Training Future Doctors in Computer Modeling

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***Abstract*—This article presents the development and evaluation of a methodology for teaching computer modeling using Augmented Reality (AR) to enhance the digital competence of future medical professionals. The study highlights the necessity and effectiveness of interdisciplinary integration, particularly the combination of anatomy and computer science. The article analyzes survey responses from 108 medical university students to assess their current attitudes toward computer modeling and proposes a methodology based on the elective course "Computer Modeling of Human Organs" that incorporates AR technologies. Observations during the implementation of this methodology revealed key factors influencing the perception and assimilation of the material. To evaluate the effectiveness of the proposed approach, a pedagogical experiment involving 108 medical students was conducted. The results of the student's t-test indicated that the difference between the control and experimental groups was statistically significant. Following the experiment, an additional survey assessed students' perceptions and attitudes toward the use of augmented reality in teaching computer modeling within the educational process.**

***Keywords*—medicine, computer modeling, anatomy, education, visualization**

I. Introduction

The modern stage of societal development is marked by the widespread integration of information technologies into nearly all areas of human activity, including medicine. Research into the didactic and methodological potential of new information technologies has shown that computer modeling is among the most promising approaches for integrating digital tools into education, allowing institutions to meet the evolving demands placed on the modern education system. The contemporary healthcare system requires specialists who are capable of continuous professional growth and self-improvement. The development of relational thinking [1], defined as the ability to identify meaningful patterns within any flow of information [2], and visual-spatial abilities, understood as the capacity to mentally manipulate objects in three dimensions [1, 3–5], are pressing issues in the education of future physicians. One of the critical conditions for delivering competitive higher medical education is to stimulate clinical reasoning in students and to apply interdisciplinary approaches to enrich their knowledge, skills, and competencies, as shown in the works [6, 7]. A future physician must be able to perceive anatomical structures, such as internal organs, not only from an external perspective but also be capable of mentally deconstructing them into their component parts and identifying their essential features. In doing so, the student does not just examine the physical object but also conceptualizes it in abstract or comparative terms.

Several of the most essential characteristics of an object can be represented through a model. Computer modeling enables students to visually and interactively study the structures of the human body. In contrast to traditional 2D anatomical atlases and textbooks, 3D models provide the opportunity to view organs and systems from all angles, examine their relative positions, and thus facilitate deeper memorization and understanding.

In medical higher education institutions in Kazakhstan, the development of a national strategy for innovative training of future doctors is a particularly urgent and relevant issue. There is a growing need for elective courses that involve modeling of objects and real-life medical scenarios requiring problem-solving skills. Teaching future doctors computer modeling makes it possible to address the following didactic goals:

- development of practical skills in computer modeling;
- formation and enhancement of professional and personal competencies;
- bridging the gap between academic disciplines and fostering knowledge integration.

The aim of this article is to describe the development and evaluation of a methodology for teaching computer modeling using Augmented Reality (AR) to enhance the digital competence of future medical professionals.

Research objectives:

- to analyze existing methods and approaches for teaching computer modeling in medical universities;
- to develop and implement a methodology for teaching computer modeling using augmented reality (AR);
- to identify the challenges faced by students and instructors in mastering computer modeling;
- to conduct a pedagogical experiment to compare the effectiveness of traditional and innovative teaching approaches.

The research methodology employs an integrated approach, combining theoretical analysis and empirical investigation. The theoretical component includes a review of scientific literature on the use of computer modeling in education, as well as an analysis of key challenges and solutions. The study is guided by an interdisciplinary perspective, merging insights from medicine and computer science to provide a comprehensive understanding of the role of computer modeling in the education of future healthcare professionals.

II. Literature Review

The global body of literature explores various aspects of computer modeling in education, focusing on its roles as a

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teaching tool, a subject of instruction, and a method of delivering educational content.

Many studies consider computer modeling primarily as a teaching tool. Researchers have proposed a variety of methodological approaches, including simulations, virtual reality, project-based learning, and other strategies aimed at improving the training of future doctors through the integration of computer modeling.

In a comprehensive scoping review, Mahmud *et al.* [6] analyzed various AR applications and concluded that AR-based tools enhance clinical competence by providing immersive, interactive experiences that are not possible through traditional methods.

Additionally, the effectiveness of collaborative learning in enhancing students' critical, creative, and metacognitive skills has been demonstrated through meta-analytical research in the biological sciences by Ramdani *et al.* [7].

Issenberg *et al.* [8] explores the use of computer simulations for the training and assessment of practical skills among medical professionals. The authors discuss various types of simulations that assist students in developing critical competencies such as diagnosis, treatment planning, and performing medical procedures.

Kneebone *et al.* [9] investigates the role of simulation in surgical education. The author emphasizes the importance of using computer models and virtual simulators to develop key surgical skills, including operative techniques and clinical decision-making.

Maran and Glavin [10] examine the application of simulators in the education of healthcare professionals. The authors evaluate methods for integrating computer modeling into the curriculum, with the goal of fostering professional competencies.

Liu and Lee [11] analyze the role of computer modeling and simulation in medical education, placing special emphasis on methodological aspects and the impact of these technologies on student learning outcomes.

Gordon and Berman [12] addresses both the challenges and opportunities associated with incorporating computer simulations and virtual technologies into medical education. The study outlines effective strategies for educators to leverage these tools in developing students' clinical skills.

Cook *et al.* [13] presents a comprehensive overview of research related to the use of computer simulations in medical education. The review highlights the variety of methodological approaches employed to enhance teaching and learning processes through simulation technologies.

Recent studies, particularly in procedural specialties, have demonstrated the effectiveness of medical simulation in high-stakes assessment contexts. Ziv *et al.* [14] developed a research and development program that led to the implementation of an Objective Structured Clinical Examination (OSCE) based on simulation, which became part of the Israeli National Board Examination in Anesthesiology.

Let us consider several authors who have examined computer modeling specifically as a teaching tool for future physicians:

Issenberg *et al.* [8] explores the use of computer simulations as an educational and training resource for medical professionals. Simulations play a vital role in preparing future doctors by providing opportunities to develop practical skills that are difficult or sometimes even impossible to acquire in real clinical environments.

Kneebone *et al.* [9] focuses on the use of simulators in surgical training. The author highlights how computer models assist aspiring surgeons in building both cognitive and motor skills, as well as in making critical clinical decisions.

Studies [10, 14] emphasize the importance of simulation technologies in medical education, noting their utility in helping students learn and master complex clinical processes and procedures.

Gaba [15] discusses the potential of simulation and computer modeling as effective teaching tools for medical students. He illustrates how simulators can be employed to train students in managing challenging clinical scenarios, such as emergency situations and surgical interventions.

The articles [16–19] examines the prospects for using virtual reality and simulations in medical education. These technologies help students not only master practical skills, but also develop a deeper understanding of complex medical concepts and processes.

Bradley [20] examines the history and future of using computer simulations as a teaching tool for medical students. The author emphasizes the importance of using such technologies to improve understanding of anatomy, physiology, and medical procedures.

Liu and Lee [11] discuss the role of computer simulation as a teaching tool for future medical professionals. They emphasize the importance of using models to enhance students' cognitive and analytical skills, helping them to better understand and apply medical concepts.

The objective of study [21] is to review the use of computer games and simulations in teaching and assessing medical knowledge and skills within the field of military medicine.

Ghanbarzadeh *et al.* [22] presents a systematic review of research related to 3D Virtual Worlds (3DVW) and classifies the findings according to their application areas in healthcare. The literature revealed six main themes: (1) treatment, (2) simulation, (3) assessment, (4) lifestyle, (5) academic education, and (6) professional education.

Choudhary *et al.* [23] highlights the potential of Artificial Intelligence (AI), particularly ChatGPT, for interactive learning in anatomical education. For future medical professionals, especially those in veterinary and biomedical fields, this creates new opportunities to engage with digital simulations and virtual patients. This is directly related to computer modeling, where not only technical construction, but also the accurate representation of anatomical structures is essential.

Choudhary *et al.* [24] explores both the potential and limitations of AI in the context of animal anatomy. It provides an in-depth analysis of the accuracy and reliability of AI tools in working with anatomical data, which is crucial for the creation of digital anatomical models used in education and simulation. This is particularly valuable for training doctors involved in biomedical modeling, as it demonstrates how AI can interpret complex biological structures — from recognition to visual reproduction.

Vickram *et al.* [25] show how AI contributes not only to education, but also to diagnostics and surgical planning, based on 3D anatomical models of animals. This provides a practical foundation for transitioning from educational modeling to clinical applications, which is especially relevant in medical training.

Together, these studies underscore the growing importance of computer simulation in medical education. They offer students the opportunity to develop not only hands-on skills, but also deep conceptual understanding through interactive technologies and simulation-based learning.

Previous articles consider the aspect of computer modeling as a teaching object [26–28]. Rakhimzhanova *et al.* [28] the developed methodology for teaching computer modeling is an open system that can be changed and adjusted taking into account the development of modern computer technology and the emergence of new computer models for visualizing medical information.

Dyakova [29] examines approaches to teaching biomedical modeling, as well as the role of computer technologies in training specialists.

The aim of the studies [3, 4] was to investigate the impact of 3D anatomical models on learning and to evaluate the quality of the relevant studies. Of the 94,616 studies, 30 included data on the impact of 3D models on anatomy learning. Anatomy requires good spatial visualization to identify structures. Visual-spatial ability is important for medical and dental students, as well as for surgeons. The ability to manipulate 3D structures is critical to understanding anatomy. Research in this area helps to assess how to improve student learning. The review aims to assess the impact of 3D models on learning and to evaluate the quality of research papers identified using the MERSQI tool. Research gaps and future directions are also discussed.

The primary objective in training future doctors within the framework of the evolving European educational space is to prepare highly qualified, competent specialists in higher medical education. One of the key conditions for delivering competitive medical education is the stimulation of clinical thinking among students and the application of interdisciplinary approaches that enrich their knowledge, skills, and competencies [30]. Moreover, future physicians must be prepared to systematically process large volumes of information and integrate knowledge from emerging disciplines. To achieve this, not only educational programs and curricula, but also pedagogical methods and formats of instruction must be aligned with these evolving demands.

Putri *et al.* [31] presents an interactive mobile learning application designed to support medical students in studying ear anatomy using a 3D model. The study also explores students' perceptions of the VLab platform and its impact on the learning process, as reflected in their academic performance.

Dumas [2] reviews literature related to the concept of relational thinking, defined as the ability to identify meaningful patterns within information streams, which plays a central role in the cognitive work of scientists, physicians, and engineers. Among the highlighted studies are those that develop computer models and algorithms to simulate relational thinking in silico, outlining future directions for further research and development.

III. Methods

As part of the qualitative phase of the study, the article identifies various factors influencing the teaching of computer modeling to future doctors, including motivation and the perceptions of both students and instructors.

A quantitative study was also conducted, providing objective data on learning outcomes achieved through the proposed methodology. The effectiveness of Augmented Reality (AR) in verifying the adequacy of constructed computer models was evaluated through a pedagogical experiment carried out at a higher education institution in Kazakhstan.

Having analyzed the results of the experiment, several challenges in teaching computer modeling to future doctors were identified.

A. Survey

Before developing a methodology for teaching computer modeling to future doctors, the authors examined existing methodological approaches used in the training of medical specialists.

Fig. 1 presents the distribution of positive responses to questions from a survey conducted among 108 medical students. The survey was designed to gather students' opinions regarding the relevance and importance of studying computer modeling as part of their medical education.

The diagram illustrates the percentage of positive responses from students to questions concerning the use of computer modeling in the educational process, particularly in the study of anatomy. The following are the key conclusions drawn from the collected data.

The highest percentage of positive responses (90.7%) was recorded for the question *"Do you know what computer modeling is?"*—indicating a high level of student awareness in this area. Additionally, a significant proportion of respondents (82.4%) reported familiarity with 3D modeling.

However, despite this high level of awareness, only 50% of students stated that they had studied computer modeling within their anatomy course, while 43.5% noted that the teaching methods used were unclear. This suggests a need to revise educational programs and enhance instructional strategies.

Moreover, 79.6% of students expressed interest in learning computer modeling as part of their anatomy curriculum, and 54.6% expressed a desire to use 3D models in Augmented Reality (AR) environments. These findings demonstrate a strong interest in the practical application of digital technologies in medical education.

By contrast, relatively low percentages (10% and 5%) were recorded for questions regarding challenges in learning computer modeling and prior experience with related projects. This may indicate both a lack of educational opportunities in this area and insufficient support for students.

Notably, 75% of respondents believe that computer modeling provides advantages over traditional methods for learning anatomy, and 69.8% consider 3D modeling skills essential for future medical professionals. These results highlight the growing importance of digital technologies in medicine and the urgent need for their integration into the medical education system.

Thus, the analysis of the diagram demonstrates a high level of student awareness regarding computer modeling, as well as a strong interest in studying and applying digital technologies. At the same time, it reveals the need to enhance teaching methods and expand the number of practical projects. For the effective integration of computer modeling in medical education, it is essential to develop well-structured educational programs and to provide students with appropriate tools for working with digital models.

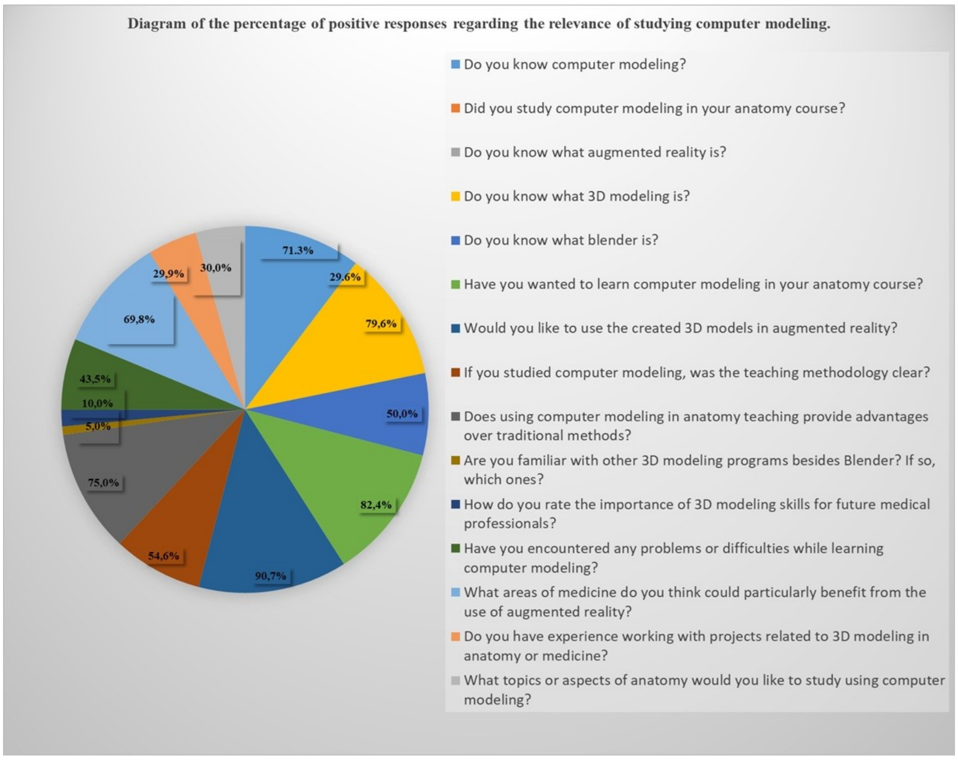


Fig. 1. Results of the survey.

B. Research Methodology

Fig. 2 presents the instructional methodology, including its objectives, content, formats, teaching methods, and instructional tools.

After completing the theoretical component, students proceed to create informational models of human organs, which serve as the basis for the next stage—developing computer models using the Blender graphics editor.

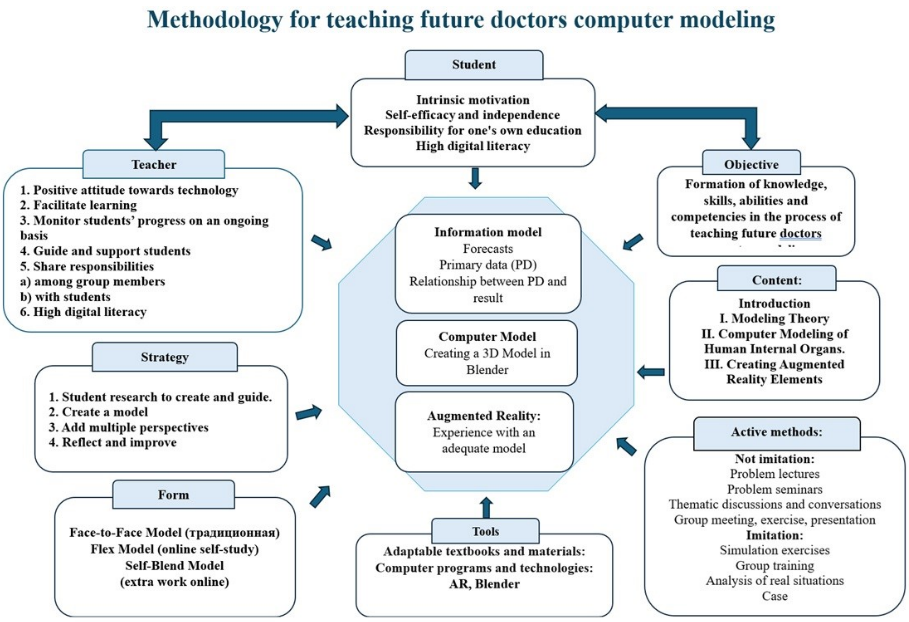
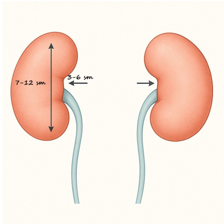
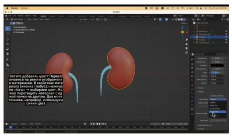


Fig. 2. Scheme of the methodology for teaching computer modeling to future doctors.

Augmented Reality (AR) enables the modeling and visualization of processes that are difficult or impossible to demonstrate in real-world settings [32, 33]. To assess the accuracy and adequacy of the constructed models, AR technology is employed. It allows students to project the developed 3D models onto a human skeleton mannequin using attached QR codes. By pointing a tablet at the QR code, students can view the computer-generated 3D organ models in context, helping them evaluate how closely the models resemble actual anatomical structures. This approach enhances students' understanding of human anatomy through immersive, interactive learning.

Table 1 presents an example of the kidney modeling process, with a breakdown of each development stage.

Table 1. Stages of kidney computer modeling

Stages of computer modeling	Model	Description	Drawing
1. Development of information model	Information model	External structure of the kidney: The kidney is a paired bean-shaped organ. The distance from the upper to the lower pole is 7–12 cm. Between the lateral (outer) and medial (inner) edges is 3–6 cm. Covered with a fibrous capsule (outer shell). Inside the kidney is the renal hilum (the entry point of the vessels and exit of the ureter). The ureters (U) are paired tubular organs through which urine flows from the kidneys to the bladder, which ensures a one-way flow of urine from the renal pelvis. Number of U-2. Length 25–35 cm. Diameter 3–7 mm (can reach up to 10 mm when stretched). Shape Narrow, flexible tube with bends	
2. Development of computer model	Computer model	Building a 3D Kidney Model in Blender: Preparation 1. Open Blender 2. Delete the default cube (X → Delete) 3. Switch to Front view (Numpad 1 or View > Front) 4. Create the general shape Cut out the renal hilum Create the internal structure (pelvis) Create the ureter shape, connect the ureter to the pelvis Image materials and texture Lighting and rendering,	
3. Validation of Models Using Augmented Reality	Model in UNITY	Unity 3D (URP/AR Template) Start the project. Add the fbx file to Assets Apply materials and animations to the model in Unity Save the kidney model as a Prefab (for reuse)	
4. Adequate modeling of the experiment	Experiment with the model	The user can use fingers on the screen (touch-gesture) or controllers/hand gestures: Zoom in/out on the object (pinch-to-zoom). Rotate in space. Drag to the desired position	
5. Clinical reasoning task	Experiment with the model	A 49-year-old patient has been found on CT to have a 3 cm tumor in the mid-portion of the right kidney, located close to a segmental artery, without signs of invasion into the collecting system or surrounding tissues. Question: Draw the tumor in the 3D model in a way that helps the surgeon decide on the treatment strategy. What specific details would you make sure to include while drawing the tumor, and why?	

C. *Observation*

During the observation of the educational process, which included lectures and practical sessions within the course "Computer Modeling of Human Organs" where the author's methodology was implemented, it was found that students demonstrated active engagement due to interactive elements such as hands-on modeling of various organs. The methodology enhances students' comprehension, as it allows them not only to study theoretical concepts but also to apply their knowledge in practice by creating computer models of organs and analyzing their behavior through augmented reality.

However, some challenges were also identified. Students require additional time to master Blender tools, which occasionally leads to delays in completing assignments. An important consideration is the need to improve students' technological adaptability and their proficiency in working with software, as well as to allocate more time for practical sessions to enable a deeper exploration of the subject matter.

Despite certain technical and organizational difficulties, this approach demonstrates high effectiveness in preparing future doctors to design and analyze computer models of human organs.

D. *Analysis*

In the process of implementing the methodology for teaching computer modeling of human organs, we examined how students develop information models, interact with modeling software such as Blender, and verify the accuracy of their models using augmented reality (AR). This analysis enabled us (Table 2) to identify several key factors that influence students' perception and assimilation of the learning material.

Table 2. Key aspects influencing the perception and assimilation of the material

Aspect	Development of an information model	Development of a computer model	Testing the adequacy of the model using AR
Perception of the process	Lack of knowledge about the structure of organs, their parts and functions in anatomy leads to difficulties and the creation of inaccurate models.	Blender's interface and features can be confusing for some people.	It is of interest because AR allows interaction with 3D models and improves the perception of anatomical relationships.
Stages of development	Requires preliminary preparatory stages to gain knowledge about the structure of organs and their functions	It is important to provide clear step-by-step instructions and examples with explanations, especially in mastering terms and concepts (meshes, textures, lighting).	The teacher creates AR using Unity on the constructed models. Students create QR codes for these objects with interest.

Efficiency of material assimilation	A lack of understanding of the structure of organs in anatomy can slow down the process of assimilation of the material and lead to simplified models.	Depends on the structure of the training and the practical focus. If the assignments are focused on real-world problems, such as modeling organs, students will master Blender faster and improve their skills.	The use of AR improves learning by allowing students to work with models in real time and see the relationship between anatomical structures.
Support and training	Consultations on anatomy. Educational materials explaining the basic principles of modeling.	Educational videos, step-by-step guides and consultations. It is important to start learning with basic skills: navigation in space, creation of objects.	Instructions and technical assistance.
Feedback	Students correct their mistakes in understanding anatomy as indicated by the teacher and improve the accuracy of the models. Eliminating deficiencies in details helps develop skills.	Allows to quickly identify problems with using Blender and suggest solutions to improve the model.	The ability to see the adequacy of the model and instantly adjust the models otherwise.

IV. Result

A. Pedagogical Experiment

The educational materials used by both groups were identical in content; however, the key difference lay in the instructional approach. The experimental group was taught using a computer modeling methodology incorporating Augmented Reality (AR) components, while the control group followed the existing elective course "Computer Modeling in Medicine".

The study sample consisted of students majoring in medical specialties. Both instructional approaches were implemented over the course of one academic semester. Students' progress was regularly monitored, and necessary support was provided to ensure the high-quality delivery of the educational program.

A quantitative research method was used to evaluate the results. Statistical analysis, including the calculation of the Pearson correlation coefficient, was applied to determine whether the differences in test scores between the two groups were statistically significant.

A pedagogical experiment was conducted with a total of 108 medical university students, equally divided into two groups: the experimental group (n_1 = 54) and the control group (n_2 = 54). The distribution of final test scores (measured on a 100-point scale) is presented in Tables 3 and 4.

Table 3. Test results for experimental group, measured on a 100-point scale

Score Range	Number of Students	% of Group
90–100	21	38.9 %
80–89	23	42.6 %
70–79	10	18.5 %
< 70	0	0 %

Note: *Experimental Group* (n_1 = 54); Minimum = 72; Maximum = 98

Table 4. Test results for control group, measured on a 100-point scale

Score Range	Number of Students	% of Group
90–100	0	0 %
80–89	8	14.8 %
70–79	23	42.6 %
< 70	23	42.6 %

Note: *Control Group* (n_2 = 54); Minimum = 55; Maximum = 88

$\overline{X}, \overline{Y}$: mean values of assessments in the experimental and control groups, respectively.

$\overline{X} = 86.5,\ \overline{Y} = 72.3$

n_1, n_2: sample sizes in the groups

$n_1 = n_2 = 54$

S_p: pooled standard deviation

S_1: standard deviation in the first group

S_2: standard deviation in the second group

$S_1 = 6.8$; $S_2 = 8.4$

$$S_p = \sqrt{\frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{(n_1 + n_2 - 2)}} \approx 7.64$$

Calculating the t-statistic

t- t-statistic

$$t = \frac{\overline{X} - \overline{Y}}{S_p\sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \approx 9.66$$

d_f : degrees of freedom

$d_f = n_1 + n_2 - 2 = 106$

B. Interpretation of the Result

An independent samples t-test was conducted to compare the groups:

$$t = 9.66;\ d_f = 106;\ p < 0.001$$

Thus, the difference between the groups is statistically significant. Students in the experimental group achieved significantly higher test scores.

C. Clarification of Assessment Tools across the Three Stages of the Study

Our study was structured into three sequential stages, each with specific assessment tools designed to evaluate both theoretical knowledge and practical skills. Below, we provide detailed clarification as requested. Table 5 presents the scores of 20 students (10 from the experimental group, 10 from the control group) obtained for constructing each stage of the modeling.

1) Development of informational models

After completing the theoretical part of the course, students were tasked with creating informational models of human organ systems. These models included detailed anatomical descriptions, functional information, and schematic representations. To assess this stage, we used standardized rubrics focused on the following criteria:

- Anatomical accuracy and correct spatial relationships between structures;
- Logical and comprehensive description of the organ's

functions;
- Clarity, organization, and technical quality of the informational model.

Evaluation at this stage was formative as well as summative, with feedback sessions allowing students to refine their models before progressing to the next phase.

2) Creation of 3D computer models in blender

The next stage involved translating the informational models into 3D computer models using the Blender software. Assessment at this phase was based on a standardized rubric with criteria such as:

- anatomical precision of shape and proportions of the modeled organ;
- level of detail included in the model, representing essential anatomical structures;
- accurate scaling and orientation of the organ in three-dimensional space;
- technical quality of modeling work in Blender (e.g., correct geometry, mesh topology, application of materials or textures where required).

During this phase, students presented interim versions of their models for feedback, which helped identify areas needing improvement before final submission.

3) Validation of models using Augmented Reality (AR)

Following the creation of the 3D models, students participated in a validation stage utilizing Augmented Reality (AR) technology. Students scanned QR codes affixed to a physical human skeleton model, allowing their 3D organ models to appear superimposed in correct anatomical locations. This step enabled students to assess their models' alignment with real anatomical context.

Assessment for this stage employed a practical performance checklist aligned with learning outcomes, evaluating aspects such as:

- precision of alignment between the 3D model and anatomical landmarks on the skeleton;
- correct scaling and spatial positioning of the model;
- functionality and stability of the AR visualization (e.g., correct loading, consistent tracking during movement);
- students' ability to critically analyze discrepancies between their models and real anatomy and to propose modifications.

Additionally, students prepared reflective reports and delivered oral presentations discussing how their 3D models corresponded to actual anatomical structures and explaining any necessary corrections identified through the AR visualization process.

Table 5. Test results for each group, measured on a 100-point scale

Groups	Modeling steps	St_1	St_2	St_3	St_4	St_5	St_6	St_7	St_8	St_9	St_{10}	Squares of deviations
Experimental group	information model	89	94	84	90	96	92	92	90	94	88	
	computer model	85	92	82	85	91	90	98	89	92	90	
	testing the adequacy model in AR	90	90	86	95	98	85	89	94	96	92	
	Average	88	92	85	90	95	89	93	91	94	90	68.1
Control group	information model	74	68	76	66	78	77	83	78	83	76	
	computer model	76	70	69	70	82	79	78	75	78	80	
	testing the adequacy model in AR	75	72	71	68	80	75	76	75	81	78	
	Average	75	70	72	68	80	77	79	76	81	78	68.8

D. Survey of the Experimental Group

A survey was conducted among students in the experimental group to assess their perceptions and attitudes toward the use of Augmented Reality (AR) in teaching computer modeling within the educational process. The survey results are presented in Table 6. This survey represented a key stage of the study, providing valuable feedback and offering a deeper understanding of how students perceive and engage with emerging technologies.

Table 6. Results of the survey of students of the Faculty of Medicine (part of the table is given)

Participant	Computer modeling with AR	Observed benefits	Difficulties	Suggestions for improvement
General medicine	Positive	- Developing skills in working with 3D models -Improved understanding of anatomy and physiology	- Requires mastering specialized software - High demands on computer hardware - Lack of training materials on modeling	- Develop practical applied tasks - Simplify program interfaces for medical students
Dentistry	Positive	- Creation of detailed models of teeth and jaws - Visualization of various dental damages before treatment	- Difficulty in mastering modeling software - Lack of teachers with AR experience - High cost of software licenses	- Introduce computer modeling courses into dental education - Create tutorials with step-by-step instructions
Pharmacy	Neutral	- Mode ling Molecular Interactions - Drug Effect Analysis in AR	- Limited number of ready-made AR models for study - Difficulty in interpreting 3D data without special training - High cost of software	- Creation of open AR model databases for training - Introduction of computer modeling courses in pharmaceutical universities
Nursing	Positive	- Improving understanding of medical procedures through AR - Simula ting emergency situations for training - Remote learning capability	Insufficient technical training of teachers - Difficulty in creating accurate AR models of procedures - Limited number of training simulations	- Develop interactive courses with AR models - Improve digital literacy of teachers

Public Health	Neutral	- Analy sis of anatomical data through 3D visualization - Plan ning of preventive strate gies	- High complexity of healthcare system modeling - Lack of specialists who can work with AR - Large computing resources required for complex models	- Development of simplified tools for modeling - Implementation of the AR course in the training of public health specialists

V. Discussion

The study highlights the importance of teaching computer modeling to future doctors. Building 3D models and using Augmented Reality (AR) for visualization fosters a deeper understanding of anatomy, enhances spatial thinking, and promotes the integration of interdisciplinary knowledge. However, the study also identifies challenges, such as difficulties in mastering specialized software like Blender, and the need to adapt educational materials to meet the individual needs of students. Despite these obstacles, the proposed methodology has demonstrated effectiveness, as confirmed by the results of both the pedagogical experiment and the student survey.

A comparison of the findings with existing research in the field of medical education shows that computer modeling is widely recognized as an effective educational tool. The reviewed literature emphasizes that simulations and 3D models significantly improve learning outcomes, particularly in areas such as surgical training and anatomy. These studies confirm that interactive technologies contribute to better comprehension of complex medical concepts and help develop clinical reasoning.

This study specifically focuses on the use of computer modeling in medical universities in Kazakhstan, including the integration of AR technologies. Unlike international studies [8, 9, 11, 13], which often emphasize virtual simulators and virtual reality (VR) environments, this research places particular emphasis on using AR to verify the adequacy of 3D organ models and their alignment with real anatomical structures — a relatively novel approach within Kazakhstan's medical education system. This enables students to interact with models in real time, facilitating a clearer understanding of the shape, size, and spatial relationships of organs.

The study pays special attention to analyzing students' perceptions of AR. According to the survey, most respondents evaluated the use of AR and 3D models positively, which is consistent with findings from previous studies [8, 16, 33], where such technologies were shown to increase student engagement and improve the quality of learning.

The results of the pedagogical experiment indicate that the incorporation of AR components enhances student motivation and academic performance compared to traditional teaching methods.

Another distinguishing feature of this study is its emphasis on interdisciplinary knowledge integration. While many international studies focus on computer modeling within the context of a single discipline (e.g., surgery, dentistry, or anesthesiology), the proposed methodology aims to merge knowledge from multiple areas of medicine with Information and Communication Technologies (ICT) to develop both informational and computer models. This approach contributes to a more holistic and comprehensive understanding of the subject matter.

Although many review articles (e.g., [9, 12]) acknowledge the importance of interdisciplinary connections in medical education, these connections are often discussed only at a theoretical level. This study offers a practical implementation of the interdisciplinary approach by integrating content from anatomy, physiology, medical imaging, and digital technologies. Moreover, the results of the pedagogical experiment suggest that such integration contributes to the development of clinical thinking, as students not only memorize theoretical knowledge but also actively analyze anatomical structures, assess their functionality, and conduct virtual experiments.

The study also addresses the importance of overcoming barriers related to the adaptation of students and instructors to new technologies. For example, as noted in [11], the primary obstacles to implementing simulation-based learning include a lack of training materials, complex interfaces, and insufficient technical training. These same issues were echoed in the current study's survey results.

Thus, the study reinforces the findings of existing literature on the benefits of computer modeling in medical education. However, what distinguishes this research is its specific focus on teaching computer modeling using AR, its interdisciplinary approach, and its analysis of the challenges associated with introducing innovative technologies into the national educational system.

While the literature [13, 10] supports the effectiveness of computer simulations as teaching tools, it also emphasizes the need for further research on their impact on academic performance.

Overall, this study confirms the main conclusions of global research regarding the importance of computer modeling in medical education and underscores the need for additional research into how these technologies can be adapted to national educational standards and the technical capacities of universities.

Despite the clear benefits, computer modeling in medical education still faces several challenges. Studies [2, 21, 30] cite issues such as the need for technical training for educators, difficulties in mastering complex software, and the high cost of equipment. These challenges were also observed during the present study.

However, unlike most reviews which focus on institutions with highly developed technical infrastructures, this study reflects the realities of implementing such technologies in medical universities in Kazakhstan. It identifies specific issues such as the lack of instructional materials in the national language, the low level of digital literacy among some students, and the need to adapt curricula to support the integration of advanced technologies.

In conclusion, this study reaffirms the findings of international research on the benefits of computer modeling in medical education while also contributing new insights into the adaptation of these technologies in local educational contexts. It highlights that the further development of computer modeling in medical education requires not only technological innovation but also the alignment of educational standards, the expansion of teaching resources, and the training of qualified professionals capable of effectively implementing new technologies in the learning process.

Thus, the scientific novelty of this study lies in the use of a teaching method for training future doctors in computer modeling with the application of AR and Blender, which differs from the traditional approach using VR simulators and makes the educational process more interactive and accessible.

VI. Conclusion and Recommendations

The results of the study are consistent with global trends in the use of computer modeling in medical education. The findings confirm the importance of computer modeling in training future doctors, demonstrating its effectiveness in developing spatial thinking, integrating interdisciplinary knowledge, and enhancing the overall quality of learning.

A key distinction of this study is the introduction of a computer modeling methodology utilizing Augmented Reality (AR) and Blender, as opposed to the traditional use of VR simulators. This approach makes the learning process more interactive and accessible. The incorporation of AR into the educational process enabled students not only to study anatomical structures in an interactive format but also to independently verify the accuracy of the 3D models they created, contributing to a deeper understanding of the subject matter.

The study identified optimal teaching methods for introducing computer modeling to future doctors and recognized the challenges faced by both students and instructors during the learning process.

The methodology supports interdisciplinary integration by combining medical and technical knowledge. The study confirms the effectiveness of an interdisciplinary approach that merges anatomy, medical imaging, and digital technologies. This integration fosters the development of clinical reasoning, encouraging students to actively engage in analyzing anatomical structures and performing virtual modeling tasks.

The practical effectiveness of the methodology was validated: students who learned computer modeling using AR and Blender achieved higher test scores compared to those in the control group, who followed traditional instructional methods. Surveys of both students and instructors revealed a generally positive perception of the technology, despite challenges such as the complexity of mastering software (e.g., Blender) and the need for additional training for educators.

Future research could focus on developing optimized teaching strategies that take into account both technical and pedagogical factors, as well as on examining the long-term impact of these technologies on the development of students' clinical reasoning skills.

In light of the results, we suggest several specific recommendations:

- Introduction of new elective disciplines taking into account the latest advances in computer modeling and digital medicine.
- Modular structure of courses, including basic, advanced and specialized areas (visualization, modeling of anatomical structures).
- Integration of related disciplines: medical image processing, computer modeling.
- Development of practice-oriented tasks based on real clinical cases and data.
- Using VR/AR to interactively learn anatomy through 3D models.
- Working with real clinical data to prepare students for real medical challenges.
- Carrying out design work together with medical institutions and IT companies.
- Improving the qualifications of teachers in the field of new modeling technologies.
- To improve the effectiveness of teaching computer modeling in medicine, a combination of theoretical knowledge, practical skills and advanced technologies is necessary. It is important to integrate digital solutions into the educational process, create conditions for working with real data and provide students with access to modern software.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

BAi—Data curation, Formal analysis, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Writing—original draft, Writing—review & editing. RL—Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Writing—original draft, Writing—review & editing. BAb—Investigation, Methodology, Writing - original draft, Writing - review & editing. All authors read and approved of the final manuscript.

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