishing Group, pp. 59–63. doi: 10.1136/leader-2018-000071.

McAdam, A. J. (2018) 'Total laboratory automation in clinical microbiology: A micro-comic strip', *Journal of Clinical Microbiology*. American Society for Microbiology. doi: 10.1128/JCM.00176-18.

Mitchell, M. and Kan, L. (2019) 'Digital Technology and the Future of Health Systems', *Health Systems and Reform*. Taylor and Francis Inc., pp. 113–120. doi: 10.1080/23288604.2019.1583040.

Mosadeghrad, A. M. (2014) 'Factors Affecting Medical Service Quality.', *Iranian journal of public health*. Tehran University of Medical Sciences, 43(2), pp. 210–20. Available at: http://www.ncbi.nlm.nih.gov/pubmed/26060745 (Accessed: 29 June 2020).

National Research Council (2011) *Prudent Practices in the Laboratory, Prudent Practices in the Laboratory*. National Academies Press. doi: 10.17226/12654.

Ortiz, G. B. and Hsiang, W. (2018) 'Focus: Medical Technology: Medical Technology', *The Yale Journal of Biology and Medicine*. Yale Journal of Biology and Medicine, 91(3), p. 203. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6153631/ (Accessed: 29 June 2020).

Ozawa, K. *et al.* (1992) 'The expanding role of robotics in the clinical laboratory', *Journal of Automatic Chemistry*, 14(1), pp. 9–15. doi: 10.1155/S1463924692000038.

Palanisamy, V. and Thirunavukarasu, R. (2019) 'Implications of big data analytics in developing healthcare frameworks – A review', *Journal of King Saud University - Computer and Information Sciences*. King Saud bin Abdulaziz University, pp. 415–425. doi: 10.1016/j.jksuci.2017.12.007.

Panteghini, M. (2004) 'The future of laboratory medicine: understanding the new pressures.', *The Clinical biochemist. Reviews*. The Australian Association of Clinical Biochemists, 25(4), pp. 207–15. Available at: http://www.ncbi.nlm.nih.gov/pubmed/18458714 (Accessed: 29 June 2020).

Patel, B. N. *et al.* (2019) 'Human–machine partnership with artificial intelligence for chest radiograph diagnosis', *npj Digital Medicine*. Springer Science and Business Media LLC, 2(1), pp. 1–10. doi: 10.1038/s41746-019-0189-7.

Pohoryles, R. J. and Tommasi, D. (2017) 'Innovation: society, research & technology', *Innovation*. Routledge, pp. 385–387. doi: 10.1080/13511610.2017.1383730.

Rai Dastidar, T. and Ethirajan, R. (2020) 'Whole slide imaging system using deep learning-based automated focusing', *Biomedical Optics Express*. The Optical Society, 11(1), p. 480. doi: 10.1364/boe.379780.

Reddy, S. (2018) 'Use of Artificial Intelligence in Healthcare Delivery', in *eHealth - Making Health Care Smarter*.

InTech. doi: 10.5772/intechopen.74714.
Resources, H. and Administration, S. (2016) *Allied Health Workforce Projections, 2016-2030: Medical and Clinical Laboratory Technologists*. Available at: http://www.ascls.org/advocacy-issues/licensure. (Accessed: 29 June 2020).
Rimac, V. *et al.* (2018) 'Implementation of the Autovalidation Algorithm for Clinical Chemistry Testing in the Laboratory Information System', *Laboratory Medicine*. Oxford Academic, 49(3), pp. 284–291. doi: 10.1093/LABMED/LMX089.
Da Rin, G., Zoppelletto, M. and Lippi, G. (2016) 'Integration of Diagnostic Microbiology in a Model of Total Laboratory Automation', *Laboratory Medicine*. Oxford Academic, 47(1), pp. 73–82. doi: 10.1093/LABMED/LMV007.
Royakkers, L. and van Est, R. (2015) 'A Literature Review on New Robotics: Automation from Love to War', *International Journal of Social Robotics*. Springer Netherlands, 7(5), pp. 549–570. doi: 10.1007/s12369-015-0295-x.
von Schomberg, L. and Blok, V. (2019) 'Technology in the Age of Innovation: Responsible Innovation as a New Subdomain Within the Philosophy of Technology', *Philosophy and Technology*. Springer, pp. 1–15. doi: 10.1007/s13347-019-00386-3.
Shah, P. *et al.* (2019) 'Artificial intelligence and machine learning in clinical development: a translational perspective', *npj Digital Medicine*. Springer Science and Business Media LLC, 2(1), pp. 1–5. doi: 10.1038/s41746-019-0148-3.
Simoes, E. (2015) 'Health information technology advances health care delivery and enhances research', *Missouri medicine*. Missouri State Medical Association, 112(1), pp. 37–40. Available at: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC6170093/ (Accessed: 29 June 2020).
Sutton, R. T. *et al.* (2020) 'An overview of clinical decision support systems: benefits, risks, and strategies for success', *npj Digital Medicine*. Springer Science and Business Media LLC, 3(1), pp. 1–10. doi: 10.1038/s41746-020-0221-y.
Tan, L. and Ong, K. (2002) 'The Impact of Medical Technology on Healthcare Today', *Hong Kong Journal of Emergency Medicine*. SAGE Publications, 9(4), pp. 231–236. doi: 10.1177/102490790200900410.
Thimbleby, H. (2013) 'Technology and the future of healthcare.', *Journal of public health research*. PAGEPress, 2(3), p. e28. doi: 10.4081/jphr.2013.e28.
Tozzoli, R. *et al.* (2015) 'Automation, consolidation, and integration in autoimmune diagnostics', *Autoimmunity Highlights*. Springer-Verlag Italia s.r.l. doi: 10.1007/s13317-015-0067-5.
Vollmer, S. *et al.* (2020) 'Machine learning and artificial intelligence research for patient benefit: 20 critical questions on transparency, replicability, ethics, and effectiveness', *The BMJ*. BMJ Publishing Group, 368. doi: 10.1136/bmj.l6927.
Walton, P. (2018) 'Artificial Intelligence and the Limitations of Information', *Information*. MDPI AG, 9(12), p. 332. doi: 10.3390/info9120332.
Wood, J. (2002) 'The role, duties and responsibilities of technologists in the clinical laboratory', *Clinica Chimica Acta*. Elsevier, 319(2), pp. 127–132. doi: 10.1016/S0009-8981(02)00033-5.
Wu, J. *et al.* (2018) 'Establishing and Evaluating Autoverification Rules with Intelligent Guidelines for Arterial Blood Gas Analysis in a Clinical Laboratory', *SLAS TECHNOLOGY: Translating Life Sciences Innovation*. SAGE Publications Inc., 23(6), pp. 631–640. doi: 10.1177/2472630318775311.
Xing, F. *et al.* (2018) 'Deep Learning in Microscopy Image Analysis: A Survey', *IEEE Transactions on Neural Networks and Learning Systems*. Institute of Electrical and Electronics Engineers Inc., 29(10), pp. 4550–4568. doi: 10.1109/TNNLS.2017.2766168.
Yang, Y. *et al.* (2020) 'The diagnostic accuracy of artificial intelligence in thoracic diseases', *Medicine*. Lippincott Williams and Wilkins, 99(7), p. e19114. doi: 10.1097/MD.0000000000019114.
Yeo, C. P. and Ng, W. Y. (2018) 'Automation and productivity in the clinical laboratory: Experience of a tertiary healthcare facility', *Singapore Medical Journal*. Singapore Medical Association, pp. 597–601. doi: 10.11622/smedj.2018136.
Zima, T. (2017) 'Accreditation of Medical Laboratories-System, Process, Benefits for Labs', *Journal of Medical Biochemistry*. Society of Medical Biochemists of Serbia and Montenegro, 36(3), pp. 231–237. doi: 10.1515/jomb-2017-0025.