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ORIGINAL PAPER

Digital morphology network for effective teaching of cytology, histology and histopathology for medical and biology curriculum. VM3.0 Erasmus+ project

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Abstract

Introduction. Digital microscopy transformation, the basis for the virtual microscopy applications, is a challenge but also a requirement in modern Medical Education. This paper presents the scope, background, methods, and results of the project "Digital Transformation of Histology and Histopathology by Virtual Microscopy (VM) for an Innovative Medical School Curriculum", VM3.0, funded by the European Union under the Erasmus+ framework (ref.no.2022-1-RO01-KA220-HED-000089017). The project was initiated at Grigore T. Popa University of Medicine and Pharmacy, Iași, Romania, with the support of Euroed Foundation, Iași, and cooperation of University partners from Gdansk (Poland), Plovdiv (Bulgaria), Alicante (Spain), and Patras (Greece) aimed to implement digital histology and histopathology teaching in a common network.

Materials and methods. The backbone of the project was the development of a Digital Slide Platform based on the scans of histological slides collected from all the partners of the participating universities and the creation of a simple and fast digital/internet communication tool that could be used to improve histology and histopathology teaching of medical and natural sciences students. The construction of a Virtual Microscopy Library (VML) has been based on the acquisition of whole scans of high-quality histological slides stained by hematoxylin and eosin (H&E) and other classical staining methods and description of the details in English as well as respective languages of the project's partners. The VML can be used for different approaches, both for students' instruction in classes as well as for individual students' work and self-testing. Universities from other countries could use the modal structure of the developed VML system on the condition that more slides are provided and the implementation of national language(s) is implemented.

Conclusions. The combined efforts of all university partners allowed to establish the dynamic low-cost virtual microscopy educational system. The VM system could help unify the standards of cytology, histology, and histopathology teaching in a quest for the digital transformation of the European educational system.

Keywords: virtual microscopy; histology; slide library; teaching; self-testing; files-sharing platform; histopathology

INTRODUCTION

The role of histology and histopathology in medical studies

Histology is a core discipline in medical studies. It is present in the structure of the degrees in medicine all over Europe and in the rest of the world as a basic subject to be taken in the first or second year of the medical curriculum. Histology allows medical students to study the microscopic structure of tissues and organs. It provides a foundation for understanding the normal organization and function of cells, tissues, and organs in the human body. This knowledge is essential for accurately diagnosing diseases and interpreting clinical findings. It helps students correlate the anatomical features they learn in gross anatomy with the cellular composition and organization of tissues. Moreover, histology serves as a basis for research in various medical fields. It enables scientists to investigate the cellular and molecular mechanisms of underlying diseases, develop new treatment modalities, and advance medical knowledge. Histological techniques, including immunohistochemistry and molecular histology, are vital tools in biomedical research.

Regarding histopathology, it is usually a mandatory subject on the third or fourth year of the medical studies. Histopathology is instrumental in recognizing and diagnosing various diseases. By studying abnormal tissue structures, such as cellular changes, inflammation, or tumor formation, medical students can identify pathological conditions and understand the underlying mechanisms. This knowledge is crucial for diagnosing diseases and planning appropriate treatment strategies.

Virtual microscopy in histology and histopathology teaching

Virtual microscopy in histology teaching refers to the use of digital technology to replicate the experience obtained by means of a traditional microscope for educational purposes. It involves the acquisition of high-resolution images of histological slides and making them accessible by the use of a computer or other digital devices.

With virtual microscopy, students can view and explore histological slides at their convenience without the need for physical microscopes or glass slides. These digital slides can be accessed *via* specialized software or online platforms designed for histology education.

Virtual microscopy offers specific benefits in histology teaching, with several advantages listed below.

- **Accessibility.** Virtual microscopy allows students to access a wide range of histological slides from anywhere and at any time, as long as they have an internet

connection. It eliminates the need for physical slides and microscopes, making it more convenient for both students and educators.

- **Enhanced learning experience.** Digital slides offer high-resolution images that can be zoomed in or out, providing students with detailed views of cellular structures. This enhances their ability to identify and understand histological features, improving their overall learning experience.
- **Interactivity.** Virtual microscopy platforms often provide interactive features such as annotations, labels, and pointers that help students focus on specific structures or areas of interest. They can also include additional educational resources like audio/video explanations or quizzes to further engage students in the learning process.
- **Collaboration.** Digital slides can be easily shared and accessed by multiple students simultaneously. This allows for collaborative learning and discussion, as students can annotate slides, share their observations, and engage in virtual discussions with peers and instructors.
- **Preservation of slides.** Physical histological slides are prone to damage, loss, or deterioration over time. Virtual microscopy eliminates these concerns by digitizing the slides, ensuring their long-term preservation and availability for future reference.

Overall, VM in histology teaching offers a versatile and efficient way to engage students in the study of cellular structures and tissue morphology. It provides an interactive and accessible platform that enhances learning, collaboration, and the overall educational experience in the field of histology.

Virtual microscopy tools

The key to a better educational process in modern times is always to embrace new technologies as educational tools. Virtual microscopy is one such advanced and innovative educational tool, particularly in teaching.

The concept of virtual microscopy emerged relatively recently, in 1997, when it was first described by the Computer Science Department at the University of Maryland and the Pathology Department at Johns Hopkins Hospital in Baltimore, Maryland [1]. Since then, a wide array of systems has been developed, and they can be broadly categorized into two groups: monitored microscopes and scanners. The partners of the VM3.0 project utilize both, with a particular focus on digital slide scanners.

The necessity for developing a European digital virtual microscopy network to improve histology and histopathology teaching for medical and health sciences curricula

In the context of worldwide digitalization, the universities participating in the European Union (EU) Erasmus+ project "Digital Transformation of Histology and Histopathology by Virtual Microscopy (VM) for an Innovative Medical School Curriculum", VM3.0, funded by the European Union under the Erasmus+ framework (ref.no.2022-1-RO01-KA220-HED-000089017) realized that the development of a Virtual Microscopy Platform would be a helpful element to improve the learning process for histology students. The development of a European digital microscopy network, with the participation of all higher education institutions from the involved five countries, is necessary to revolutionize the European medical curricula, leading to digital transformation through the development of digital readiness, resilience, and capacity. The use of VM library platforms may increase the undergraduate and postgraduate students' vocational skills for new, modern medicine and health sciences domains. Moreover, the digitalization of microscopy teaching addresses the students' interest in new technologies and methods. Furthermore, VM libraries may be used as alternative or additional didactic tools, complementary to traditional microscopy teaching. The VM3.0 Erasmus+ project has been actually developed to establish a dynamic VM educational system in response to the increasing pressure for digital transformation of the educational systems of the participating universities and countries.

The partners of the VM3.0 Erasmus+ project

The University of Medicine and Pharmacy "Grigore T. Popa", (UMFIASI), located in Iasi, Romania (<https://www.umfiasi.ro/en>), is a student-centered university that provides high quality education, develops high-class research that supports learning, and keeps strong international contacts. UMFIASI is the second oldest and largest public medical university in Romania with four faculties, over 926 academic staff and more than 9,900 students. Research activities are carried out in all university departments, financial support being mostly provided through grants or research contracts. The university operates with two centers of excellence, eight research centers and two research platforms.

Since 2009, the University has implemented 30 national and European projects apart from being a partner in the Erasmus mobility programs, having bilateral agreements with many European universities.

The Medical University of Gdańsk, (MUG), (<https://mug.edu.pl>) is the largest medical university in northern Poland. The MUG was awarded an eighth place in the prestigious

national Excellence Initiative — Research University competition of the best 10 Polish universities. More than 6000 undergraduate and postgraduate students at four faculties (Medicine, Pharmacy, Public Health, and Biotechnology, the last one together with the University of Gdańsk) are being taught by 1,216 full-employed academic staff. MUG also offers programs in English such as Premedical Course, Medicine Doctor, Pharmacy and Nursing. International students constitute more than 15% of the MUG's students and represent more than half of all international students in Gdańsk.

MUG has participated in Erasmus+, Key Action 2 project during 2014–2020 (project “CLILMED”) and also in Erasmus Mundus Joint Masters project in current EU Program 2021–2027 (Project “Sustainability, drug discovery, Erasmus Mundus Joint Master — S-DISCO”), and, currently, in the VM3.0 Erasmus+ project that is subject of this special article.

The Medical University — Plovdiv, (MUP), (<https://mu-plovdiv.bg/en>) provides training of students in Medicine, Dental Medicine, Pharmacy, and Public Health as well as postgraduate training of PhD students and specializing medical professionals in Medical College of the University. MUP provides high quality education for almost 6,000 students from all over Europe, with international students comprising 2/3 of all students. The staff of MUP consists of 865 academics including 205 professors and associate professors. The study curricula are closely connected with the introduction of e-learning and interactive methods in the training process.

The Medical University Plovdiv has been awarded first place in the category “medicine” among the medical universities in Bulgaria twice and took second place in the top Research Universities in Bulgaria. Clinical training is conducted in six university hospitals. Medical Simulation Training Center presents the highest state-of-the-art medical training center recognized by American College of Surgeons as a “Comprehensive Education Institute”. MU-Plovdiv is a member of the European University Association with more than 150 academic bilateral and international agreements with universities from both European Union and non-EU countries. The MU-Plovdiv is certified as meeting the requirements of ISO9001:2015 in educational activities.

The University of Alicante (UA) (<https://www.ua.es/en/index.html>) was created in 1979. Today, it educates and trains more than 36,000 students, including 3000 international students, and offers more than 80 undergraduate and 96 postgraduate programs, making it one of the fastest-growing universities in Spain. The UA houses 227 research groups and employs over 2,400 academic staff.

The UA makes an important commitment to using new technologies in teaching-learning processes. Specifically, an effort has been made to bring the digital, online and virtual approach to different educational methods, which allows a more efficient use of available resources while reducing barriers to access higher education. In this regard, transnational partnership in the VM3.0 Erasmus+ program provided an opportunity to standardize the curricula in histology and histopathology.

The University of Alicante is firmly interlinked with its socio-economic environment and is considered a point of reference for many companies, providing to them technical assistance, student training programs, and continuous post-graduation education. The UA participates, as a partner or coordinator, in a large number of research cooperation projects from different funding programs.

The UA has been included in many programs as a strategic and core partner. Its Faculty of Health Sciences, especially well-known in Spain for its Nursing Department, has been evaluated as one of the most productive faculties regarding healthcare research in Spain, being always in the top three faculty rankings in the Spanish Education Quality assessment program.

The University of Peloponnese (UP) (<https://uop.gr/en>) was established in 2000 and accepted its first students in 2002. The University of Peloponnese central premises are located in Tripolis, while schools and departments operate in five other cities (Corinth, Nafplion, Sparta, Kalamata, and Patra) throughout the Peloponnese and Western Greece Region. Altogether approximately 20,000 students study in five major schools.

The Department of Electrical and Computer Engineering (ECE) belongs to the School of Engineering based in Patra. The curriculum offers a basic education of six academic semesters, followed by four academic semesters, in which students specialize in four Electrical and Computer Engineering programs. In the second cycle of studies, ECE offers a Postgraduate Program entitled “Smart Information and Communication Technologies and Services”. ECE is strongly involved in research and innovation and actively participates in national and international projects (funding from Horizon 2020, Erasmus+, and others). ECE is staffed by thirty members of teaching research staff and six members of technical laboratory personnel on the permanent employment basis. ECE makes a special effort to warrant the European/international scientific and/or professional perspective for the graduates, through the implementation of the ECTS score system, the participation in Erasmus+ programs, and other forms of academic and research exchanges through bilateral agreements with countries that excel in engineering studies.

EuroEd Foundation (<https://euroed.ro>) is a non-profit organization located in Iași, Romania, that commenced its activity in 1992.

EuroEd's relevant experience lies with coordinating and participating in EU funded projects, as well as in strategies and methodologies of co-operation at local, regional, national and trans-national levels. From 1998, EuroEd Foundation coordinated and implemented over 100 national and international educational projects in various fields, including medicine. EuroEd projects have been awarded European distinctions of the highest level, such as 10 international awards in the last five years for the quality of its projects: eight European Label Awards and a Worldaware distinction.

EuroEd has also gained experience from the implementation of related projects. They included VOICE — vocational education and training for speech and language therapists and parents for rehabilitation of children with cochlear implant (VOICE) how to speak, Tiramisu — First Aid Improve Survival, HOPE — How Oncogenetics Predicts & Educates, ZoonosesOnlineEducation, online courses with videos for the field of veterinary communication dealing with prevention, diagnosis and treatment of diseases transferable from animals to humans, and Palliative Care MOOC — Massive open online courses with videos for palliative clinical communication.

Aims of the VM3.0 Erasmus+ project

Light microscopy sharing examination, in which the educator stands close by the student and alternatively examines the slides, using the same microscope to analyse each tissue/cell/organ, has represented traditional microscopy education. This method has been challenged during the COVID-19 pandemic and has forced innovation as to continue teaching microscopy. Consequently, teaching *via* VM seemed an optimal alternative for histology and histopathology education. Whole Slide Imaging (WSI) has emerged as the digital pathology platform of choice for teaching in recent years, demonstrating its utility in both undergraduate and graduate medical education, primarily by leveraging stored teaching libraries, study slide sets, and individual cases to enhance didactic teaching, to monitor the acquisition of new skills (*e.g.*, staining interpretation), and to assess competences through slide examination/testing. Furthermore, VM software reproduces high-quality images with meticulous clarity and added features that allow students and teachers to highlight, annotate, pan the whole specimen and zoom on the specific structures or details. Thus, VM represents a modern tool with increased quality and utility in microscopy education.

Several medical curricula around the world have adopted the VM to complement the effectiveness of competency-based education in medical education. Unfortunately, very few VM teaching possibilities are available in Europe. Therefore, one of the basic aims of the VM3.0 project was to improve students' skills in the acquisition and interpretation of the normal and pathological structures in microscopic slides prepared by the use of the paraffin technique and stained by (H&E) method. Moreover, a selection of slides stained by other methods was planned to be included in the slides' set to demonstrate to the students the power of microscopy for further differentiating of the cellular and tissue structures.

Another further aim was to prepare a short description of each of the slides in English and the language of the participating universities' to create a basis for common curricula for teaching histology and histopathology. Moreover, a practical guide for students and teachers had to be set up to explain the optimal options for using the VM system.

An important task of the VM3.0 project was to create a fast and low-cost online system for sharing the scanned microscopic slides stored on the VM library platform in a safe but easily accessible way.

Finally, the creation of the VM library is expected to increase the students' understanding of the morphological structures by introducing them to the scans not only during the didactic process at the university but also enable self-learning through online access to the scan library.

Thus, the general didactic VM3.0 project's aim was the improvement in the understanding of microscopic structures as a result of the digital transformation of traditional methods of teaching and learning of histology and histopathology.

MATERIALS AND METHODS

Selection of the microscopic slides

Researchers from participating universities (apart from the University of Peloponnese and EuroEd) had selected more than 250 good-quality slides to be scanned for the preparation of the virtual library. It was assumed that the collection should contain slides representing normal tissues and organs stained mainly by H&E method, as well as approximately 40 slides showing pathological specimens. To ensure technical homogeneity of scanning, the procedure was performed mainly by one person (A.D.T.) at the Departments of Histology and Histopathology of the University of Medicine and Pharmacy "Grigore T. Popa" (Iași, Romania).

The Aperio AT2 Slide Scanner (Leica Biosystems) was used with objective magnification of $\times 20$ and digital scanned slides viewing was accomplished by Aperio ImageScope free software (<https://aperio-imagescope.software.informer.com>). [2, 3].

Strategy for description of slides

It had been decided that, for students' use, each slide should be characterized in a concise way to avoid repetition of detailed slides' descriptions present in many histological atlases. Each slide was also associated with three to five keywords along with a specific hyperlink. Additionally, several self-testing multiple-choice questions included into each teaching module may enable students self-learning and self-assessment.

Preparation of practical guide to use the VM system

In order to help users to navigate and use effectively the VM system, a practical guide was proposed. This guide is aimed to contain short videos that offer a comprehensive overview of accessing the system, navigating the interface, using the slide library (searching, filtering results), viewing the slides (opening, panning and zooming), making and managing annotations.

Setting up online network to access the VM slide library from the digital systems of the participating universities

General description of the applied methods

To ensure optimal performance and reliability, the partners at the University of Peloponnese were granted access (S.S.H. with root permissions) to a system hosted by the coordinating partner (UMFIASI) that meets the following specifications: operating system — Linux Debian 12 “bookworm” or Ubuntu; at least 8 GB of RAM, a storing capacity of at least 2 TB; internet connection. The UP partners remotely installed a range of software and extensions essential to support the application, such as PHP 8.2, Composer, Node.js, MariaDB, Apache2, and also libraries and tools necessary for high-performance image processing tasks, such as libvips42 and libvips-tools.

Setting up this server configuration allowed the establishment of an online network that provided efficient access to the VM slide library from the digital systems of all participating universities.

The procedure of uploading the collection of scanned slides was performed by the same person responsible for the digital scanning process (A.D.T.), ensuring the correct

distribution of the digital slide files in the virtual library according to the established curricula.

For each slide, the description with the keywords was uploaded, first in English, verifying the correspondence between the keywords and the fields on the virtual slide.

RESULTS

The preliminary results consisted of an easy, online-accessible digital educational platform designed to assist students and young pathologists in understanding the science of normal and pathological tissue structure and function at the microscopic level.

The virtual platform included:

- a user-friendly interface with a login access menu;
- a search functionality allowing users to quickly find specific slides, topics, or keywords,
- an extensive slide library encompassing 20 teaching modules (sections) with digital slides, providing a wide range of examples for study;
- a tutorial part with step-by-step video tutorials covering instructions for the effective use of the platform;
- detailed and comprehensive descriptions for the collection of slides, including keywords representing histological or histopathological diagnostic criteria;
- slide annotations software module offering the possibility for the user to save his own annotations for the slides;
- a quiz and assessment part composed of multiple answer questions to test users' understanding of the material.

The login access menu (Fig. 1) provides access to the platform for teachers, medical students, and training pathologists using a username and a password, the accessibility being limited to each category as follows: teaching staff is permitted to access, edit, modify, and save different descriptions and annotations visible to every user, whereas student accounts have limited access, simply viewing the slides, making personal annotations, taking notes, and highlighting areas of interest, viewable only under their account.

Using the dashboard menu button, the user can access the virtual slide library, select a slide of interest, navigate on it, and create, save, and share annotations *via* email. The annotation section uses tool buttons to allow the user to highlight areas, to draw different shapes and to add personal notes.

The following Figures will present screenshots that correspond to the subsequent steps in studying slides related to the specific teaching module (section).

The next logical step in the student's work will be a selection of a specific slide from the collection of 298 currently available scanned slides. The screenshot shown in Figure 2 presents a way of finding the slide indicated by the educator by using the "Filter" option. Only the option "View" is accessible to the students, whereas the options "Edit" and "Delete" are available for teachers only, *e.g.*, to correct/add the slide's description or to substitute it with a new, better scanned slide.

The viewing section of the slide is presented in Figure 3. The screenshot demonstrates that the VM3.0 system's options allow smooth panning and zooming, with the possibility of viewing only a full screen by hiding the adjacent slide description.

Types and number of the selected and scanned microscopic slides

The scanned microscopic slides were ordered and classified into respective teaching modules (sections) that correspond to the typical histological classification of tissues and organs. They have been listed in Table 1. The number of slides required in the curriculum were different according to the modules, as shown in Table 1.

An important part of the VM3.0 platform consists of the teaching module associated with each of the histological slides. It includes a concise description of slide's characteristics features with keywords, and hyperlinks to the images that present those features (Table 2). The latter feature represents the basic core of the system since it enables an efficient and fast online connection with the image database.

DISCUSSION

Challenges of medical education in 21st century

Digital histology and pathology implementation in medical education have opened the perspectives for a significant shift in the design of the medical curriculum. Light microscopy sharing examination, in which the teacher stands close to the student and alternatively examines the slides, using the same microscope in order to analyse each tissue/cell/organ, along with tandem microscopic review or "double-scoping" of histology and pathology slides have represented traditional way of microscopy education. However, these methods require a close proximity of educator and students and/or the use of a double- or multi-headed optical light microscope which is not amenable to physical distancing.

Alternatively, a shift toward teaching *via* VM provides a readily available, physically distanced, and cost-conscious alternative for histology and histopathology education. The use of VM has been already demonstrated to enhance student learning and overall performance in a more clinically oriented and dynamic learning environment, being highly accepted and adopted by several medical schools across the globe. Thus, VM can also provide a modality that helps to bridge the gap for students with inadequate clinical exposure.

Digital microscopy also facilitates the integration of advanced image analysis tools. These tools can automatically identify and quantify cellular structures, aiding in more precise and efficient learning and diagnoses. The ability to annotate slides and share these annotations with peers and instructors promotes better communication and collaborative learning. Additionally, digital storage of slides mitigates the risk of physical degradation over time, preserving valuable specimens indefinitely.

Several Medical Programs around the world have adopted the VM to compliment the effectiveness of competency-based education in medical education. Digital pathology has paved a path to address some of the core competencies and collaborative models in various education and post-graduation programs. Therefore, it is imperative that medical students become familiar and proficient in the VM system applications. Through survey data, the immediate needs of our project have been measured. Existing technology may not be initially optimized for a dynamic virtual experience, resulting in lag time with image movement, problems of focusing, image quality issues, and a narrower field of view; however, these technological barriers can be overcome through hardware and software optimization.

Mapping research

In the first stage of the project, Mapping research on the current situation of the use of VM in the partner countries was performed. Extensive literature research was conducted as well as contacting 35 histology experts and asking them to complete a questionnaire. Figure 5 shows the increasing interest in the field of VM applied to histology and histopathology teaching.

Regarding the available publications, using the combination of keywords (“virtual” and “microscope” or “microscopy” and “histology”), the authors found 521 papers. After reviewing the list of publications, we selected those that were more closely related to the exact purpose of the project. As a result, Table 3 shows the main characteristics of the 47 articles selected at this stage of the mapping research [4–50].

We found a scarcity of publications related to the use of VM in histology education in international journals. From those published, the main conclusion is that there are no differences in the achievement of learning objectives between students taught histology using VM and those taught using traditional light microscopy in-class approach.

Supplementary Table 1 shows the country distribution of the experts. We asked them to answer a questionnaire related to the use of VM in teaching histology and histopathology (Suppl. Fig. 2). Generally, in the opinion of the experts, VM seems to be a desirable teaching method, with more advantages rather than disadvantages. Most responders find that it is necessary to include clear instructions on using the VM platform and quizzes/tests to assess the efficacy of the teaching and learning process. There is also a consensus that a combination of VM and traditional microscopy teaching methods should be employed. The Supplementary Figure 1 presents answers to each of the questions.

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Apart from the Likert questions, we asked the experts to provide their opinions on the benefits of using VM in histology teaching in an open format. Supplementary Figure 2 shows a word cloud with the most common terms used.

While virtual microscopy offers many benefits in histology education, it is important to consider some of its drawbacks and potential problems:

- **Lack of haptic feedback:** Virtual microscopy cannot replicate the tactile experience of using a physical microscope. The ability to feel and manipulate the slide, adjust focus, and perceive depth through haptic feedback is lost in the digital environment. This tactile feedback can be valuable in developing fine motor skills and spatial understanding, essential in histological analysis.
- **Limited real-time interaction:** Virtual microscopy platforms may have limitations in providing real-time interactions. Students may face delays or difficulties in navigating the digital slides, adjusting magnification, or accessing

specific regions of interest. This can affect the flow of the learning process and hinder the spontaneous exploration of histological features.

- **Technical requirements and access:** Virtual microscopy relies on computer technology and internet connectivity. Access to suitable devices, software, and a stable internet connection may pose challenges for some students, especially those from economically disadvantaged backgrounds or regions with limited infrastructure. Technical issues or compatibility problems with different operating systems or devices can also hinder the learning experience.
- **Loss of whole slide context:** Virtual microscopy often involves viewing high-resolution images of individual fields or regions of a histological slide. This approach may limit the ability to appreciate the entire context of the tissue sample. Students may miss the overall architecture and relationships between different regions of the slide, which can be crucial in understanding tissue organization and identifying abnormal features.
- **Lack of physical slide examination:** Virtual microscopy eliminates the opportunity to examine physical slides under different lighting conditions, which can provide valuable information about the staining quality and structural characteristics. Observing slides under different light sources, such as polarized light or phase contrast, may reveal additional details that are not easily replicated in the digital format.
- **Loss of authenticity:** Virtual slides may not capture the exact appearance of the original histological samples due to variations in image quality, colour representation, or resolution. This loss of authenticity may impact the accuracy and realism of the learning experience, especially when it comes to subtle histological features or artifacts that are challenging to digitally replicate.

Despite these drawbacks, virtual microscopy remains a valuable tool in histology education, particularly when used in conjunction with traditional microscopy. Combining virtual microscopy with hands-on laboratory experiences can help mitigate some of these limitations and provide a more comprehensive learning environment.

Future development plans

In future, the VM3.0 system will include a tool called “Microscopic image description cassette” containing slide-specific keywords. This cassette will be available by a specific link.

The VM3.0 platform development will include a quiz section based on a collection of multiple-choice questions, three for each virtual slide section, comprising approximately 60 questions. The student can generate a test of ten questions from a specific module or from different selected modules, save the results, and thus, he will have his own statistics about his knowledge of histology or histopathology.

CONCLUSIONS

In summary, the cooperation of six European universities in the development of an innovative the VM3.0 project under the frames of the European Union Erasmus+ program resulted in the creation of a fast, and low-cost international online platform that will increase effectiveness of teaching/learning histology and histopathology, light microscopy-based sciences that are indispensable in the medical sciences studies curricula.

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Data availability statement

Data presented are original and available upon reasonable request.

Ethics statement

The data comply to the Ethics regulations.

Author contributions

All authors contributed to the article and agreed on the submitted form.

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Conflict of interest

There is no conflict of interest.

Supplementary material

Supplementary materials are available on Journal's website.

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Table 1. The teaching modules of the VM3.0 project’s library

Number	Name of teaching module (section)	No of slides
1	Histology of epithelial tissue	29
2	Histology of connective tissue proper	9
3	Histology of specialized connective tissue	5
4	Histology of muscular tissue	3
5	Histology of nervous tissue	2
6	Blood & hematopoiesis	2
7	Histology & histopathology of cardiovascular system	17
8	Histology & histopathology of immune system	12
9	Histology, histopathology & cytology of endocrine system	11
10	Histology & histopathology of the oral cavity and digestive tract	25
11	Histology, histopathology & cytology of glands associated	29

	to the oral cavity and digestive tract	
12	Histology & histopathology of respiratory system	20
13	Histology & histopathology of urinary system	22
14	Histology, histopathology & cytology of female reproductive system	34
15	Histology & histopathology of male reproductive system	13
16	Histology, histopathology & cytology of mammary glands	5
17	Histology & histopathology of integumentary system	13
18	Histology & histopathology of the nervous system	14
19	Miscellaneous histology, histopathology & cytology	5
20	Training pathologists' collection	29

Table 2. Example of histology and histopathology slide descriptions on the VM3.0 platform with hyperlinks

Section	Title & slide number	Description	Keywords	Hyperlink to VM3.0 platform
Histology of Muscular Tissue	Striated cardiac muscle, #42	The slide shows a heart section, containing striated cardiac muscle (myocardium), which is composed of branching cardiac muscle cells (cardiomyocytes) with a single centrally placed nucleus for each	cardiac myocyte	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=38.33759992447474&x=0.42766746903592456&y=0.3344392700574031
			nucleus	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=150.91090225563912&x=0.5071168587516031&y=0.13726224150709515
			intercalated disks	https://vm-vl.projects.umfiasi.ro/en_GB/admin/slide/view/42#zoom=75.40820288040075&x=0.5888613961454934&y=0.27820521

		muscle cell. Each cell end is connected with the ending of an adjacent cardiomyocyte <i>via</i> specialized junctions called intercalated disks. They are usually unstained but occasionally appear as thin, dark lines between adjacent cells. Yellow-brown granules of lipofuscin pigment are visualized near the nucleus of some cells.		60790237
			lipofuscin pigment	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=150.91090225563912&x=0.5368358999042452&y=0.18239768625390837
			cardiac myocyte	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=38.33759992447474&x=0.42766746903592456&y=0.3344392700574031
			nucleus	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=150.91090225563912&x=0.5071168587516031&y=0.13726224150709515
			intercalated disks	https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=125.7590852130326&x=0.51709664185093&y=0.1801713049046873
Histology, Histopathology & Cytology of	Breast ductal carcinoma, #183	The slide shows breast fibro-adipose tissue containing infiltrative solid nests,	infiltrative solid nests	https://vm-vl.projects.umfiasi.ro/en_GB/admin/slide/view/183#zoom=16.07510288065844&x=0.3232073308842591&y=0.41221007964595435
			moderately	https://vm-

Mammary glands		cords, or individual tumor cells with moderately enlarged nuclei, with conspicuous nucleoli, eosinophilic cytoplasm, and variable mitoses that compress the prominent desmoplastic stroma. A focus on ductal carcinoma in situ (DCIS) is observed.	enlarged nuclei	vl.projects.umfiasi.ro/en_GB/admin/slide/view/183#zoom=46.29629629629631&x=0.31692180010959287&y=0.4320062549453528
			desmoplastic stroma	https://vm-vl.projects.umfiasi.ro/en_GB/admin/slide/view/183#zoom=12.920446631187666&x=0.27319972201033654&y=0.5019024278061817

Table 3. Bibliographic references used on the mapping research

DOI or bibliographic reference	Publication year	Region (EU and other countries)	Reference
https://doi.org/10.1002/ar.b.10037	2003	USA	1
https://doi.org/10.1002/ar.b.20066	2005	USA	2
https://doi.org/10.1186/1746-1596-3-S1-S10	2008	EU — Czech Republic	3
https://doi.org/10.1016/j.acthis.2008.09.003	2009	Israel	4

https://doi.org/10.1016/j.humpath.2009.04.010	2009	USA	5
https://doi.org/10.1016/j.aanat.2010.01.008	2010	EU — Germany	6
https://doi.org/10.4415/ANN_10_02_07	2010	EU — Italy	7
https://doi.org/10.1186/1746-1596-5-73	2010	EU — Hungary	8
https://doi.org/10.1038/modpathol.2009.190	2010	Canada	9
https://doi.org/10.4415/ANN_10_02_03	2010	EU — Italy	10
https://doi.org/10.1186/1746-1596-6-S1-S13	2011	EU — Poland*	11
https://doi.org/10.5858/135.2.211	2011	USA	12
https://doi.org/10.1186/1472-6920-11-4	2011	USA	13
https://doi.org/10.1002/ase.262	2011	USA	14
https://sciendo.com/pdf/10.2478/v10052-011-0003-4	2011	EU — Poland*	15
https://doi.org/10.1111/j.1600-0463.2011.02869	2012	UK — Northern Ireland	16
https://doi.org/10.1002/ase.1350	2013	USA	17
https://doi.org/10.1002/ase.1353	2013	EU — Belgium	18
https://doi.org/10.1186/s13000-014-0208-6	2014	EU — Poland*	19
http://dx.doi.org/10.1016/j.humpath.2014.06.007	2014	USA	20
http://hdl.handle.net/10045/49169	2015	EU — Spain*	21
http://drj.mui.ac.ir/index.php/drj/article/view/1870	2017	India	22
https://doi.org/10.1002/ase.1844	2018	Canada	23
https://doi.org/10.1097/JPA.000000000000198	2018	USA	24
https://doi.org/10.21815/JDE.018.084	2018	Brazil	25
https://doi.org/10.1002/ase.1774	2018	USA	26
https://doi.org/10.1111/eje.12410	2018	EU — Czech Republic & Austria	27
https://doi.org/10.21315/eimj2019.11.4.5	2019	Malaysia	28
https://doi.org/10.1002/ase.1940	2019	Taiwan	29
https://doi.org/10.1109/ISETC50328.2020.9301150	2020	EU — Romania*	30
https://doi.org/10.1109/ISETC50328.2020.9301122	2020	EU — Romania*	31
https://doi.org/10.1109/EHB50910.2020.9280225	2020	EU — Romania*	32
https://doi.org/10.32015/JIBM/2020-12-1-8	2020	EU — Romania*	33

https://doi.org/10.4103/JMAU.JMAU_67_20	2020	Saudi Arabia & Egypt	34
https://doi.org/10.1016/j.jds.2021.03.011	2021	Taiwan	35
https://doi.org/10.1111/ahc.12765	2021	EU — Czech Republic & Austria	36
https://doi.org/10.1002/ase.2072	2021	Brazil	37
https://doi.org/10.1002/ase.2038	2021	Australia	38
https://doi.org/10.18295/squmj.4.2021.009	2021	United Arab Emirates	39
https://doi.org/10.1177/23742895211006819	2021	USA	40
https://doi.org/10.21315/eimj2021.13.4.4	2021	Malaysia	41
https://doi.org/10.34808/x55q-sz53_dyr_roz3	2022	EU — Poland*	42
https://doi.org/10.1002/ase.2239	2022	USA	43
https://doi.org/10.1016/j.acpath.2022.100059	2022	USA	44
https://doi.org/10.1016/j.jds.2022.04.008	2022	Taiwan	45
https://doi.org/10.1016/j.mjafi.2022.02.002	2022	India	46
https://doi.org/10.3390/diagnostics13030558	2023	Commonwealth of Nations (Grenada, Cayman Islands, UK, Australia & India)	47

*Country of a VM3.0 partner

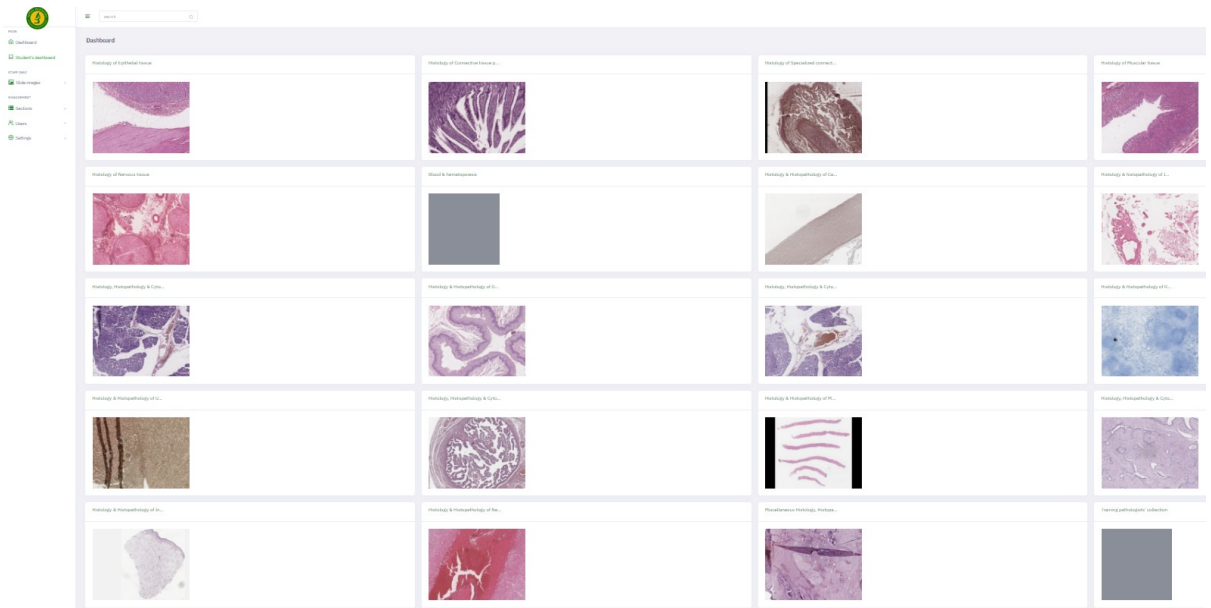


Figure 1. The opening screen of the VM3 platform. After logging in, a screen with a navigation menu is displayed on the left side with the following items: Dashboard — a general interface for the teacher/administrator, containing general data on the number and kinds of users and statistics, and Student's dashboard — a screen for the student/end user. Below are the drop-down menus (Slide images, Sections, Users, Settings). The central section contains photomicrographs of slides with their names. Top right — shortcuts: language selection, light/night mode, full screen, and user shortcut (name/login).

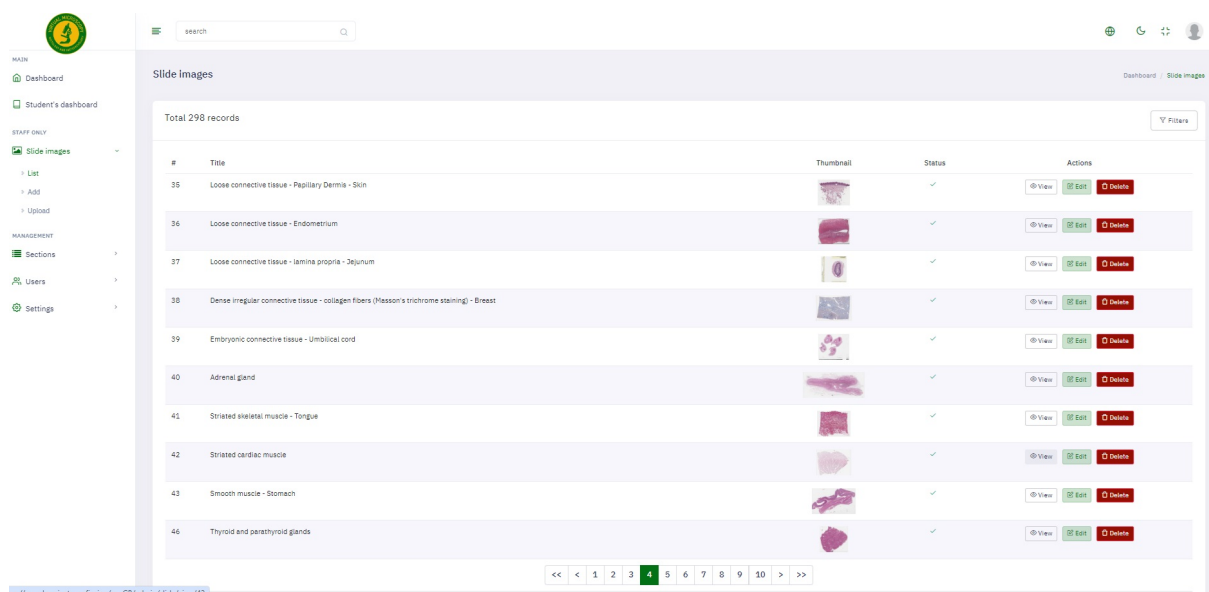


Figure 2. Selecting a histological slide on the VM3 platform. From the “Slide images” drop-down panel on the left side of the screen, the student can select the appropriate slide. The teacher/admin can edit (adding, deleting, editing names and descriptions) slides. The main panel contains the slide number, its name, thumbnail, and the option to view it in the same or new window. There are shortcuts for editing (editing, deleting) slides for the teacher/admin. There is a filter option at the top allowing you to search the platform by slide or section name.

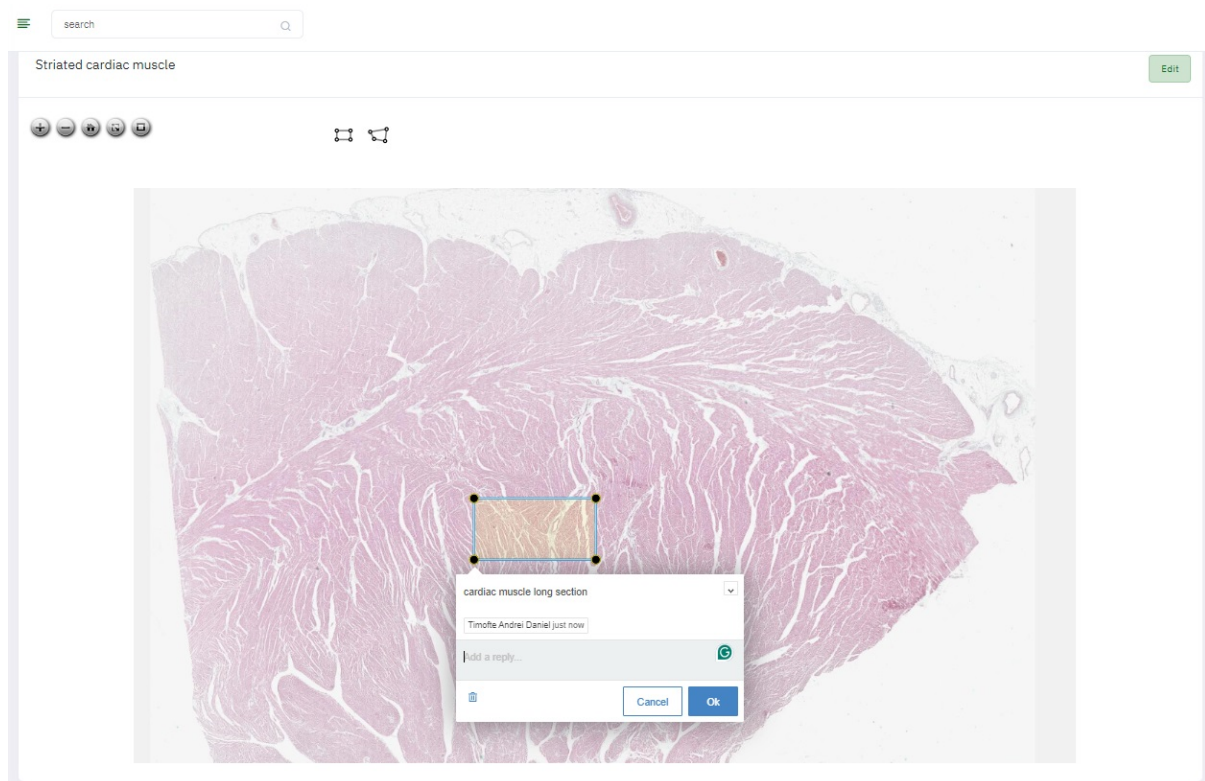


Figure 3. Studying slide image. After selecting the “View” option for a given slide, here, cardiac muscle, a scanned image of the stained histological section appears at the lowest magnification. At the top, there are shortcuts for actions (zoom in, zoom out, home, full screen, and take a screenshot) of the currently viewed part of the slide with an important option of direct saving to the default directory in .png format. Next to the shortcuts, there is an option to outline details in the form of a rectangle or any other shape. Once applied, the user can place a description in this field, which will appear on the screen after clicking on it. In result, the introduced outline details are saved and stored on the dedicated server so that they can be checked online by teachers.

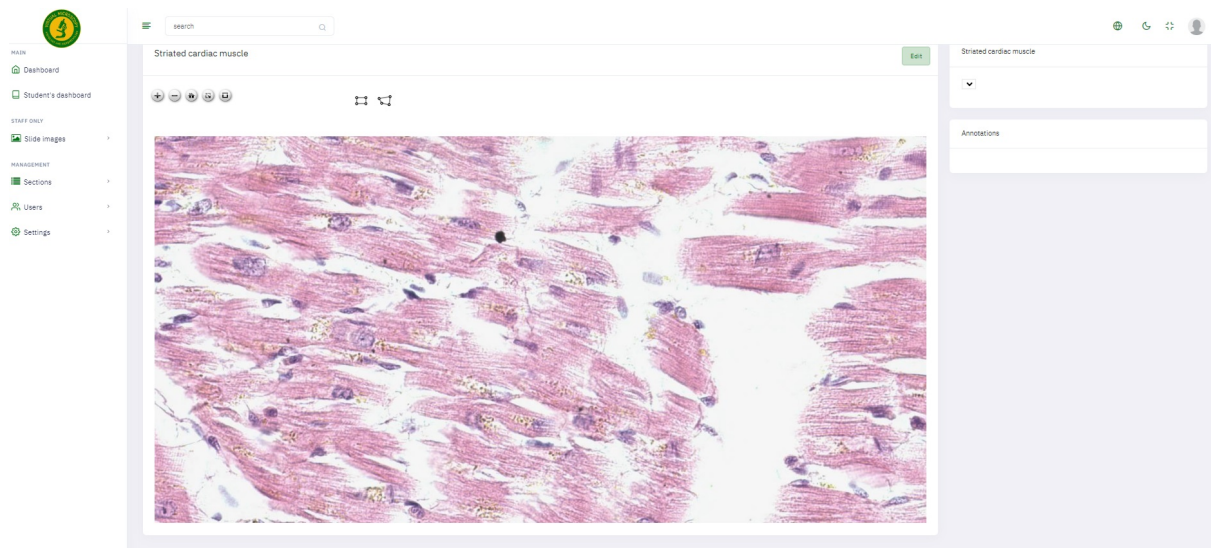


Figure 4. Keywords directly link the specific details of the slide to the corresponding images. This image appears when the user clicks on a hyperlink placed in the slide’s characteristics as shown in Table 2 (here, the “intercalated disk” hyperlink from Table 2 https://vm-vl.projects.umfiasi.ro/en_GB/app/viewer/42#zoom=125.7590852130326&x=0.51709664185093&y=0.1801713049046873). The image is centered on the appropriate detail (at the magnification appropriate for the specific detail/area of the slide), without marking by other methods. The image can also be obtained manually by using the zoom-in shortcut or using the mouse wheel.

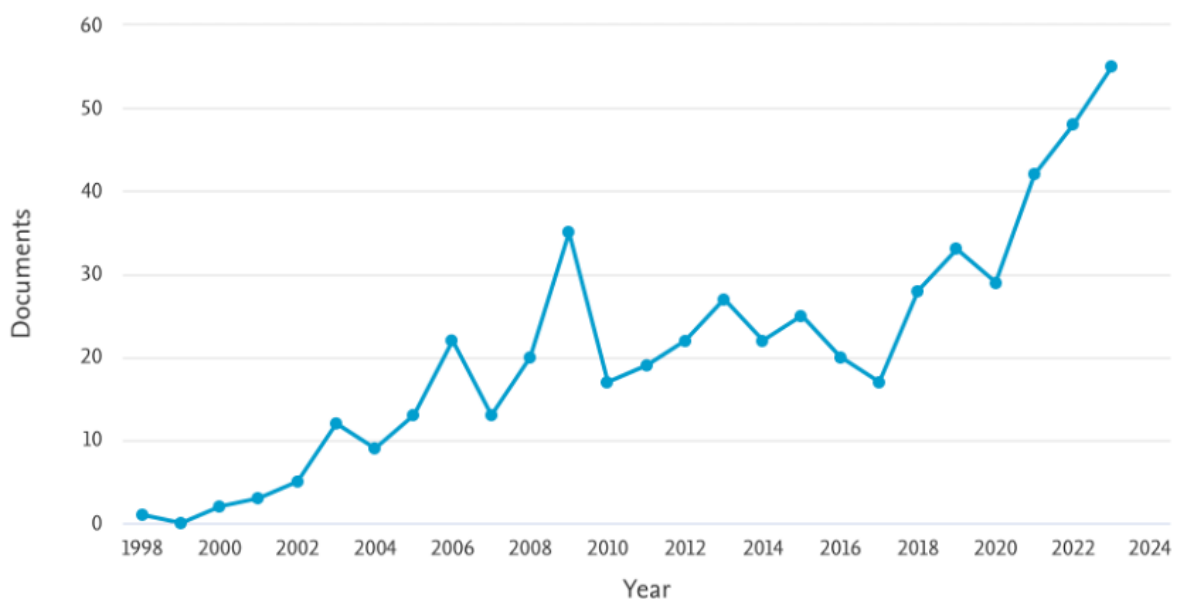
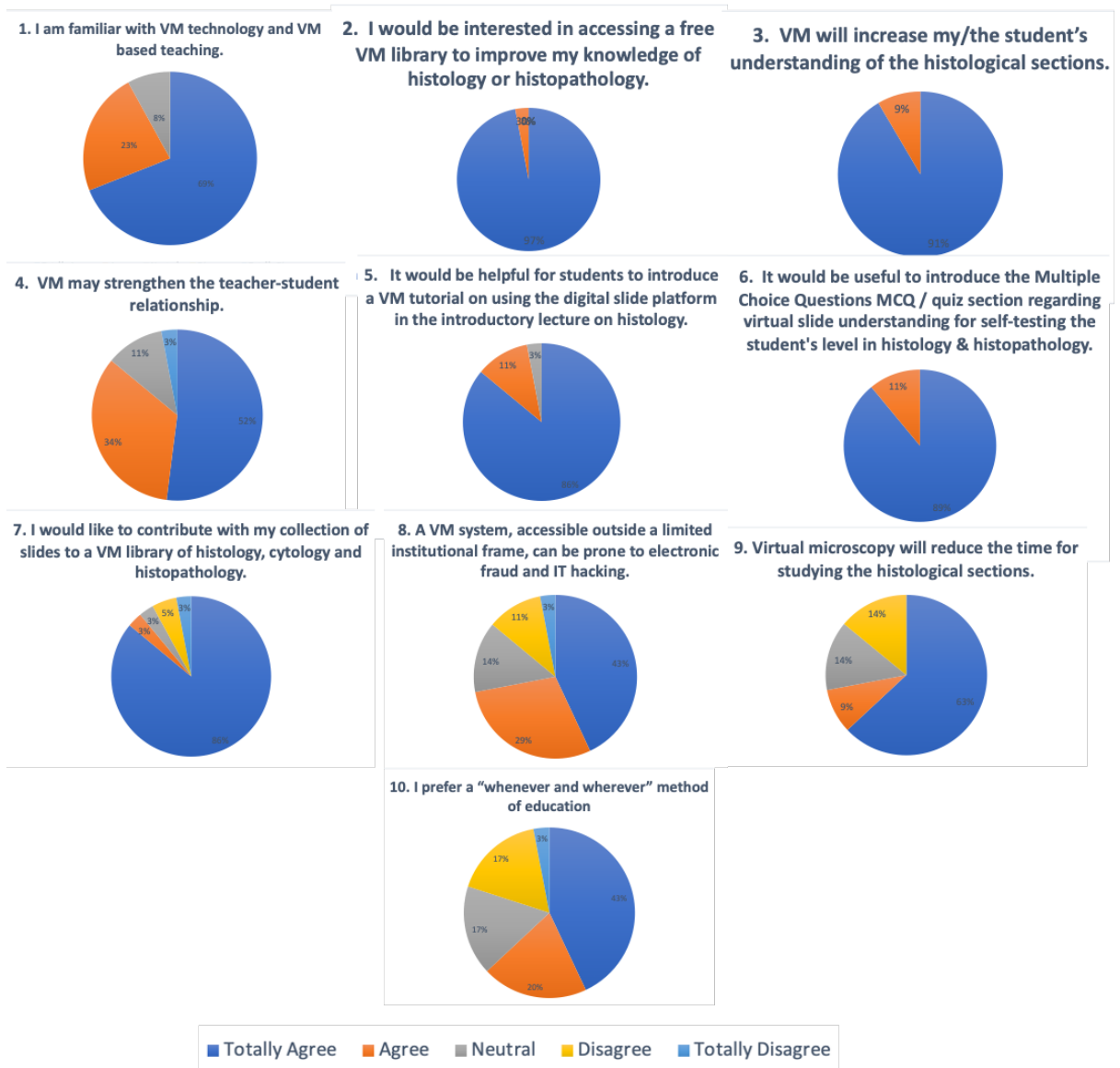


Figure 5. Number of publications *per* year related to the use of VM in teaching histology after a search on SCOPUS with the keyword's combination: "virtual" and "microscope" or "microscopy" and "histology"

Supplementary Table 1. Distribution by country of the experts participating in the mapping research of the project.

Partner	Country	Number of experts
P1: „Grigore T. Popa” University of Medicine and Pharmacy, Iasi	Romania	10
P2: Gdanski Uniwersytet Medyczny	Poland	15
P3: Meditsinsky Universitet-Plovdiv	Bulgaria	5
P4: Universidad de Alicante	Spain	5



Supplementary Figure 1. Answers provided by the experts on the questionnaire used in the mapping research strategy.



Supplementary Figure 2. The most common terms used in the open-answer part of the experts' questionnaire on the advantages of VM in histology teaching.