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Impact of 3D printing on medical students' learning: a systematic review.

Impacto de la impresión 3D en el aprendizaje de estudiantes de medicina: una revisión sistemática.

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Abstract: The use of 3D printing has spread in various areas, including medical education, from its support for the study of human anatomy to the training of surgical techniques given the benefits of " *Hands-On-Learning" learning.* The objective of the present research is to clarify the impact of 3D printing on the learning of medical students, as well as to determine in which areas of their curriculum it has been implemented. To do this, a systematic review of the available literature was carried out. The databases used were PubMed, CINAHL, PsycINFO, ERIC, Web of Science and SCOPUS, using the following 4 concepts: "3D Printing" AND "Medical Education" AND "Outcome of Education" AND "Higher Education". Publications in English and Spanish were considered. 3,326 studies were identified up to October 2023 (705 duplicates). Using the PRISMA 2020 protocol and the COVIDENCE software, four authors reviewed the results and selected those that met inclusion and exclusion criteria. 2,561 studies were excluded, with 60 studies identified for full-text reading. Of these, 34 met the proposed inclusion criteria, and were ultimately reviewed and synthesized by the authors. Among the findings, there is a trend to investigate the educational role of 3D printing in areas of anatomy, various pathologies, radiology, and simulation. When comparing 3D printing with 2D models, better post-intervention scores were found in the 3D group. Regarding cadaveric models, 3D printing again shows better results in anatomical learning, although there were also studies that did not show significant differences, however, none reported inferiority of 3D printing as a teaching tool. Finally, a limited number of studies were found on its impact on long-term learning. 3D printing is shown to have a positive impact on learning in various areas of medical training.

Keywords: 3D printing; Medical education; Educational outcomes; Higher education.

Resumen: El uso de la impresión 3D se ha difundido en diversas áreas, incluyendo la enseñanza de la medicina, desde su apoyo para el estudio de anatomía humana hasta en el entrenamientos de técnicas quirúrgicas dado los beneficios del aprendizaje por "*Hands-On-Learning*". El objetivo de la presente investigación es esclarecer el impacto de la impresión 3D sobre el aprendizaje de estudiantes de medicina, así como determinar en qué áreas de su currículum ha sido implementada. Para ello, se realizó una revisión sistemática de la literatura disponible. Las bases de datos usadas fueron PubMed, CINAHL, PsycINFO, ERIC, Web of Science y SCOPUS, usando los siguientes 4 conceptos: "3D Printing" AND "Medical Education" AND "Outcome of Education" AND "Higher Education". Se consideraron publicaciones en inglés y español. Se identificaron 3.326 estudios hasta Octubre 2023 (705 duplicados). Mediante el protocolo PRISMA

2020 y el software COVIDENCE, cuatro autores revisaron los resultados y seleccionaron aquellos acordes a criterios de inclusión y exclusión. 2561 estudios fueron excluidos, identificándose 60 estudios para lectura de texto completo. De estos, 34 cumplieron criterios de inclusión propuestos, siendo finalmente revisados y sintetizados por los autores. Entre los hallazgos, se destaca una tendencia a investigar el rol educativo de la impresión 3D en áreas de anatomía, diversas patologías, radiología y simulación. Al comparar la impresión 3D con modelos 2D se evidenció mejores puntuaciones post-intervención del grupo 3D. En cuanto a modelos cadavéricos, nuevamente la impresión 3D muestra mejores resultados en aprendizaje anatómico, aunque también hubo estudios que no evidenciaron diferencias significativas, sin embargo, ninguno reportó inferioridad de la impresión 3D como herramienta didáctica. Por último, se encontró un número limitado de estudios sobre su impacto en el aprendizaje a largo plazo. La Impresión 3D evidencia tener un impacto positivo en el aprendizaje en diversas áreas de la formación médica.

Palabras clave: Impresión 3D; Educación Médica; Resultados de Educación; Educación Superior.

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1. Introduction

3D Printing (3D) is a new technology, whose diffusion has grown exponentially in recent years (1). This tool consists of the conversion of a three-dimensional digital model into a physical one through a layered manufacturing process (2). Its use has been widespread in different areas, from the aerospace industry, dentistry and medicine (3), given its rapid capacity to produce models with a high level of detail and precision, as well as allowing the customization of its qualities according to the needs of its users (1). Within the medical sciences its use has been varied, ranging from preoperative planning (3) to medical education, within the latter its use stands out in areas such as the teaching of anatomy (4), radiology (5), pediatrics (6), as well as in the training of surgical techniques (7).

The main advantage of 3D lies in the haptic feedback offered by the manipulation of three-dimensional models (3), stimulating learning through "Hands-On-Learning". This is a teaching approach that is characterized by employing the student's body and senses in the learning process, using their perceptual intelligence in order to give a tangible meaning to symbolic or abstract concepts (8). For example, within medicine, the relevance of this teaching method is evident in anatomy courses, where when studying regions of high spatial complexity, traditional teaching modalities, such as two-dimensional (2D) textbooks or cadaveric illustrations, may not be sufficient to fully understand them (2). Given the above, anatomy has used dissection as a cornerstone within its teaching, later incorporating the use of plastinated preparations (7). Despite this, its limited availability, high cost and underlying biological risk has led to I3D starting to be used more in this area, being proposed by some authors as a valid alternative for its teaching (3).

According to a recent review by Brumpt et al., the use of 3D as a teaching tool is highly effective in terms of learning achievements as well as student satisfaction, with better results if it is incorporated early in medical training (4). This is of interest, since much of the available literature focuses on the use of 3D within resident training programs in medical specialties, predominantly surgical. In turn, as exemplified above, the great concentration of its use in medical students (MS) has been centered on anatomy courses, so it is worth investigating other areas in which this technology could be beneficial.

The aim of the following research is to clarify the impact of I3D on EM learning, as well as to determine in which areas of its curriculum it has been implemented. To this end, a systematic review of the available literature was carried out.

2. Methods

This review was carried out in October 2023. It did not require approval by an ethics committee, since it corresponds to a systematic review of the published literature. In order to ensure the quality of the articles, they were selected exclusively from scientific journals that require peer review found in indexed databases. For the realization of this systematic review, the PRISMA 2020 guidelines (9) were used as guidelines. The protocol of this review was published on the Prospero platform prior to obtaining the articles. (crd.york.ac.uk/prospero/display_record.php?RecordID=473723).

The keywords to be used in the search were defined as “3D Printing” AND “Medical Education” AND “Outcome of Education” AND “Higher Education”, and the concepts were expanded through the use of the ERIC and MESH (Medical Subject Headings) thesaurus. The search strategy is specified in Table 1. The strategy was implemented in the databases defined for this systematic review: PubMed, CINAHL, PsycINFO, ERIC, Web of Science, SCOPUS.

The search was conducted on October 25, 2023. The results obtained from all databases were exported and processed in the COVIDENCE software in order to facilitate the review of the publications obtained. In a first stage, duplicate articles were eliminated, and then the total number of publications was randomly distributed among the authors MZ, FS, FM. Subsequently, a title and abstract screening was carried out applying the inclusion and exclusion criteria defined for this research (Table 2). Discrepancies were resolved by author MR. The articles selected at this stage advanced to the full-text review stage. Similarly, through COVIDENCE, the resulting studies were distributed among the same authors to carry out their complete reading, again attributing to the author MR the role of conflict resolver. Subsequently, Snowballing of the bibliographic reviews and meta-analyses that met the inclusion criteria up to this stage was carried out. From these studies, the studies used in their preparation were extracted in order to include them in the present review, being exported to COVIDENCE to be subjected to the same review process described above. Finally, through COVIDENCE, the information extraction phase of the included articles was carried out. For this, a table was prepared incorporating the following information: name of the article, name of the main author, journal, year and country of publication, main purpose of the study, reasoning, design, evaluation tool used, sample (population/size), information collection methods, evaluation methods, data analysis techniques, results, strengths and limitations. At the same time, as the information was systematized, it was ensured that the findings obtained were significant according to their statistical data analysis technique, in order to ensure their reliability and validity.

Table 1. Search strategy: Identification and expansion of concepts.

Searches	Search Strategy
Search 1: Expansion of the *3D printing concept*	From Thesaurus or MeSH: Three-Dimensional Printing* OR 3-Dimensional Printing* OR 3-D Printing* OR 3 D Printing* OR Three-Dimensional Printing OR Three Dimensional Printing OR 3D Printing* Free Search: Additive manufacturing
Search 2: Expansion of the	From Thesaurus or MeSH: Medical Education OR Clinical Experience OR Clinical Teaching OR Medical School Faculty OR Medical School* OR

Medical Education concept	Medical Student* OR Medicine OR Premedical Student* OR Medical Education OR Undergraduate Medical Education Free Search: None
Search 3: Expansion of the *Outcome of Education concept*	From Thesaurus or MeSH: Outcome* of Education OR Instructional Effectiveness OR Success Free Search: Impact on learning OR Impact on education OR impact
Search 4: Expansion of the concept of *Higher Education*	From Thesaurus or MeSH: Higher Education OR Postsecondary Education OR Undergraduate Stud* OR Universit* Free Search: Tertiary education
Search 5: Combination of searches from 1 to 4	Search 1 AND Search 2 AND Search 3 AND Search 4

Table 2. Inclusion and Exclusion Criteria

Inclusion Criteria	**Exclusion Criteria**
Empirical studies, review articles and publications regarding the impact of learning any form of 3D printing.	Non-empirical studies or secondary studies, such as editorials, commentaries and books.
Studies reporting research on medical students.	Studies in populations other than medical students, such as residents or other health professions.
Studies available in Spanish or English.	Studies published in languages other than Spanish or English.

3. Results.

A total of 3,326 studies were identified up to October 2023, of which 705 duplicates were eliminated. It is noteworthy that when performing Snowballing, three of the journal/meta-analysis publications were not found in any of the databases used. After title and abstract screening, 2,561 studies were excluded, identifying 60 studies for full-text reading. Of these, 34 met the proposed inclusion criteria, including within this total the 6 reviews on which Snowballing was performed, as well as the 8 new studies resulting from this process. The main reasons for excluding publications were: It does not assess learning of any kind, it focuses on the subjective perception of learning by students, it incorporates variables that alter the ability to compare their results, it does not incorporate medical students or those with non-empirical methodology. Figure 1 shows the PRISMA diagram of this review.

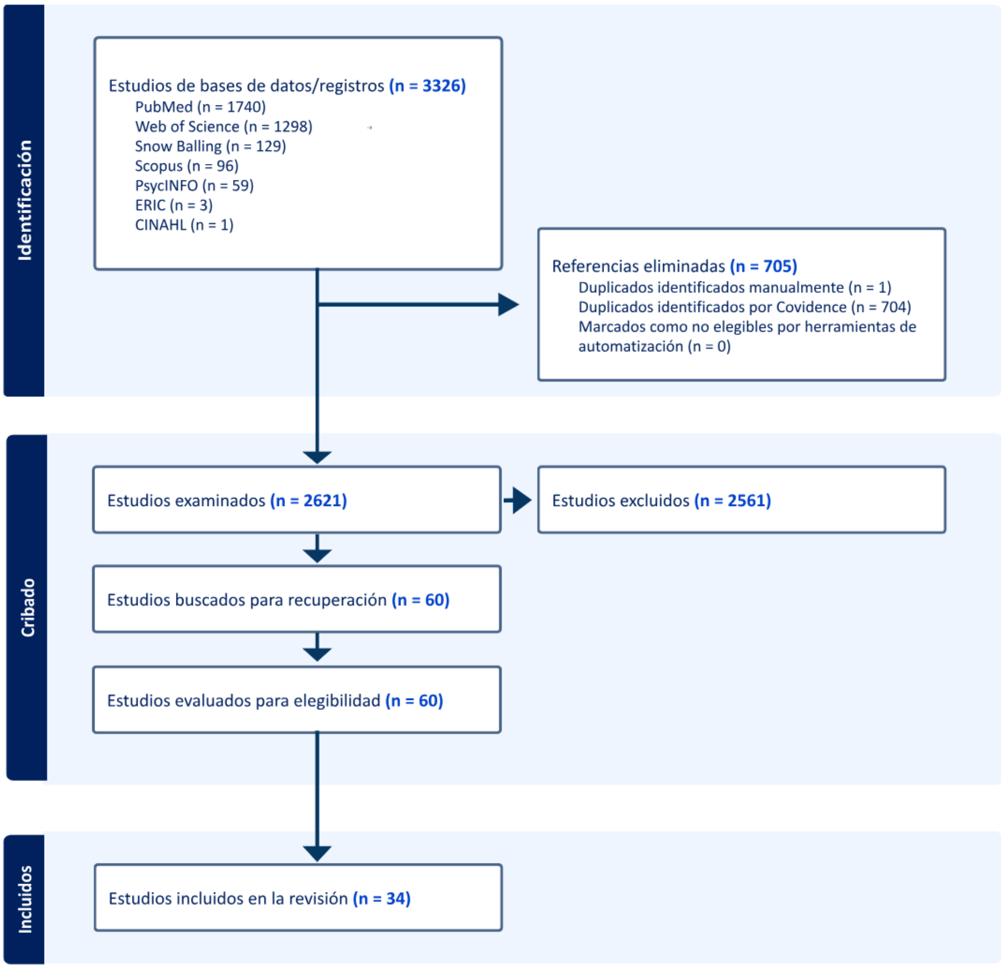

Figure 1. Flowchart of the Study Search and Selection Process.

3.1 Characteristics of the Studies

The selected studies were published between 2015 and 2023, most frequently from China, followed by the United States, and focused primarily on the use of 3D printed models as a learning tool compared to traditional methods. The methodologies used were qualitative and quantitative, with the latter being the most common. The types of assessments described included multiple choice or open-ended questionnaires and, occasionally, personal perception questionnaires about the experience. The design most frequently described in the studies was the performance of a pre-intervention assessment to assess students' baseline knowledge, followed by a theoretical class and then separating the group into those who continued with the traditional methodology and those who were exposed to 3D printed models, ending with an immediate common questionnaire to assess what was learned. Some designs include second assessments up to 6 weeks after the intervention to determine long-term learning retention. The included studies, as well as their different characteristics, are presented in Table 3.

3.2 Areas of use of 3D described in the literature

Among the included publications, there is a clear tendency to investigate the educational role of 3D within anatomy courses, being implemented for the teaching of relevant anatomical structures such as: cardiac anatomy (10,11), liver segments (12), bronchial segmental anatomy (5) and skull anatomy (13,14). Likewise, its use was also preferred to facilitate the teaching of structures characterized by a high three-dimensional complexity, such as the pterygopalatine fossa (15), the ventricular system (16) and the gastrocolic trunk (17).

On the other hand, the available literature has also shown a significant interest in the incorporation of this technology in the teaching of certain pathologies, notably those with an evident anatomical alteration that could be captured in a 3D model. Its use in fractures (vertebral (18), pelvic (19), bone (20)) as well as tumors (prostate cancer (21), bone (22)) and cardiac pathology (congenital malformations (23–25) and valvular disease (26)) stands out.

In turn, I3D models have also been implemented for teaching radiology, as demonstrated in the study by O'Brien C, et al. where an I3D model of the tracheobronchial tree was used to facilitate learning the visualization of its branches in multiparametric CT (5).

Finally, I3D has also been described as a tool for creating educational simulators, for example, for performing an ophthalmoscopy (27). A summary of the areas of use of I3D is attached in Table 4.

Table 3. Summary of Included Studies

Ref #	Purpose of the Study	Reasoning	Design	Evaluation Methods	Results	Strengths	Limitations
12	Compare effectiveness in learning I3D, V3D model with 2D liver segment atlas.	Liver segments are difficult to learn. 2D material is insufficient for this.	Prospective randomized controlled	Introductory class; group study (I3D, V3D, 2D); application of first questionnaire; application of second questionnaire 5 days later	I3D and V3D did not show significant differences between them in the short or medium term, but always achieved better results than 2D.	High fidelity and realism models Evaluated knowledge retention	Low number of participants No demographic information Does not specify tests used It does not prevent the exchange of information between students within a period of 5 days
30	Long-term knowledge retention using 3D craniosynostosis vs 2D illustration	Craniofacial pathology characterized by its complexity, benefiting from 3D models.	Randomized controlled	Theoretical class divided into groups (I3D, 2D). Pre-assessment of familiarity with I3D/V3D. Assessment 21 days later (COM)	I3D significantly improves long-term retention over 2D	Assesses EM's prior familiarity with I3D and V3D and spatial intelligence Adequate number of participants Standardization of classes carried out Avoid passing information between students	Pre-assessment does not consider basic EM knowledge EM knew in advance about the intervention and the group in which they will participate
29	Investigate the educational value of I3D in craniofacial pathology.	Plastic surgery requires physical manipulation for learning	Prospective randomized controlled	Pre-intervention assessment; group study session (I3D, control); post-intervention assessment	I3D group presented higher scores in post-intervention evaluation than control, but without statistical significance.	Pre and post intervention evaluation. Consider demographic information. Excludes EM with prior knowledge of the area	The I3D group received a double intervention (2D presentation + I3D), while controls received only 2D presentation. Low number of participants
22	Determine the feasibility of incorporating I3D in bone	The use of I3D to teach pathology is an area not yet explored.	Randomized Controlled	COM pre-assessment; pre-recorded educational session on bone tumors assisted by	Both groups improved scores at the second assessment.	Does not use statistical tools.	Low number of participants; Technical difficulties described during activity; Same COM used pre and post intervention;

	pathology.			2D (Control) or 3D (intervention) images; COM post-assessment			Does not assess long-term retention.
15	To evaluate the impact of using I3D on the anatomical understanding of the pterygopalatine fossa.	The reduced space and poor accessibility make the pterygopalatine fossa a difficult structure to understand.	Controlled randomization.	Pre-assessment: A self-assessment guide is provided along with images from an anatomy atlas. The sample is then divided into 2 groups, one group receiving a sectioned skull and the other group receiving a 3D model of a skull.	The intervention group had better results in the post-intervention evaluation compared to the control group.	Multicenter. Took into consideration student demographics Sufficient sample to perform analysis between both groups.	Includes students from other majors; sample heterogeneity. Oversimplified 3D structures. Possible selection bias (voluntary participation). Long-term learning is not assessed.
21	Ability to identify prostate cancer location with I3D compared to other traditional modalities.	The accuracy of localization of prostate cancer is difficult and can be supported by a series of measures including I3D.	Observational Cross-sectional	Exposure of each group to a type of intervention (I3D, MRI, MRI presentation); tumor identification in diagram.	EM's performance was worse in MRI submissions. Their error rate was 1.7x higher in I3D than in MRI reports, but this did not significantly impact I3D scores (-2.3%). I3D had higher scores than MRI submission.	The proposed diagram allows to quantify the magnitude of the error committed. The study compares I3D with other frequently used resources in urology teaching (RNM).	Does not consider long-term retention. The validation of the evaluative diagram was done with data extracted from the same research. Limited number of participants
19	To elucidate the role of I3D in understanding pelvic fractures.	The diagnosis and classification of pelvic fractures is difficult in MS due to its three-dimensional complexity.	Prospective randomized controlled	Theoretical class on pelvic anatomy, types and mechanisms of fractures; division into I3D and control groups (traditional imaging); Post-intervention evaluation.	Significant improvement in correct classification according to Young-Burgess, in inference of fracture mechanism and evaluative response speed with I3D.	Consider demographic characteristics. Homogeneous sample.	It does not assess basic knowledge. Does not assess long-term retention.
16	To evaluate the effectiveness of using I3D in teaching the ventricular	It is difficult for students to understand the anatomy of the ventricles and their	Prospective randomized controlled trial.	Pre-intervention test. Three groups were formed: 2D images, 3D images and 3D images. All were given a 20-	The percentage of change from pre- to post-test was statistically significant in all 3 groups. The groups using 3D and 3D imaging	Pre and post intervention evaluation. Experts evaluated the realism of the 3D models and I3D.	The sample was relatively small. The study did not include brain tissue as a teaching aid.

	system.	relationships by studying classical atlases.		minute introduction to the topic, then 5 minutes to explain their learning method to each group and then 20 minutes to interact with their method. The test ended with a post-intervention test.	performed better than the 2D imaging group on the practical questions and on the total post-intervention score.		
33	Determine the impact on anatomical learning of a dynamic simulator of the knee joint	Traditional anatomy teaching encourages more memorization than understanding.	Prospective randomized controlled	Functional anatomy of the knee teaching session; division into groups (I3D and traditional teaching with skeleton); post-assessment COM.	Better scores in I3D group. The gender of the EM did not impact the results.	The level of knowledge (1st year of medicine) was considered when making the evaluation (restricted to level 3 of Bloom's taxonomy) Consider demographic information	The simulator only had bone material. Small number of participants Does not consider long-term retention
23	To evaluate the impact of I3D of MCC on structural understanding and pathophysiology .	MCCs are complex to teach, and the available modalities are insufficient for their conceptualization.	Randomized controlled	Traditional MCC teaching seminars, providing the intervention group with I3D models; post-intervention COM	The group treated by I3D presented better results, especially in structural conceptualization. Demographic characteristics of the sample did not impact results.	Consider demographic information	It does not use a pre-assessment to measure basic knowledge. Reduced number of participants Does not consider long-term retention
14	Determine the impact on learning of 3D models of skull bones.	Human skulls tend to be arranged only for external viewing, making it impossible to learn about their individual components, which are complex to study.	Prospective randomized controlled	Pre-intervention evaluation; Theoretical class and division into groups (I3D and real skull); post-intervention evaluation.	Post-intervention evaluation results without significant differences. When comparing the difference in scores between pre and post intervention, the I3D group had a more marked improvement.	Pre and post intervention evaluation Adequate number of participants The study evaluates medium-term learning (most studies only short or long term) Consider demographic characteristics	No measures were put in place to prevent students from sharing information with each other.

28	To determine the impact of I3D on anatomy teaching	In recent years the quality of anatomy teaching has declined, requiring new tools to compensate for this.	Randomized Controlled	Pre-intervention assessment; Theoretical class on pulmonary anatomy; Division into I3D and control groups (traditional 2D teaching); Post-intervention assessment.	No significant differences in pre-assessment. I3D results were superior in post-assessment.	Incorporates pre-assessment Adequate number of participants	The lack of availability of intravascular contrast for the cadaveric model to highlight these structures puts the control group at a disadvantage.
31	To evaluate the effectiveness of I3D in cleft lip and palate medical education over traditional techniques.	R3D field with great development potential, especially in health teaching and within hospitals.	Controlled randomization.	Pre-intervention evaluation; theoretical presentation of the topic; division of students into groups (I3D model, 2D control); Application of post-intervention evaluation	Pre-assessment showed no differences between groups or universities. Group I3D presented significantly greater increases in knowledge (compared to pre-intervention assessment) than group 2D.	Consider demographic characteristics Diversity of participants by incorporating students from two centers.	Reduced number of participants Does not assess knowledge retention
26	Evaluate whether I3D models are superior to conventional cardiac models for medical education	Previous studies have evaluated the use of I3D in cardiac disease, but no randomized studies with a cardiac model are available.	Randomized controlled	Group distribution a) I3D model b) traditional cardiac model; valvular disease session; post-intervention evaluation	Students in the I3D group responded to COM more quickly, but there was no significant difference between scores.	Consider demographic characteristics	Traditional model allowed better distinction of heart valves Small sample size Does not assess basic knowledge of students
27	Design an ocular model that simulates the fundus to teach ophthalmoscopy	Students have difficulty learning to use ophthalmoscopic instruments for short periods of time	Randomized controlled	Theoretical presentation; Division into group A (I3D model and peer examination) and group B (peer examination)	Group A achieved successful background visualization 93.4%; Group B 45.65%. A higher visualization speed was evident in Group A.	Consider demographic information. Incorporates reaction time as a variable. The I3D model achieves adequate realism. Adequate number of participants.	Low population diversity. The students knew in advance the assigned group. I3D accuracy suitable for displaying background and text, but not for background photos.
18	Investigate the impact of I3D on vertebral fracture	Human vertebrae are rare, so other methods must be	Randomized controlled	Division of students into I3D group, 3D imaging and CT; Educational	Students in the I3D and 3D groups presented similar but superior	Considers demographic characteristics and incorporates them among	Selection bias due to small number of participants It does not directly assess basic

	identification and gender differences in its application	sought to show their fractures.		session with respective interventions; Post-Intervention Evaluation	results to TC. Men presented better scores in 3D, there were no differences in other groups.	research objectives. Compare multiple modalities	knowledge The model did not include muscular/neurovascular structures
35	Compare I3D model of pelvis with traditional textbook	N/A	Randomized Controlled	Assessment with COM 1; Self-study with textbook or I3D model; Assessment with COM 1 and COM 2	Similar baseline knowledge between both groups After the intervention, COM 1 and 2 scores were significantly higher in I3D.	Measures baseline knowledge of participants	Low number of participants Incorporates non-MS participants
12	To develop a 3D model of liver segments as a teaching tool and evaluate its impact on learning	The study of liver segments is often carried out with textbooks and 2D illustrations, which requires a difficult mental reconstruction of the same.	Randomized controlled	Division into study groups: a) session with I3D model (3 groups) b) session with anatomical atlas (1 group); Post-intervention evaluation; New surprise evaluation 5 days later to evaluate retention	The three I3D models present different results in terms of paper scores, however, they are always higher than the control.	Evaluates medium-term knowledge retention Second assessment participants are not informed, making results more reliable	It does not assess long-term knowledge Does not establish a knowledge base with pre-assessment Does not demographically characterize participants
10	To evaluate the effectiveness of I3D models against cadaveric models for external cardiac anatomy.	N/A	Double blind randomized controlled	Pre-intervention assessment; Division into three self-learning groups (cadaveric material, I3D model, combined); post-intervention assessment.	Pre-intervention results were similar in both groups. Post-intervention results highlight a significant increase in the I3D group.	Students without prior exposure to content assessed in intervention Strict study in execution of its methodology Double blind	Only evaluates one anatomical region Differences in pre- and post-intervention assessment formats make comparison difficult There were more female participants in the combined group
24	Investigate the role of I3D in improving immediate and long-term knowledge in MCC.	N/A	Prospective cohort	Distribution in two groups with access to V3D model and 2D diagrams. Only one group receives MCC I3D model; Evaluation 1; Evaluation 2 (6 weeks	Evaluation 1 results were marginally higher in I3D I3D did not improve long-term knowledge retention.	Includes long-term evaluation Measures baseline knowledge of participants Greater diversity of participants incorporating 2 generations of MS.	Without pre-assessment Participants with tertiary education already completed within the sample Students may have practiced completing Assessment 2 previously

				later)			
17	Investigate the effects of I3D on learning of the gastrocolic trunk of Henle compared to 2D images	N/A	Prospective randomized controlled	Pre-intervention evaluation; Division into 2 groups, one acting as a control with 2D images, the other receiving a 3D I model. Both accessed a surgical video; Post-intervention evaluation	All groups improved their scores after the seminar, with a significant difference in favor of the I3D group.	It incorporates participants from two centers	Low number of participants Does not assess long-term knowledge retention Does not consider demographic characteristics Inmates may have had prior knowledge of the area
11	To compare the effectiveness of 3D printed and plastinated specimens of neck and heart anatomy as teaching tools.	3D models would have a similar educational benefit to plastinated models for complex anatomical regions.	A two-phase randomized crossover study.	Evaluation before and after the intervention.	Both groups showed significant improvement. There were no significant differences between the plastinated and 3DP groups.	6-week *wash-out* period between cardiac and cervical evaluation. Freshmen only. Participants were unaware of the study topic in both phases.	Same questions for pre- and post-test assessments, which carried a risk of recall bias despite the fact that the sequence was randomized. It does not assess long-term knowledge retention.
34	Simultaneous use of I3D, V3D	Learning anatomy with 2D tools, such	Crossed	Pre-intervention evaluation; division into	The combined group significantly improved	Consider demographic information of	The intervention and control groups evaluated different

	and 2D images optimizes the study of anatomy in transverse sections	as radiology, is difficult.		two groups: A) Combined, with V3D + I3D of the chest B) 2D, with images of abdominal transverse sections; Post-intervention evaluation	their ability to identify structures in transverse chest sections and showed a greater increase in score between both assessments.	participants; Assesses baseline visuospatial skills; Pre and post intervention assessments were different; Strict methodology to prevent the passage of information between students.	anatomical segments (Thorax v/s abdomen) When using V3D and I3D simultaneously, the results cannot be attributed to one or the other modality.
13	To investigate the educational effectiveness of a 3D I skull compared to a real skull and study with 2D atlas.	Dissection is a useful educational tool, however, it is difficult to access, making it interesting to study alternatives.	Controlled Randomized	Pre-intervention evaluation; Randomized distribution in group A) I3D of skull B) Real human skull C) 2D Atlas; Post-intervention evaluation (COM + Laboratory)	The final evaluation highlights better performance of I3D over the other two groups (total score and Laboratory), with no differences in the COM between the three groups.	Assesses baseline knowledge. Consider demographic information Strict experimental conditions	Sample taken from a highly demanding university, so above-average learning skills could attenuate differences between groups.
5	To evaluate whether the use of I3D improves the interpretation of tracheobronchial anatomy in multiplanar CT.	Radiological imaging requires interpretation of three-dimensional anatomical structures from a two-dimensional image. 3D printed models could improve understanding of spatial anatomy.	Prospective randomized study	Distribution of students into two groups: A) I3D; B) 2D Printed Image; COM, immediately after the intervention and a 2nd COM two weeks later.	In COM 1, 2D group scored better than 3D (not statistically significant) COM 2 scores significantly lower in 2D group and similar scores in 3D group.	Evaluates information retention. Demographic differences between participants were taken into account.	The participants were aware of the follow-up test, so they were able to prepare for it in advance. Relatively small number of participants plo
25	Evaluate the usefulness of I3D for teaching medical students four MCCs	I3D allows 2D images to be converted into physical replicas that could help	Prospective randomized controlled	COM pre-intervention; Randomization of participants into I3D and control groups; MCC theoretical class, where	Objective knowledge was higher in the I3D group after the intervention for each type of MCC model	Pre-intervention evaluation Employs multiple MCC models	Does not assess long-term knowledge retention I3D models do not necessarily correctly represent characteristics of a real heart

		teach MCC		only the I3D group is allowed to manipulate the MCC model; COM post-intervention			
32	Identifying the impact of 3D versus 2D illustrations in teaching craniofacial trauma	Teaching craniofacial trauma is a challenge given its regional and visuospatial complexity.	Prospective randomized controlled	Didactic session using I3D; Didactic session using 2D illustrations; Post-intervention evaluation	The I3D model presented better evaluation results, especially in biomechanical aspects	Take I3D familiarity pre-assessment. Consider demographic characteristics Adequate No. of Participants	The methodology did not include long-term knowledge retention assessment.
20	To determine the effect of I3D on learning anatomy and bone fractures	Learning bone anatomy is key in MS, but it is unknown whether I3D increases it.	Randomized controlled study.	Division into I3D groups and traditional radiological teaching; post-intervention COM	There was no significant difference in upper/lower extremity knowledge; in pelvis/spine, the I3D group responded to the COM more quickly and obtained better results.	Article attached COM used for evaluation. Compare performance in anatomy to ensure homogeneity of participants	Relatively small number of participants. Does not perform a pre-intervention test.

EM (Medical Students) 2D (Two-dimensional) 3D (Three-dimensional) I3D (3D Printing) V3D (Three-dimensional Virtual Model) COM (Multiple Choice Questionnaire) N/E (Not Specified) MRI (Magnetic Resonance Imaging) CT (Computed Tomography) MCC (Congenital Heart Defect) ANOVA (Analysis of Variance) PSTT (Paired Sample T-Test) ISTT (Independent Sample T-Test)

3.3 Impact of I3D on learning

Most of the included studies describe an educational impact produced after EM exposure to 3D I models. Notably, all the studies that compared 3D I exclusively with 2D models (Atlases, illustrations or radiological images) showed better post-intervention scores of the intervention group, both in anatomy teaching (16,17,28) and pathology teaching (22, 25, 29–32).

Another comparative approach of interest to the literature was to contrast the results of I3D with cadaveric models, among which generally favorable results were reported for I3D in anatomy teaching (10,13,33). This was attributed to the high level of detail of the printed models, as well as their role in reducing the psychological stress of MS when facing cadavers for the first time (10). Despite the above, there were also studies that did not show significant differences in immediate post-intervention evaluations (11,14), however, none reported inferiority of I3D as a teaching tool.

On the other hand, some studies sought to compare the educational impact of I3D with three-dimensional virtual models (V3D), without showing significant differences between both tools when measuring the acquisition of immediate knowledge (12,16,24) or long-term knowledge retention (24).

Although most studies evaluated learning in a theoretical context, certain publications highlight the role of 3D in acquiring practical skills among MS. Notably, the study by Wu C, et al. shows how the use of a fundus model improves the ability and speed of visualization of relevant structures by ophthalmoscopy (27), as well as the study by Chen S, et al. that showed higher scores in the applied anatomy laboratory among MS exposed to 3D skull models compared to human skulls and 2D illustrations (13). In turn, the study by O'Brien, et al. stands out within the field of radiology, where it shows that compared to education with 2D images, the use of a 3D model better consolidates the knowledge acquired during the intervention (5).

On the other hand, 3D has demonstrated a role in dynamic teaching of anatomy and pathology, given the ability to create articulated and multicomponent models. An example of this is the study by Nicot R et al, where 3D facilitates the learning of the biomechanics of craniofacial trauma (32), as well as the publication by Yan M et al, which shows a positive association between the use of 3D and understanding of pelvic fracture mechanisms (19), and the knee joint simulator designed by Cai B et al, which allows the teaching of functional anatomy (33).

Finally, it is worth noting that a limited number of studies highlight the positive effects of I3D in promoting long-term learning compared to 2D models (30) and 2D images (5). These findings were not reproduced in the publication by Lau I et al, which compares I3D with V3D (24).

Table 4 contains a summary of the impact that I3D has had according to the area in which it has been incorporated.

Table 4. Areas of employment of 3D printing and educational impact

Area of Application (number of articles)	Impact
Anatomy Teaching (n = 13)	It provides a better spatial and relational

	understanding of anatomical structures that are difficult to internalize through classical atlases or cadaveric models.
Teaching of Pathologies (n = 13)	It allows for a better understanding, compared to classical methods, of various pathologies in which the anatomical substrate acquires great relevance for the pathophysiological understanding of these, especially in areas that medical students traditionally consider more arid and complex. Some of the most addressed topics are, for example, congenital heart diseases and fracture traits.
Radiology Teaching (n = 1)	It provides a greater ability to correctly identify structures in cross sections of the chest. It should be noted that this result cannot be fully attributed to the fact that the investigated group simultaneously used I3D.
Simulators (n = 1)	3D I in ocular models helps to improve visualization of the optic disc and better identify the cup/disc relationship.

4. Discussion

The analysis of the results obtained shows a positive impact of the introduction of 3D technologies in various areas of medical training, both in theoretical learning and in practical skills in certain areas, such as anatomy (28), traumatology (20), surgery (29) and radiology (5). It was shown that 3D was able to offer more efficient learning environments, allowing the development of more detailed and specific models to simulate different pathologies or anatomical structures, thus facilitating their study (26). 3D facilitates the visuospatial understanding of certain topics, in turn decreasing the cognitive load required for their learning (11), thus being preferably incorporated in subjects that require a conceptualization of three-dimensionally complex structures (23).

4.1 I3D presents better results than 2D models

Several studies have shown widely favorable results for the use of 3D over two-dimensional models. Physical models have an advantage over 2D tools, especially within topics that involve a kinesthetic component (28), since their haptic component facilitates the development of a more comprehensible mental image of the object of study (30), which was complemented in several studies by incorporating materials of various textures and colors to facilitate the recognition and differentiation of different structures (11). In turn, topics commonly known for their difficult understanding through classical teaching, such as the morphology of congenital heart disease (26), as well as craniofacial pathology (32), benefited from the incorporation of this type of tool.

4.2 I3D as a valid alternative to cadaveric models

Regarding anatomy, 3D has been introduced as a technology with the potential to become an accessible source of high-quality educational materials, reducing financial, ethical, cultural and logistical barriers associated with maintaining a cadaver-based curriculum (10). It has been described that the use of cadaveric models can generate psychological inhibitions, such as anxiety, fear and restlessness among certain students, compromising their learning (10,11). In addition, 3D has the advantage of allowing greater accessibility to rare pathologies, such as anatomical malformations, where the availability of cadaveric preparations is limited (23). In turn, since cadaveric materials are fragile and difficult to maintain, their natural deterioration decreases their teaching quality (14), as evidenced in the study by Chen S, et al (13). where, despite expecting similar results when comparing 3D with cadaveric skulls, the former obtained better scores, partly attributed to the deterioration of the cadaveric models used. It is worth noting that although certain studies did not show differences between the results obtained when comparing I3D with cadavers (11,14), none concluded any harm after using this technology, positioning it as an efficient alternative when teaching anatomy.

4.3 3D can reduce costs and increase accessibility

3D is a feasible method to implement, with a higher cost-effectiveness than commercially available models, and even plastinated ones (11). 3D is less expensive than obtaining and maintaining cadaveric models, so they could be acquired by more medical schools, increasing their accessibility (11).

4.4 Strengths

Among the strengths of this work, we can highlight an exhaustive and rigorous study of the literature, incorporating publications from multiple databases as well as performing Snowballing of the results of various systematic reviews of relevance in the area. At the same time, it highlights its contribution to the knowledge regarding general medical training, which is frequently left aside in favor of I3D research in the context of specialist training. At the same time, it offers a comprehensive view of the application of I3D among EM, given that the reviews available to date tend to focus on particular areas, such as pediatrics (6) and anatomy (1,2,7), rather than a general view of the didactic capabilities of this technology.

4.5 Limitations

Among the limitations described for the present review, the small number of studies that aim to assess long-term learning stands out, which limits the ability to determine the true educational impact of this technology (30). In turn, the predominantly single-center design of the studies makes this difficult, since, after the intervention, the EMs of I3D groups could come into contact with students of the control group, causing a diffusion of knowledge between both populations affecting subsequent evaluations. On the other hand, it was also evident that most of the studies designed their own evaluations, as well as validated them with the same results of their intervention, evidencing in turn the direct participation of the researchers within the educational/evaluative sessions, which entails a high risk of bias. One way to counteract this would be to assign the examining role to an external entity, as Lim KHA, et al did (10). The present review also showed a relevant methodological heterogeneity between studies, as well as problems in their designs, such as not adequately measuring the baseline knowledge of their students (12), incorporating individuals into the sample on their own initiative, which could attract individuals with greater baseline knowledge in the area to be evaluated (15) or combining 3D digital model techniques with 3D I, making it impossible to conclude that their results were attributable to one or the other technology (34).

4.6 Future Studies

It is necessary to open the doors to the design of new studies with more rigorous methodologies, ideally multi-center, focused on evaluating the impact of this technology on long-term learning, as well as evaluating its impact within subjects other than those described above.

5. Conclusions

- Traditional learning methodologies, such as textbooks, 2D presentations and illustrative atlases have achieved adequate educational results in the medical career, however, with the emergence of new technologies, such as 3D, this process can be optimized in time, resources and quality, making it more efficient for the next generations and their new needs.
- 3D could be a good alternative to cadaveric models for the study of anatomy, reducing the gaps in opportunities for access to three-dimensional educational models, while maintaining an adequate level of detail and fidelity to reality.
- Further research is needed into the effects of 3D I on the long-term learning of medical students to fully determine the effectiveness of its implementation as a study tool, given that the current scientific literature is scarce.

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