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REVIEW

Standardization through education of molecular pathology: a spotlight on the European Masters in Molecular Pathology

Marius Ilié[1] · Vivien Lake[2] · Enrique de Alava[3,4] · Serena Bonin[5] · Sandra Chlebowski[2] · Aurélie Delort[2] · Elisabeth Dequeker[6] · Raed Al-Dieri[7] · Arjan Diepstra[8] · Olli Carpén[9] · Catarina Eloy[10] · Ambrogio Fassina[11] · Falko Fend[12] · Pedro L. Fernandez[13] · Gregor Gorkiewicz[14] · Simon Heeke[15] · Rui Henrique[16] · Gerald Hoefler[14] · Pablo Huertas[17,18] · Michael Hummel[19] · Karl Kashofer[14] · Jeroen van der Laak[20] · Rocio Martinez de Pablos[17,18] · Fernando Schmitt[21,22] · Ed Schuuring[8] · Giorgio Stanta[6,23] · Wim Timens[8] · Benedikt Westphalen[24,25] · Paul Hofman[1]

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Abstract

Despite advancements in precision medicine, many cancer patients globally, particularly those in resource-constrained environments, face significant challenges in accessing high-quality molecular testing and targeted therapies. The considerable heterogeneity in molecular testing highlights the urgent need to harmonize practices across Europe and beyond, establishing a more standardized and consistent approach in MP laboratories. Professionals, especially molecular pathologists, must move beyond traditional education to cope with this heterogeneity. This perspective addresses critical issues in molecular pathology (MP), such as limited access to high-quality molecular testing, leading to disparities in cancer treatment, and the consequences of inconsistent practices. Recognizing the necessity for a standardized framework for education to address these issues, educational programs play a pivotal role in updating professionals' skills to achieve standardization in MP. European experts from the Steering Committee, the Pathology Section of the European Union of Medical Specialists, and the European Society of Pathology have proposed creating a comprehensive Master's degree program called the "European Masters in Molecular Pathology" (EMMP). This program emerges as a strategic response to the demand for a specialized and standardized framework for education in MP, catering to professionals who concurrently work and study. The program's design aligns with evidence-based education methods, ensuring effective learning and engagement while integrating computational pathology to analyze complex molecular data, enhance diagnostic accuracy, and improve treatment outcomes. EMMP's structured curriculum, strategic partnerships, and regular updates underscore its significance in standardizing MP practices. Exploring future developments, this perspective delves into technology integration and interdisciplinary collaboration, anticipating ongoing advances and harmonization. Challenges and future directions in MP education are discussed, emphasizing the necessity for dynamic curriculum updates, seamless technology integration, and interdisciplinary cooperation. This perspective underscores EMMP's pivotal role in preparing pathologists for this dynamic field, advocating continuous advancements in education and training to uphold excellence in MP practices and maintain the highest patient care standards.

Keywords Molecular pathology · Standardization · Education · Masters · Europe

Overview and challenges of molecular pathology

Substantial progress has been achieved in cancer treatment, particularly in addressing specific molecular vulnerabilities across diverse cancer types [1]. Integrating complex "omics" profiles with clinical data represents a key advancement, essential for developing strategies for cancer prevention, early detection, diagnosis, and treatment [2].

However, many cancer patients, especially in resource-limited settings, struggle to access molecular testing and targeted therapies. Barriers such as regulatory, financial, logistical, educational, and clinical issues contribute to this gap, exacerbating health disparities and limiting access to innovative preventive measures, therapies, and clinical trials [3, 4].

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Furthermore, challenges extend beyond testing limitations to include a shortage in therapeutic development due to insufficient data on treatment responses, toxicity, and resistance mechanisms [5]. Addressing these dual challenges requires a comprehensive approach to ensure that the benefits of advanced cancer treatments are accessible worldwide. This approach must address both scientific and systemic barriers to promote global access to effective cancer care [6].

The increasing complexity of molecular data highlights the need for robust data management, analysis, and interpretation. Integrating bioinformatics into routine practice is essential, but it demands specialized training, expertise, and collaboration with bioinformaticians [7]. Moreover, variability in testing capabilities and laboratory practices can lead to inconsistent results, making it crucial to standardize protocols and establish accreditation standards to ensure reliable outcomes.

Adopting artificial intelligence (AI) and other advanced technologies in healthcare raises ethical concerns related to model biais, lack of explainability (the "black box"), patient privacy, data security, and responsible implementation. Compliance with regulatory frameworks is essential to address these concerns and maintain patient trust and confidentiality.

Incorporating emerging technologies or new tools like liquid biopsies, single-cell sequencing, and broad next-generation sequencing (NGS) into routine clinical practice presents technical and logistical challenges. Validating the accuracy, reliability, and reproducibility of these methods is crucial for successful implementation in patient care, since no novel technique is entirely free from false negative and false positive results [8, 9].

In the field of precision medicine, molecular pathology (MP) encourages pathologists to extend their expertise beyond traditional pathology education. In pathology, "traditional" education may involve classroom-based learning, laboratory sessions, and clinical rotations focused on acquiring fundamental concepts, techniques, and diagnostic skills. It often emphasizes theoretical understanding and hands-on practice within established protocols and methodologies. The evolution of traditional learning methods in professional education can incorporate various innovative approaches to enhance effectiveness and engagement, such as blended learning, interactive simulations, gamification, virtual reality, augmented reality, and collaborative learning platforms.

While the morphologic scrutiny of tissues and cytological samples remains integral, the rapid advent of molecular, imaging, and computational technologies demands a more comprehensive understanding of the genetic and molecular underpinnings of diseases. Diagnostic pathology encompasses several levels: macroscopic examination, histologic and cytologic analysis, complemented with computational analysis, and the latest addition, molecular evaluation. While the first two levels benefit from shared knowledge and international standardization, the molecular level lags behind due to lack of standardization and the rapid evolution of technology, despite regular updates of international guidelines [10, 11].

Advancements in genomics, epigenomics, transcriptomics, proteomics, and bioinformatics, alongside the emergence of personalized medicine and the integration of artificial intelligence in healthcare, mandate an advance beyond conventional education [8].

The shortage of pathologists and the increasing complexity of specialized testing further underscores the need for comprehensive training and access to specialized reference laboratories [12]. Access to specialized reference laboratories has become pivotal in this evolving landscape, presenting a challenge for trainees who lack direct access to such facilities and expertise. This lack of access poses a significant obstacle, hindering the acquisition of essential competencies crucial for aspiring pathologists to thrive in their professional roles. Addressing these challenges is essential to ensure a well-prepared and adept group of pathologists capable of navigating the intricacies of modern diagnostics and molecular practices.

Effective interdisciplinary collaboration is vital for translating molecular findings into actionable clinical insights. Breaking down silos and opening up access to data for pathologists, clinicians, molecular biologists, clinical scientists, bioinformaticians, researchers, and industry stakeholders fosters collaborative partnerships that drive innovation and improve patient outcomes [12, 13].

Limited access to specialized equipment, reference laboratories, and expertise leads to significant barriers to adopting advanced molecular testing methods, particularly in resource-constrained settings. Addressing these constraints through capacity-building initiatives and strategic partnerships is essential to promote equitable access to molecular diagnostics and therapies.

Finally, disparities in access to molecular testing and targeted therapies based on geographical location, socioeconomic status, and/or healthcare infrastructure contribute to significant inequalities in patient care. Efforts to bridge these gaps through policy interventions, stakeholder efforts, community outreach, and innovative healthcare delivery models are essential for promoting health equity and improving patient outcomes globally [14].

The need for standardized education framework in molecular pathology

Over the past 10 years, there has been a proliferation of MP training initiatives, all geared towards enhancing the proficiency in genomics and preparedness of both current

and future healthcare providers. The educational strategies employed in these initiatives are multifaceted, spanning immersive and experiential learning programs, opportunities for interdisciplinary and inter-professional education, and the creation of several national Master's programs, short courses and workshops, continuing professional development programs, and use of electronic or web-based resources [15]. Due to the wide-ranging differences in content, delivery methods, and target audiences across these programs, it is evident that a robust, standardized, and fundamental structure is essential for effective MP education. Such a structured foundation facilitates immediate learning and serves as a springboard for continuous, lifelong learning throughout one's career in the medical field [16, 17].

In parallel, disparities in molecular testing rates are evident across European nations. Austria, Belgium, Denmark, Finland, France, Germany, Ireland, Italy, Portugal, the Netherlands, Norway, Sweden, Spain, and the UK particularly stand out for their high adoption of Next-Generation Sequencing (NGS)-based testing. Intriguingly, these countries also rank highly in terms of access to, and reimbursement for precision medicine [3, 9]. In contrast, Southern and Eastern European countries face significant challenges, exhibiting notably lower access to both testing and the corresponding targeted therapies. This discrepancy is often linked to an underdeveloped diagnostic laboratory infrastructure in these regions, especially in the public sector, and the lack of availability of drugs depending on the country, contributing to suboptimal performance in these crucial healthcare measures [3, 9] (Fig. 1).

In addition, as an example, recent findings underscore the considerable heterogeneity in molecular testing practices within both thoracic pathology and MP laboratories across Europe. Notably, even among facilities recognized for their expertise, considerable variations persist in testing capabilities, turnaround time, reflex testing procedures, and laboratory accreditation. This emphasizes the urgent need to harmonize decision-making algorithms throughout Europe to establish a more standardized and consistent approach [5].

Inconsistent practices in MP can result in dangerous consequences, including misdiagnosis or delayed diagnosis, suboptimal treatment outcomes, or ineffective therapies [18]. Moreover, inconsistent practices may affect research efforts, hindering collaboration and potentially slowing down advancements in the field. The consequences extend to resource utilization, with increased healthcare costs and potential legal and ethical implications, including litigation risks and ethical concerns. Inconsistent practices may also undermine trust in healthcare, affecting patient confidence and public perception. Addressing these issues requires standardized practices, enhanced quality control, and ongoing education and collaboration within the field of MP to optimize patient care and outcomes [4].

Education plays a crucial role in enhancing MP professionals' skills. A standardized educational framework ensures uniform expertise and knowledge, leading to improved diagnostic accuracy and consistency. This framework helps reduce variability in testing capabilities, turnaround times, reflex testing practices, and multidisciplinary decision-making, ultimately resulting in more reliable results. Standardized education also equips professionals with the latest technologies and decision-making algorithms, fostering field harmonization and enhancing patient care by minimizing misdiagnosis and optimizing treatment

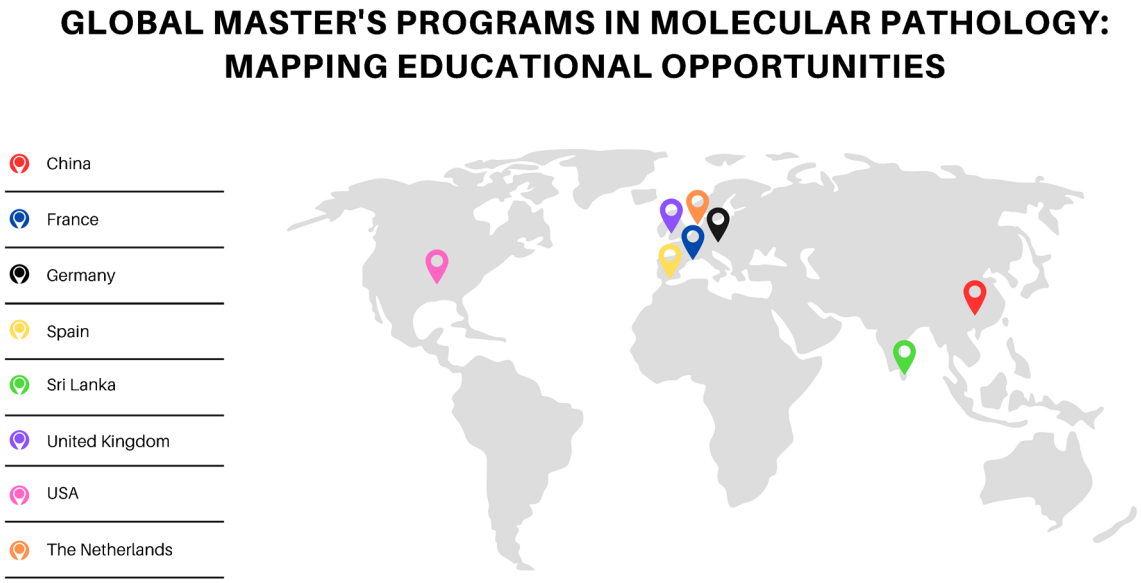

Fig. 1 Global Master's Programs in Molecular Pathology: Mapping Educational Opportunities. *Countries are listed by alphabetical order*

outcomes. Overall, a standardized educational approach enhances the quality of MP practices, ensuring higher standards of care and accuracy in diagnoses and treatment decisions. It is crucial to interpret molecular findings within the relevant clinical context to ensure accurate and meaningful diagnoses.

European Masters in Molecular Pathology (EMMP)

Considering the above statements, the Pathology Section of the European Union of Medical Specialists (EUMS, https://uems.eu/) discussed, approved, and proposed to the European Society of Pathology (ESP) and to several European experts (Steering Committee), to open a comprehensive Master's degree at the University Côte d'Azur, Nice, France, entitled the "European Masters in Molecular Pathology" (MSc EMMP) (https://univ-cotedazur.eu/msc/european-msc-molecular-pathology). Together they have recognized the pressing need to standardize molecular analyses to ensure patient safety, result reproducibility, and seamless collaboration among European health institutions (Fig. 2).

The Steering Committee's choice materialized in the creation of a 2-year Master's degree, centrally organized at the University Côte d'Azur in Nice, France, and enriched by partnerships with European Universities: Barcelona, Berlin, Graz, Groningen, Helsinki, Leuven, Munich, Porto, Radboud, Nijmegen, Seville, Trieste, and Tübingen. Notably, the initiative has forged vital alliances with key partners and stakeholders such as ESP, the European Society of Medical Oncology (ESMO), the European Liquid Biopsy Society (ELBS), Bigpicture, the Organisation of European Cancer Institutes (OECI), IHU RespirERA, and Ulysseus University. The curriculum aims to cultivate specialized theoretical and practical proficiencies encompassing the full spectrum of methodologies and technologies within molecular diagnosis for routine clinical practice, innovation, and research.

The availability of education in MP for pathology residents varies largely worldwide. European countries such as France, Germany, the Netherlands, Spain, Sweden, Switzerland, and the UK are known to provide education in MP for pathology residents (Fig. 1, Supplementary Table 1). EMMP stands out for its comprehensive 2-year curriculum, combining in-depth theoretical knowledge with practical experience through blended learning. Unlike programs such as the University of Tübingen's and Charité Berlin's MSc in Molecular Medicine, which focus broadly on various medical disciplines, EMMP is specifically tailored for pathologists and emphasizes molecular pathology with direct clinical applications. Its structure includes both online and onsite components, providing flexibility similar to the University of Manchester's programs but with additional internships that offer hands-on experience. This contrasts with fully online

Fig. 2 Governance of the European Master in Molecular Pathology and the main missions of the Steering Committee

courses like the Molecular Oncology Master, which may lack practical training. Additionally, compared to shorter 1-year programs like those at Texas Tech and Manchester, EMMP offers a more extensive timeframe to explore the rapidly evolving field, ensuring graduates are well-prepared for professional development. Its target audience of pathologists at graduate and post-graduate levels, along with a competitive fee structure and scholarship opportunities, make it particularly appealing for those seeking advanced specialization in molecular pathology within a European context.

Program overview

The primary focus of the program is to train a new generation of molecular pathologists, equipping them with the knowledge and skills needed to advance the practice of MP at both the European and international levels.

Specifically designed for residents in pathology (graduate level) or practicing pathologists (post-graduate level), with a background in histopathology (Table 1), this tailored program ensures that participants receive specialized education to contribute to the field and disseminate high-quality MP practices on a broader scale. Given the rapidly evolving landscape of molecular pathology and precision medicine, the program prepares participants for continuing professional development after graduation, supporting the increasing demand for diagnostic, prognostic, and predictive biomarkers that are essential for informed treatment decisions.

The program enhances participants' ability to understand and interpret complex results from diagnostic and clinical research molecular analyses, contributing to the standardization of practices and ensuring proficiency in evaluating intricate data. Additionally, it offers objective verification of knowledge and competencies, providing a standardized and harmonized framework for young pathologists within the European Union. This verification process facilitates the mobility of professionals and significantly contributes to the harmonization of both clinical and molecular pathology practices.

EMMP is designed to be recognized internationally, particularly because of its support from the UEMS and the ESP. These endorsements ensure that the degree meets rigorous standards in MP education and training, which is likely to enhance its global recognition.

As demand for MP grows, this degree equips graduates to access emerging roles that increasingly require specialized expertise. The comprehensive curriculum, which includes both theoretical and practical training, ensures that graduates are equipped with the necessary skills and knowledge to fill advanced positions. This includes roles that may specifically require a background in MP, such as diagnostic laboratories, research institutions, pharmaceutical companies, and healthcare settings focusing on precision medicine.

Furthermore, the EMMP's focus on harmonization and standardization MP practices across Europe prepares graduates to work in diverse healthcare environments, enhancing their mobility and employability globally. In the future, we anticipate that employers will increasingly recognize and seek out this qualification for advanced pathology roles, providing graduates with a competitive edge in the job market and the potential to pioneer new positions that necessitate expertise in MP.

Program structure and curriculum design

The EMMP is a 2-year program with a modular structure of six modules each year (Table 1). In the first year, the educational goals include fostering an in-depth comprehension of the genetic and molecular underpinnings of diseases, covering conditions like cancer and infectious diseases. The aim is for participants to acquire proficiency in a diverse range of molecular diagnostic methodologies, encompassing sample procurement, processing, and analysis, with a focus on diagnosis and treatment tracking.

Additionally, the first year seeks to cultivate awareness of the pivotal role pre-analytical steps play in MP. This involves understanding sample collection, handling, and processing, along with recognizing how pre-analytical variables influence the precision and dependability of molecular assessments. Participants are supported to attain expertise in comprehending, analyzing, interpreting, and reporting genomic data to facilitate disease diagnosis, prognosis, and the formulation of personalized therapeutic strategies having a prominent role in molecular tumor boards.

The second year aims to develop expertise in immunopathology, exploring the interplay between the immune system and disease evolution, along with the integration of immunological methods into MP. Further to this, the participants garner proficiency in various aspects of quality assurance within MP, encompassing comprehension of quality control principles, quality assessment methods, and accreditation procedures. Digital pathology is explored in depth, utilizing digital images for diagnostic, investigational, and educational purposes. Added to this expertise in the potential applications of artificial intelligence (AI) within MP is another goal, encompassing the implementation of machine learning algorithms for diagnostic, prognostic, and treatment decision-making functions. Participants are expected to cultivate the skill to critically appraise and verify AI algorithms for practical clinical deployment, along with a nuanced comprehension of the ethical and legal considerations surrounding AI usage in MP.

The program also aims to foster an understanding of the latest technological advancements within MP. This includes the use of liquid biopsies, single-cell sequencing, and NGS technologies for diagnostic and treatment monitoring

Table 1 Curriculum overview of the European Masters in Molecular Pathology (academic years 2023–2025)

Modules	Module overview	Module goal
World of DNA 6 ECTS Online and onsite	Genetics mechanisms are essential for normal development and maintenance of tissue physiology. Disruption of genetic regulation is at the root of many pathologies. The module will cover the basics of DNA metabolism, which is key for a molecular pathologist's understanding of disease	An introduction to the concept of genome, epigenome, and its evolution in disease
World of RNA 3 ECTS Online and onsite	The RNA molecule is the link between the genome and the proteome Changes in its expression are in the base of many diseases Through several clinical examples, the students will get familiar with the RNA world and its impact on disease	An introduction to the concept of transcriptome and its evolution in disease
World of Proteins 3 ECTS Online and onsite	Proteins are the effectors of the genomic information. Their biology is going to determine the physiological or pathological status of the tissues and the organisms During this module, students will understand how proteins modulate health and disease	An introduction to the concept of proteome and its dynamics and evolution in disease
Pre-analytical and analytical methodology 6 ECTS Online and onsite	The main purpose of this module is to allow students to appreciate the importance of pre analytical procedures and to develop an understanding of sample characteristics and the quality parameters required for valid results. Furthermore, this module provides an overview of current methods used and their pre-analytical requirements and will compare the different methods that are used in molecular pathology. Students will translate clinical questions into molecular markers to be analyzed as well as selecting appropriate methods for biomarker analysis. Ultimately, the module aims to enable harmonization of molecular testing in a European setting	This module focuses on standardizing pre-analytical and analytical methodologies, delving into the fundamental principles of essential methods employed in molecular pathology concerning the samples used for molecular diagnostics
Infectious diseases 3 ECTS Online and onsite	This module is designed as a practical approach to molecular infectious disease (ID) pathology starting with case identification, pre-analytical considerations as well as analytical and post-analytical steps needed to diagnose an infectious disease based on a pathology specimen In general, the module is designed as a hands-on in the lab course but touches also computational methods, legal aspects, and quality assurance measures important in ID pathology	The overall aim is to be proficient in the selection and performance of molecular tests to achieve a correct diagnosis in infectious disease pathology
Applied molecular pathology in oncology 6 ECTS Online and onsite	This module provides a comprehensive and detailed understanding of molecular pathology in the context of neoplastic diseases. The focus will be on the role of molecular testing for tumor classification, prognostication, and therapeutic prediction Application of molecular pathology to routine as well as emerging clinical diagnostic practice for common types of cancer will be addressed. A certified molecular pathologist can recommend the appropriate molecular (or non-molecular) markers and can evaluate, interpret, and report molecular diagnostic cases following international and local guidelines, and will be able to use a common language on molecular pathology	To integrate molecular diagnostics with histopathology, pathogenesis and clinical characteristics to provide tumor classification, means of prognostication and enable personalized medicine in a clinical setting

Table 1 (continued)

Modules	Module overview	Module goal
Immunopathology 3 ECTS Online and onsite	For choosing the best, personalized, treatment options for cancer, the molecular pathologist is key to integrate the histopathological diagnosis, the outcome of molecular analysis, and the diagnostic information needed for eligibility for immunotherapy. This module will, after refreshing the basics of immunology, start with building knowledge on the role of tumor immunity and tumor-based immune inhibition in the natural course of cancer This module will then lead the molecular pathologist to understand possibilities and effects of therapeutic intervention in tumor immunity and give the opportunity, by building blocks and hands-on experience, to master and improve skills in diagnostics related to eligibility for those interventions and to their (systemic) side effects	Obtaining adequate knowledge about interactions of the immune system within immune-related diseases, tumor-immune system interactions, about interventions that maximize tumor attack by immune cells and about related pathology diagnostics, including side effects of the interactions
Digital pathology, bioinformatics, and A.I 3 ECTS Online	Digital pathology, bioinformatics, and artificial intelligence transform (A.I.) the practice of pathology worldwide. A.I. has been described as the fourth pathology revolution, clearly underlining the large expectations of this innovative technology. This module will focus on the backgrounds of tissue section digitization, digital workflows, and the opportunities to apply artificial intelligence techniques to aid the diagnostic process. The module will be mostly pragmatic, focusing on real-world application more than theoretical background. After finishing the module, the participant will be able to play an active role in the digitization of the microscopic workflow, introduce and validate A.I. solutions, and participate in research projects that aim to develop and evaluate A.I. in pathology	This module highlights the transformative impact of digital pathology, bioinformatics, and A.I. on the practice of pathology worldwide and proposes a module to improve the competency and knowledge of pathologists using these technologies, while also providing guidance on their validation and verification for standardized clinical use
Quality controls, regulation, and accreditation 3 ECTS Online and onsite	Can I trust the result of molecular test performed on FFPE slides? How can we improve our work to have reliable results? What about regulations and standards such as IVDR and ISO norms Through the module Quality Control, we answer Quality control and Quality assurance is not just a theoretical concept, but can have a concrete impact on people live. Society sets high expectations around quality and safety and so the authorities increasingly impose obligations regarding quality assurance in laboratories, healthcare organizations, or companies. This requires not only professional and administrative adjustments. It is an integral process that requires the involvement of all employees in an organization. In practice, short-term improvement regularly proves successful, but permanent improvement is a seriously difficult challenge	

Table 1 (continued)

Modules	Module overview	Module goal
New technological developments 6 ECTS Online	This teaching module is designed to provide students with a comprehensive overview of the latest technological and research developments in molecular pathology Students will learn about the latest cutting-edge technologies and techniques that are currently being used to investigate the molecular basis of disease. The module will cover a wide range of topics, including next-generation sequencing, gene editing, and advanced imaging techniques, and will explore their applications in both research and clinical settings By the end of the module, students have acquired various molecular pathology methods commonly used in research. They have also gained the ability to apply these methods in creating a scientific project that addresses a specific research question through the completion of a full grant application. The module's emphasis on grant writing is crucial to effective research Teams and methods are randomly assigned, so students must learn to collaborate with people from diverse backgrounds and gain insights into new fields	This teaching module offers a comprehensive overview of the latest technological and research developments in molecular pathology, covering cutting-edge technologies and techniques used to investigate the molecular basis of disease and emphasizing grant writing and collaboration skills
Biobanking 3 ECTS Online	This module introduces the general practices of biobanking in Europe and discusses the role of the molecular pathologist as the main actor of the biobanking process. Molecular pathologists are seen as being crucial to biobanking due to their access to tissue samples A molecular pathologist can drive the samples collection of a biobank, ensuring the guarantee of high-quality specimens. Thus, the secured future of high-quality and standardized biobanking in Europe is inherently connected to the collaboration with molecular pathologists, and you will be shown the tools that can help with this. This module will also give you the opportunity to build on, and put into further practice, skills, and knowledge gained in previous modules of the program	This module is about the awareness of the importance of biobanking and of the crucial role of molecular pathologists in the collection of high-quality samples to give value to biobanks and to aid in standardized practices across Europe

Table 1 (continued)

Modules	Module overview	Module goal
Liquid biopsies 6 ECTS Online and onsite	This module provides students with a comprehensive overview of the concept and techniques used in liquid biopsy. It begins with a general introduction to the concept of liquid biopsy and its relevance in the field of molecular pathology. It covers the different types of samples that can be used for liquid biopsy, such as blood, urine, and cerebrospinal fluid, and their advantages and disadvantages. The preanalytical phase is a crucial step in liquid biopsy, and the module dedicates a section to discuss the methods used in sample collection, processing, and storage to ensure high-quality results The module then delves into the two primary components of liquid biopsy: circulating-free DNA (cfDNA) and circulating tumor cells (CTCs). The students learn about the origin, detection methods, and clinical significance of cfDNA and CTCs. They also explore other circulating components like vesicles and non-coding RNA and their potential roles in liquid biopsy The module further explores the application of liquid biopsy in basic, translational, and clinical research. It also covers the practical aspects of liquid biopsy in daily clinical practice	This module provides an in-depth understanding of liquid biopsy and its relevance in molecular pathology and clinical practice. The students gain practical skills and knowledge that enable them to apply liquid biopsy techniques effectively in their research and clinical settings

purposes. Participants are encouraged to attain the capacity to critically evaluate and validate novel molecular technologies for their suitability in clinical contexts, understanding the potential advantages and constraints of these innovations, as well as develop the habit of continuing to follow technological developments beyond their time as students. The program emphasizes the development of adeptness in effective communication and collaborative engagement with fellow healthcare professionals. This encompasses pathologists and clinicians, as these abilities are deemed paramount for advancing molecular diagnosis and enhancing patient outcomes within MP.

EMMP is a professional qualification; therefore, alongside the knowledge acquisition expected in a master's level program, participants are required each year to complete a continuous 6-week internship. The hosting laboratories are selected by the Steering Committee adhering to strict accreditation criteria that ensure the quality and standards of the hosting laboratory, thus ensuring the continued high quality and excellence of the program and giving the students the best possible advantages for career progression and standardization in their future clinical practice. The internship topic must align with the educational content of the program.

In the first year, after understanding the activities and workflow of an MP laboratory, the internship could be based on DNA, RNA, and protein mechanisms and their impact on disease through clinical examples, standardization of preanalytical procedures, translation of clinical questions on molecular markers to be analyzed as well as selecting appropriate methods for biomarker analysis, practical approach to molecular infectious disease pathology, molecular testing for tumor classification, prognostication and therapeutic prediction for a selected disease, the outcome of molecular analysis and the diagnostic information needed for eligibility for immunotherapy, digital pathology, bioinformatics, and artificial intelligence, quality controls, regulation, accreditation, latest technological and research developments in MP, biobanking, and liquid biopsies.

In the second-year internship, students will engage in a more focused activity, aligning with their professional aspirations, and they will gain practical experience in the field of MP under the guidance of their supervisor. The aim of the second internship is to support students as they gradually transition to greater autonomy, taking on more initiative, demonstrating proactiveness, and developing a critical mindset.

Thus, the curriculum of this 2-year master's aims to be broad yet comprehensive, giving opportunities to participants to experience the full range of genomics, proteomics, transcriptomics, preanalytical and analytical technologies, immunopathology, digital and computational pathology, quality control, production control, and biobanking in MP.

Finally, in order to evaluate student progress and the criteria that will decide graduation, all modules of the master's require a minimum of two grades mapped to the learning outcomes of each module. Where possible, authentic assessment is being implemented, i.e., assessments that reflect real-world activities which molecular pathology students might face, such as case studies and molecular tumor boards, alongside this, traditional exams (i.e., multiple choice questions, short essays) can be used for more factual based content. The internships carry the greatest weight in terms of both ECTS and student workload: each internship must be followed up with an internship report, and the 2nd year internship also requires an oral viva. Grading is based on the system 0–20. In order to graduate, students must satisfy a minimum of 10 in each module, and on final grading, an average of minimum 10 across each year.

Program and learning design

Following the elaboration of the curriculum and program content, the importance of implementing evidence-based pedagogical approaches will be seen as key to the success of the program—approaches that consider the holistic needs of the students, advancements in the delivery of higher education and health education, as well as the European-wide, distributed faculty. To this end, a blended learning approach was adopted, as this method addresses the reality of the changing nature of student cohorts, offers flexibility, and is shown to enhance the student experience [19]. In particular, the EMMP student cohort is a perfect example in highlighting the changes that are occurring in student profiles across higher education: all EMMP students are professional pathologists at various stages in their careers, working full time. It would be unrealistic to expect a 2-year break in their careers. Thus, delivering blended learning, a mix of online and intensive on-campus sessions at partner universities across Europe, enables flexibility for students to study while continuing to work, and in turn, widens the scope for potential student applications.

EMMP further recognizes the essential role of blended learning in fostering effective education in the field of MP, leveraging blended-learning methods to address the increasing complexity of cancer care, the challenges brought about by the COVID-19 pandemic, as well as mitigating the environmental impact of a pan-European educational program [20]. Finally, a blended learning approach is also a driver in enabling the affordances of technology-enhanced learning, opening opportunities for more diverse content delivery, and more authentic assessment.

The particular blend of learning for EMMP sees the majority of content delivery and learning taking place online asynchronously, requiring approximately 20 h of work per week, augmented by intensive on-campus classes spread throughout the academic year. There are 17 on-site face-to-face days in the first year and 8 days in the second year. As a component of and complement to the blended-learning design, a flipped classroom methodology has been implemented for the majority of modules, meaning participants have asynchronous access to an online learning platform and course materials, and activities which they can consult at their own pace, in their own time, as well synchronous video sessions with teachers through Zoom software, all to take place before scheduled on-campus classes held at various partner universities around Europe. Flipped learning can maximize the effectiveness of the on-campus classes [21], where students have the opportunity to apply what they studied online, through active learning strategies such as hands-on practice and lab work, group discussions, and even game-based learning. Finally, each year includes a 6-week laboratory internship, which students have found manageable by arranging training days or using leave time with their employers. By leveraging the affordances of technology and incorporating evidence-based practices from the learning sciences and learning design methodologies, EMMP aims to provide a comprehensive learning experience for its students, enhancing student learning and engagement. Through deliberate planning and practice, EMMP ensures that learners are actively engaged and equipped with the necessary knowledge and skills. Furthermore, EMMP prioritizes equity, diversity, and inclusion in its educational approach, emphasizing the importance of creating a supportive and accessible learning environment for all students. The adoption of blended learning, consistent reflection and iteration on program design and delivery, and keeping up to date with technology-enhanced learning practices at EMMP underscores the commitment to innovation and excellence in MP education.

Student selection and admisssion

In line with the blended learning approach, EMMP attracted in its first year a diverse cohort of participants, comprising clinical pathologists at different career stages actively engaged in clinical settings. The cohort, with an average age of 37 years, consists of 14 women and 12 men who were carefully selected from a large pool of 145 applicants (Fig. 3).

The selection process involves two steps. Firstly, the Admission Committee evaluates application files, which include the applicant's CV, cover letter, short presentation video, previous university degree and transcripts, letter of recommendation, and proof of English proficiency at a minimum level of B2/C1. Applicants who pass this initial evaluation are then invited to an online interview. The interview, lasting about 30 to 45 min, allows the committee to understand the candidate's motivations for applying and

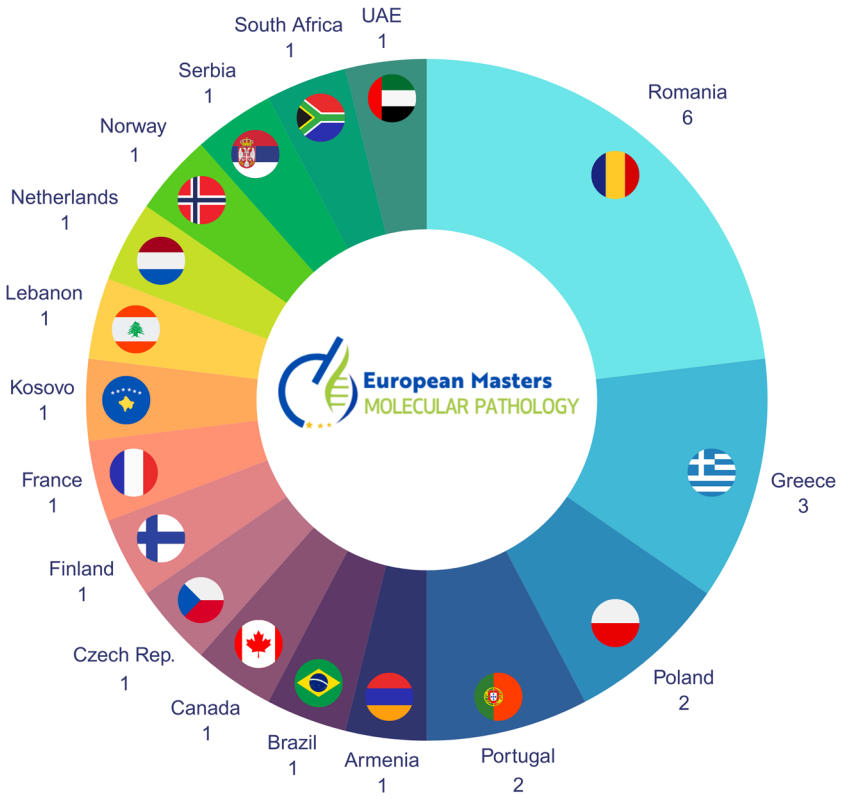

Fig. 3 Distribution of countries of origin in the first EMMP cohort

their career aspirations. It plays a decisive role in the selection process. Each year, the program aims to enroll approximately 25 students.

Among the 26 enrolled students in 2023, 10 were awarded scholarships, including three sponsored by the Université Côte d'Azur in collaboration with Thermo Fisher Scientific (e.g., "IDEX Excellence Scholarship," "Women in Molecular Pathology," and "Equity for Molecular Pathologists"), and seven supported by ESP. The first cohort at EMMP represents a dynamic blend of professionals seeking to enhance their expertise in MP while continuing their full-time professional commitments.

While the number of graduates may seem modest, EMMP focuses on creating highly skilled specialists who are expected to have a significant impact on the field. By providing an intensive and comprehensive education, the program aims to produce graduates who will become leaders and innovators in MP, capable of driving advancements and implementing new practices across Europe. Moreover, the small cohort size allows for personalized training and mentorship, ensuring that each graduate possesses a deep understanding of MP and its applications. This approach not only guarantees quality education but also encourages collaboration and networking among participants, fostering a strong professional community that can influence change beyond the immediate number of graduates. In addition, each graduate is expected to have a ripple effect in their respective institutions and countries, sharing their expertise and contributing to the broader adoption of cutting-edge molecular pathology practices. As these professionals take on roles in diagnostic laboratories, research institutions, and healthcare settings, they will be instrumental in promoting the standardization and harmonization of practices throughout Europe.

Governance and steering comittee

The Steering Committee plays a pivotal role in overseeing the program's goals and focus, ensuring their continuity and quality (Fig. 2). It holds the responsibility of electing module coordinators and new faculty members, while periodically reviewing the participation of the current faculty. It conducts periodic reviews of program issues and develops proposals for policy revision when necessary. It is responsible for monitoring the curriculum's level, breadth, and effectiveness, proposing changes when needed. It collaborates with participating faculty to maintain courses and implement changes in them. The committee, together with the pedagogical engineer, closely interacts with faculty members to develop new courses. Any requests for changes in the curriculum, whether in course content or the addition/deletion of courses, are brought to this committee for consideration. Additionally, the committee is tasked with maintaining

the consistently high quality of graduate student education throughout the program.

By orchestrating annual updates to the master's curriculum, the Steering Committee of the program can effectively monitor the evolution of knowledge. This proactive approach ensures the continuous education of aspiring molecular pathologists in Europe and beyond, facilitating the potential distribution of standardized materials across institutions.

The Admissions Committee plays a key role in student admissions, evaluating applications for the program. The Examination Committee takes charge of organizing the assessments and oral viva, ensuring the proper conduct of assessments in the program.

Future directions

EMMP acknowledges the rapid evolution of diagnostic technologies and methodologies as a key challenge in modern pathology education. It offers a specialized curriculum focused on MP, providing in-depth knowledge and skills in personalized medicine. This specialized curriculum ensures that students are well-prepared to adopt and leverage cutting-edge techniques enhancing diagnostic accuracy in clinical settings (Fig. 4). The program fosters effective interdisciplinary collaboration among molecular pathologists, clinicians, clinical molecular biologists, bioinformaticians, and researchers, which is essential for improving patient outcomes. Collaborations with leading institutions further strengthen networking opportunities and access to the latest technologies, contributing to EMMP's international reputation and attracting a diverse student and faculty.

Despite these strengths, EMMP faces challenges such as resource constraints that limit hands-on training opportunities and access to specialized laboratories. Geographic limitations may also affect diversity and inclusivity, particularly for students from certain regions (Fig. 4).

Nevertheless, EMMP is well-positioned to meet the growing demand for skilled professionals in MP, driven by advancements in personalized medicine. Rapid advancements in technology present opportunities for EMMP to continuously update its curriculum and incorporate new tools and techniques. Expanding outreach and offering online components can further broaden the program's reach and accessibility to a wider audience of students and professionals.

Fig. 4 "SWOT" analysis for the European Masters in Molecular Pathology

In driving these opportunities and challenges, EMMP must adapt to evolving regulatory frameworks and accreditation standards. Financial constraints and competition for skilled faculty may impact the program's sustainability and quality of instruction [22, 23]. By leveraging its strengths in specialized curriculum, partnerships, and innovative teaching methods, EMMP is positioned to address technological challenges in MP education and align with the evolving landscape of diagnostic practices and patient care.

Conclusions

The EMMP program offers education and training in MP, focusing on the field's evolving nature, technological advancements, and fostering collaboration among professionals. This program equips students to handle the complexities of MP, enhances their skills, and promotes a standardized approach to molecular diagnostics. Finally, it aims to improve diagnostic accuracy and patient care by regularly updating its curriculum, integrating new technologies with an emphasis on accuracy and validation, and encouraging interdisciplinary collaboration. Overall, we stongly believe that the program is valuable for tackling current challenges and preparing future molecular pathologists for the changing landscape of molecular diagnostics.

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University of Bern, Switzerland: Inti Zlobec.

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Authors and Affiliations

Marius Ilié[1] · Vivien Lake[2] · Enrique de Alava[3,4] · Serena Bonin[5] · Sandra Chlebowski[2] · Aurélie Delort[2] · Elisabeth Dequeker[6] · Raed Al-Dieri[7] · Arjan Diepstra[8] · Olli Carpén[9] · Catarina Eloy[10] · Ambrogio Fassina[11] · Falko Fend[12] · Pedro L. Fernandez[13] · Gregor Gorkiewicz[14] · Simon Heeke[15] · Rui Henrique[16] · Gerald Hoefler[14] · Pablo Huertas[17,18] · Michael Hummel[19] · Karl Kashofer[14] · Jeroen van der Laak[20] · Rocio Martinez de Pablos[17,18] · Fernando Schmitt[21,22] · Ed Schuuring[8] · Giorgio Stanta[6,23] · Wim Timens[8] · Benedikt Westphalen[24,25] · Paul Hofman[1]

✉ Marius Ilié
ilie.m@chu-nice.fr

1 Laboratory of Clinical and Experimental Pathology, Hospital-Related Biobank BB0033-00025, Nice University Hospital, University Côte d'Azur, FHU OncoAge, IHU RespirERA, 06000 Nice, France

2 Center for Active Learning and MSc International Office, IDEX Université Côte d'Azur, Nice, France

3 Institute of Biomedicine of Sevilla, IBiS/Virgen del Rocio University Hospital/CSIC/University of Sevilla/CIBERONC, 41013 Seville, Spain

4 Department of Normal and Pathological Cytology and Histology, School of Medicine, University of Seville, 41009 Seville, Spain

5 Molecular Histopathology Laboratory, DSM-Department of Medical Sciences, University of Trieste, Trieste, Italy

6 Department of Public Health and Primary Care, Biomedical Quality Assurance Research Unit, University of Leuven, Kapucijnenvoer 7 blok g - bus 7001, 3000 Leuven, Belgium

7 European Society of Pathology, Brussels, Belgium

8 Department of Pathology and Medical Biology, University of Groningen, University Medical Center Groningen, Groningen, Netherlands

9 Department of Pathology, University of Helsinki and HUS Diagnostic Center, Helsinki University Hospital, Helsinki, Finland

10 Pathology Laboratory, Institute of Molecular Pathology and Immunology of the University of Porto - IPATIMUP, Porto, Portugal

11 Pathology Department, Pathology Section of UEMS, University of Padova, Padova, Italy

12 Institute of Pathology and Neuropathology, Tübingen University Hospital, Tübingen, Germany

13 Pathology Department, Hospital Germans Trias i Pujol, IGTP, Autonomous University of Barcelona, Badalona, Spain

14 Diagnostic and Research Institute of Pathology, Medical University of Graz, Graz, Austria

15 Department of Thoracic/Head & Neck Medical Oncology, The University of Texas MD Anderson Cancer Center, Houston, TX, USA

16 Department of Pathology and Cancer Biology and Epigenetics Group - CI-IPOP@RISE (Health Research Network) Porto Comprehensive Cancer Center Raquel Seruca (Porto.CCC) & Department of Pathology and Molecular Immunology, ICBAS-School of Medicine and Biomedical Sciences, Portuguese Oncology Institute of Porto (IPO Porto), University of Porto, Porto, Portugal

17 Departamento de Genética, Universidad de Sevilla, Sevilla, Spain

18 Centro Andaluz de Biología Molecular y Medicina Regenerativa-CABIMER, Universidad de Sevilla-CSIC-Universidad Pablo de Olavide, 41092 Sevilla, Spain

19 Molecular Diagnostics Institute of Pathology Charité, Universitätsmedizin Berlin, Berlin, Germany

20 Department of Pathology, Radboud University Medical Center, Nijmegen, Netherlands

21 Department of Pathology, Faculty of Medicine of University of Porto, CINTESIS@-RISE, Health Research Network, Porto, Portugal

22 Molecular Unit, IPATIMUP, University of Porto, Porto, Portugal

23 Biobanking and Molecular Pathobiology Working Group OECI, OECI, Brussels, Belgium

24 Comprehensive Cancer Center Munich & Department of Medicine III, Ludwig-Maximilian University of Munich, Munich, Germany

25 German Cancer Consortium (DKTK Partner Site Munich), Heidelberg, Germany