Since January 2020 Elsevier has created a COVID-19 resource centre with free information in English and Mandarin on the novel coronavirus COVID-19. The COVID-19 resource centre is hosted on Elsevier Connect, the company's public news and information website.

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Narrative review

Future developments in training

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ABSTRACT

Background: The coronavirus disease 2019 (COVID-19) pandemic has demonstrated the value of highly skilled and extensively trained specialists in clinical microbiology (CM) and infectious diseases (ID). Training curricula in CM and ID must constantly evolve to prepare trainees for future pandemics and to allow trainees to reach their full clinical and academic potential.
Objectives: In this narrative review, we aim to outline necessary future adaptations in CM and ID training curricula and identify current structural barriers in training with the aim of discussing possibilities to address these shortcomings.
Sources: We reviewed literature from PubMed and included selected books and online publications as appropriate. There was no time constraint on the included publications.
Content: Drawing from the lessons learnt during the pandemic, we summarize novel digital technologies relevant to CM and ID trainees and highlight interdisciplinary teamwork and networking skills as important competencies. We centre CM and ID training within the One Health framework and discuss gender inequalities and structural racism as barriers in both CM and ID training and patient care.
Implications: CM and ID trainees should receive training and support developing skills in novel digital technologies, leadership, interdisciplinary teamwork and networking. Equally important is the need for equity of opportunity, with firm commitments to end gender inequality and structural racism in CM and ID. Policy-makers and CM and ID societies should ensure that trainees are better equipped to achieve their professional goals and are better prepared for the challenges awaiting in their fields.
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Introduction

In a world of emerging and rapidly evolving infections, trainees and specialists in clinical microbiology (CM) and infectious diseases (ID) are at the forefront of patient care. As the most recent example, the coronavirus disease 2019 (COVID-19) pandemic has demonstrated two valuable lessons: first, the fundamental value of highly skilled and extensively trained specialists in CM and ID, and second, the necessary ability of these specialists to quickly adopt a 'pandemic mode' guided by continuously evolving scientific evidence. In this 'pandemic mode', CM and ID specialists had to rapidly understand the benefits and drawbacks of different diagnostic tools and develop their clinical and epidemiological skills. Based on the lessons learnt, we believe certain adjustments should be considered in CM and ID training.

Close collaboration with neighbouring disciplines such as infection control, immunology, epidemiology and public health proved essential to ensure optimal patient care during the pandemic. A stronger emphasis on skills in networking, leadership development and interdisciplinary teamwork may prepare trainees for future pandemics. Novel digital technologies in diagnostics, patient care, epidemiological surveillance and contact tracing enabled practical solutions during the pandemic and deserve inclusion in training. Comprehensive knowledge of the interplay between human and animal health (One Health) in the emergence of new zoonotic infectious diseases now seems indispensable for CM and ID specialists to anticipate and assess potential future pandemics. Furthermore, antimicrobial stewardship was largely neglected during the pandemic, resulting in a renewed need to reactivate this knowledge in CM and ID training. Pre-pandemic imbalances in women's access to and representation in research activities and funding aggravated during the COVID-19 pandemic [1]. Lastly, disproportionately high mortality and morbidity rates due to COVID-19 were incurred in socio-economically disadvantaged populations and ethnic minorities. This has poignantly demonstrated the need for CM and ID specialists to pay special attention to inequities within the medical system.

All of these topics do not yet rank high on CM and ID training agendas, but training curricula must remain versatile so that trainees retain the necessary skills to face future pandemics.

Novel digital technologies

During the last two decades, access to digital devices and the internet has become practically ubiquitous, facilitating the development of novel digital technologies. Numerous digital innovations successfully address different health-care and patient needs, enabling health care to become more accessible, convenient and cost-effective [2,3] (Table 1).

Major advances were made in the rapid development and implementation of novel models of care such as telemedicine [4]. During the COVID-19 pandemic, telemonitoring of patients with COVID-19 from home has helped to care for these patients. ID trainees should be methodically taught how to maintain the patient–doctor relationship in the absence of in-person contact, thereby overcoming any lingering concerns about telemedicine (e.g. security issues, lack of in-person contact, technology limitations) [5].

Novel digital technologies also accelerated the efficiency of epidemiological surveillance. Artificial intelligence has successfully been used to predict future outbreaks, identify disease clusters and conduct contact tracing (Table 1). The post-pandemic future of public health is likely to become increasingly digital [6] and efforts should be made so that CM and ID training will not lag behind these rapid advancements in technology.

Table 1
Examples of emerging digital technologies and their applications in clinical microbiology and infectious diseases

Applications	Description	Examples of emerging technologies	References
Telemedicine	Provision of long-distance health care, including diagnosing, treating, and monitoring of patients using digital devices	• Remote patient monitoring (e.g. using Internet of Things [IoT] -assisted blockchain systems) • Tele-rehabilitation • Electronic consultations (e-Consults) • Electronic visits (E-visits) • Mobile health (mHealth)	[2,3,12,13]
	Telemedicine programmes for triage, monitoring and patient communication within a hospital setting	• Robotics • Wearable devices and mobile sensors • Tablets	
Epidemiological surveillance	Monitoring, surveillance, detection and prevention of communicable diseases (e.g. COVID-19 epidemic and Ebola outbreak)	• IoT in combination with next-generation telecommunication networks (e.g. 5G) • Big-data analytics • Artificial intelligence (AI), based on deep learning and machine learning algorithms • Blockchain technology • Social media platforms (e.g. Twitter) • Internet search engines (e.g. Google Trends) • Digital contact-tracing apps (e.g. Quick response-based screening) • Geographic information systems (GIS) and global positioning system (GPS)	[3,13–16]
Diagnostics	Diagnostic algorithms based on imaging and clinical data	• AI, supported by blockchain technology/deep learning (e.g. for CT scan differentiation between COVID-19 and other clinical entities)	[3,8,9,16–19]
	High-throughput diagnostics with automation and digitalization	• Total laboratory automation • Digital microscopy/digital image analysis • Lab-on-a-drone • AI, deep learning • Smartphone-based point-of-care tests	

In recent years, artificial-intelligence-based algorithms were found to be on a par with or even more accurate than human experts in diagnosing diseases and drug discovery [7–9]. For example, machine-learning-based image analysis could potentially replace agar plate inspection and even classical microscopy, radically changing the workflow in microbiological laboratories and the basics of microbiology training itself [10]. Using big data from electronic health records, artificial-intelligence-based algorithms can predict clinical events and improve clinical decision-making processes. Two recent reviews [8,9] identified 97 and 60 machine-learning systems aiming to assist CM and ID specialists, respectively. Consequently, trainees will inevitably have to become acquainted with the concepts of bioinformatics and data handling, and anticipate the advances in digitalization and automation [11]. With novel technology becoming increasingly important in CM and ID, adapting our curricula to incorporate these emerging technologies and advancements is necessary.

Trainee networks and networking

During the COVID-19 pandemic, trainee networks served as a support system for CM and ID trainees who were faced with disrupted teaching and training, and increased workloads (Bouiller et al., 2021, unpublished). Networking is commonly overlooked as an extracurricular activity, but is important regardless of the chosen career path in CM and ID. It is defined as 'the process of interacting with peers, experts and faculty members to exchange information and develop professional and social contacts' [61]. Trainee networks may initiate research collaborations and information exchange, and can facilitate access to experts in other centres, ultimately improving patient care.

In several European countries, trainees have undertaken initiatives to build national trainee networks in CM and/or ID. This has led to webinars, workshops, mentee-programmes, educational exchange and platforms to connect across the country in informal settings. These networks can be used to promote trainee-mobility, and help trainees to diversify and complement the training they receive [61]. For example, the French CM trainee network (ReJMiC) created an open-access archive with information on every clinical mycology and parasitology internship in France. Trainee networks also collaborate actively with other specialties: the French ID trainee network (RéJIF) has participated in political lobbying with trainee networks of other specialties to improve compliance with restriction of clinical hours in order to protect dedicated training time [20]. The German CM trainee network (jDGHM) co-organizes an interdisciplinary symposium to foster exchange among CM, ID, infection control, tropical medicine and veterinary medicine. Previous networking and strong partnerships among CM, ID, public health, infection control and epidemiology have been essential to tackle the COVID-19 pandemic and will remain important in the future.

Networking is also important at the European and international levels. The Trainee Association of ESCMID (TAE) conducted a survey exposing highly heterogeneous training conditions in Europe and suggested areas for improvement [21]. TAE also shed light on personal life and working conditions [22], supervision of trainees [23] and mentorship practices [24] in Europe. Such initiatives are necessary to pinpoint challenges in training, to promote harmonized training curricula and advocate for improved CM and ID training conditions as well as to serve as a communication bridge between senior and early-career scientists. Additionally, fruitful partnerships from such networks can arise, as illustrated by the recent collaboration between TAE and the young leader circle of the American Society for Microbiology [25].

Networking skills do not come naturally to everyone. Therefore, possibilities to network need to be facilitated in CM and ID training and should be supported by national and international scientific societies.

Leadership skills, professional development and interdisciplinary teamwork

High standards of training, research, and clinical practice are constituent parts of effective leadership [26–28]. A leader in CM and ID needs to emphasize teamwork across different disciplines and professions, balance autonomy and liability, and direct all actions at improving patient outcomes [27–29]. Efficient time management, emotional intelligence, excellent communicational and interpersonal skills, strategic assertiveness and constructive conflict management are further examples of necessary skills [30]. Overall, leadership is about creating a shared vision, inspiring other team members to identify with the common goal, and empowering less-experienced team members [28]. During the COVID-19 pandemic, leadership in CM and ID also entails managing infection control teams and pandemic management in general. Of course, the aforementioned skills are not easily acquired. Fortunately, there are many useful courses [31]. Through hands-on exercises and dynamic discussions, trainees may learn about leadership best practices. Indeed, a capacity-building workshop specifically designed for future leaders in CM and ID had been planned by TAE in 2020 but, unfortunately, had to be postponed because of the COVID-19 pandemic.

Currently, leadership skills, professional development and interdisciplinary teamwork are insufficiently implemented in CM and ID training [28,32]. Scientific societies and medical institutions should contribute to empower trainees in these competencies.

One Health and antimicrobial resistance

Severe acute respiratory syndrome coronavirus 2 (SARS-CoV-2) is the latest in a series of recent emerging zoonotic diseases, several of which have involved viruses with origins in bat populations, including SARS-CoV-1, Nipah virus and Ebola virus. All previous pandemics have originated in animals, usually wildlife, and have emerged due to complex and interconnected environmental and socio-economic factors: agricultural expansion, deforestation, wildlife trade, meat consumption and the climate emergency. These complex interconnections of humans, animals and the wider environment are described in the One Health concept. It takes into account that the spread of infectious diseases and antimicrobial resistance are a result of these complex interconnections [33,34].

Any action that brings humans, livestock and wildlife into closer contact increases the chance for animal pathogens to find new animal and human hosts. Animals kept in close, crowded conditions, such as in factory farming, may provide perfect conditions for viruses to spread and mutate. The emergence of a novel SARS-CoV-2 variant in mink farms is a recent example of concern [35].

Rising antimicrobial resistance is also of increasing concern [36,37]. Despite warnings early in the pandemic [38], patients with COVID-19 continued to receive broad-spectrum antimicrobials regardless of the implications on antimicrobial resistance. This comes at an inopportune time, as increased travel and global trade have already broadened the reach of multidrug-resistant bacteria, fungi and parasites [39–42]. It is well known that resistance genes emerge as a result of selection pressure exerted by antimicrobials during treatment. What is less well known is that the extensive use of antibiotics for growth promotion in livestock and of antifungals for crop preservation has been implicated in the spread of multidrug-resistant pathogens. CM and ID trainees

must understand the complex interplay between these factors in order to better inform policy on these issues and to improve antimicrobial prescribing. To anticipate and prevent future pandemics, knowledge on biodiversity loss, mechanisms of pandemic emergence and antimicrobial stewardship is essential for trainees in CM and ID.

Basics of the One Health concept can be obtained through the One Health European Joint Programme website [43]. The ESCMID Study Group for Antimicrobial Stewardship conducted several One Health themed sessions at ECCMID 2021, indicating the growing importance of this topic in clinical practice. Furthermore, the ESCMID study group for Antimicrobial Prescribing (ESGAP) frequently offers postgraduate educational courses on antimicrobial stewardship. However, there is a need to formally integrate these concepts as a core component of regular CM and ID curricula. This could be achieved, for example, by implementing interprofessional case-based training together with veterinarians [44].

Inequalities and discrimination based on gender, economic status and ethnicity/race

The COVID-19 pandemic has disproportionately affected socioeconomically disadvantaged groups and ethnic minorities. As doctors we must ask ourselves how discrimination in medicine impacts not only our patients, but also our colleagues. What can CM and ID doctors, and their training bodies, do to build a more inclusive world?

Discrimination is a very real problem for CM and ID doctors. In 2011, the parity commission of ESCMID found that 68% of ID and CM specialists in Europe reported that they believed there was discrimination in the medical sciences, with 26% of survey respondents reporting first-hand experience of discrimination [45]. Specifically, gender-based discrimination was the most commonly reported (29.8% of female and 6.2% of male respondents), followed by discrimination based on ethnicity (4.2%), nationality (8.0%), religion (3.7%) and sexual orientation (3.2%) [45].

Gender-based discrimination persists in academic publishing where women are under-represented in authorship, peer-reviewing and editorial positions [46]. Women are also under-represented as researchers and senior clinicians, especially in ID [47]. These disparities have increased during the COVID-19 pandemic [1]. Reasons for this gender gap may include structural shortcomings in the academic setting, such as unequal opportunities for women to progress in their careers, and unequal access to funding, grants and leadership positions [1,48]. Especially during early career stages, pregnancy and lack of child care may translate into prolonged career disadvantages, such as time constraints to publish and conduct research or difficulties in attending scientific conferences [49]. Nearly twice as many female CM and ID specialists as male report not being able to have children because of work commitments [45].

Additionally, discrimination based on ethnicity and race poses a significant problem to CM and ID as well. BIPoC (Black, Indigenous, Persons of Colour) trainees are faced with structural racism and racist attitudes in various learning environments, which comprise their learning outcomes [50]. Structural racism is 'not simply the result of private prejudices held by individuals, but is also produced and reproduced by laws, rules and practices, sanctioned and even implemented by various levels of government, and embedded in the economic system as well as in cultural and societal norms' [51].

Most importantly, structural racism and disparities between ethnic minorities impact patient care. The use of 'racial' correction in risk calculation for heart disease and chronic kidney disease has been successfully challenged [52]. However, has CM and ID faced up to its own blind spots? Does our training reflect the needs of the patient populations that we serve? Infectious diseases, including COVID-19, disproportionately affect ethnic minorities and economically disadvantaged populations [53–55]. Medical training often overlooks the basics of care for marginalized populations; ask yourself how often have you seen common rashes taught on non-white skin [56]? Equally, how often have you prescribed treatments of infections in pregnant women despite their exclusion from most clinical trials? This failure to reflect our populations' demographics harms those that are most vulnerable.

Unfortunately, discriminatory environments are present in medical institutions across Europe and even among national CM and ID societies. Microaggressions perpetuate discriminatory attitudes, which permeate workplaces and create a toxic, hostile environment for marginalized groups, be they patients, students or co-workers [57]. A more inclusive environment must be fostered at all levels of training and in patient care. Trainees need to challenge structural racism and gender-based discrimination within academic institutions and medical services to avoid perpetuating harmful stereotypes. Importantly, they need their immediate superiors, and also national CM and ID societies, to lead by good example.

Implications

COVID-19 may feel never ending, but it will not be the last pandemic. The training repercussions and shortcomings revealed by this pandemic cannot be addressed by interventions aimed solely at the individual training level. Hence, in the future, national and international CM and ID training should not only include updated formal curriculum content on antimicrobial resistance, One Health and novel digital technologies, but also practical learning opportunities for trainees to gain experience in networking, leadership development and interdisciplinary teamwork. This is best achieved through interdisciplinary and interprofessional education [58]. As an example, training institutions and CM and ID societies could actively promote interdisciplinary and case-based educational courses and workshops incorporating bioinformatics, bioengineering and veterinary medicine. Collaboration with pharmacists would be indispensable for interdisciplinary training in antimicrobial stewardship [58]. As a further example, ESCMID's TAE Steering Committee established an online forum for discussions and exchange to mitigate the lack of in-person networking. Similar online initiatives for supervision and mentorship of trainees may prove helpful even after the pandemic.

CM and ID curricula must also be updated to mitigate discrimination and inequities, which are still highly prevalent in medical training [46,59]. ESCMID, along with other CM and ID societies, has established consensus guidelines to prevent exclusion of women from early-career awards [60]. Similar regulations for equal representation of speakers at scientific conferences and as authors in journals are needed to enable trainees to achieve their full academic potential [46]. Discrimination and inequities in CM and ID patient care need analogous attention, possibly also with initiatives by CM and ID societies to laud best practices and raise awareness among members.

This COVID-19 crisis gives us the opportunity for improvement of patient care and training by creating a forward-thinking generation of CM and ID trainees, equipped to face new pandemic challenges.

Transparency declaration

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Author contributions

KL, NP and AB contributed to conceptualization; KL, NP, SD, PV, AS, VS and AB contributed to the investigation and to writing the original draft; and KL, NP, SD, PV, AS, IAA, MJL, VS and AB contributed to reviewing and editing. All authors have read and approved the submitted manuscript.

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