

3D Printed Liver Biomodels and Problem-Based Learning for Teaching Hepatobiliary Pathological Anatomy .

Biomodelos Hepáticos Impresos en 3D y Aprendizaje Basado en Problemas para la Enseñanza de la Anatomía Patológica Hepatobiliar.

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Summary.

The teaching of pathological anatomy faces increasingly limited access to real anatomical material, which has driven the incorporation of digital modeling and 3D printing technologies as a complementary teaching resource. **Objective** : To evaluate the effect of a combined teaching strategy that links the design and creation of 3D-printed liver biomodels by the students themselves with their application through Problem-Based Learning (PBL), compared to traditional lecture-based teaching. Additionally, the technological acceptance of the biomodel design and creation process and its relationship with academic performance in fourth-semester medical students at the National University of Chimborazo (Ecuador) were analyzed. **Methods** : A quasi-experimental pretest-posttest study was conducted with an experimental group (n=40) and a control group (n=32), with a total of 72 students. Under instructor guidance, students in the experimental group segmented and designed, using DICOM images of a patient with confirmed liver cirrhosis, a biomodel of the cirrhotic liver and, through digital post-processing of the same case, a biomodel of the healthy liver. Both were fabricated using FDM printing in PLA and applied in the classroom as part of a Problem-Based Learning (PBL) approach. A Knowledge Test and the Technology Acceptance Model (TAM) questionnaire were used, the latter specifically addressing the process of designing and fabricating the 3D biomodels. **Results** : The groups did not differ in the pretest (p=0.908). The experimental group showed greater learning gain than the control group (7.79 vs. 5.58 points) and high technological acceptance of the design and fabrication process, with no significant correlation with academic performance, possibly due to a marked ceiling effect in the posttest. **Conclusion** : The combination of 3D liver biomodels and PBL was associated with better academic performance than traditional teaching, although high technological acceptance was not related to that performance. Since the quasi-experimental design does not allow for separating the effect of the three-dimensional resource from that of the active methodology, the improvement cannot be attributed solely to 3D printing, but rather to both components together (3D-PBL).

Keywords: 3D Printing; Digital Anatomical Modeling; Problem-Based Learning; Pathological Anatomy; Academic Performance; Technology Acceptance.

Resumen.

La enseñanza de la anatomía patológica enfrenta un acceso cada vez más limitado a material anatómico real, lo que ha impulsado a la incorporación de tecnologías de modelado digital e impresión 3D como recurso didáctico complementario. **Objetivo:** Evaluar el efecto de una estrategia didáctica combinada, que vincula el diseño y la elaboración de biomodelos hepáticos impresos en 3D por los propios estudiantes con su aplicación mediante el Aprendizaje Basado en Problemas (ABP), en comparación con la enseñanza expositiva tradicional. Adicionalmente se analizar la aceptación tecnológica del proceso de diseño y elaboración de los biomodelos y su relación con el rendimiento académico en estudiantes de cuarto semestre de Medicina de la Universidad Nacional de Chimborazo (Ecuador). **Métodos:** Se realizó un estudio cuasi-experimental pretest-posttest con un grupo experimental (n=40) y un grupo control (n=32), con 72 estudiantes en total. Bajo guía docente, los estudiantes del grupo experimental segmentaron y diseñaron, a partir de imágenes DICOM de un paciente con cirrosis hepática confirmada, el biomodelo del hígado cirrótico y, mediante posprocesamiento digital del mismo caso, el biomodelo del hígado sano; ambos se elaboraron por impresión FDM en PLA y se aplicaron en el aula bajo ABP. Se emplearon una Prueba de Conocimientos y el cuestionario del Modelo de Aceptación Tecnológica (TAM), este último referido específicamente al proceso de diseño y elaboración de los biomodelos 3D. **Resultados:** Los grupos no difirieron en el pretest ($p=0,908$). El grupo experimental mostró mayor ganancia de aprendizaje que el control (7,79 frente a 5,58 puntos) y una aceptación tecnológica alta hacia el proceso de diseño y elaboración, sin correlación significativa con el rendimiento académico, posiblemente por un efecto techo marcado en el posttest. **Conclusión:** La combinación de biomodelos hepáticos 3D y ABP se asoció con mejor rendimiento académico que la enseñanza tradicional, aunque la alta aceptación tecnológica no se relacionó con ese rendimiento. Como el diseño cuasi-experimental no permite separar el efecto del recurso tridimensional del de la metodología activa, la mejora no puede atribuirse de forma aislada a la impresión 3D, sino a ambos componentes en conjunto (3D-ABP).

Palabras clave: Impresión 3D; Modelado Anatómico Digital; Aprendizaje Basado en Problemas; Anatomía Patológica; Rendimiento Académico; Aceptación Tecnológica.

1. Introduction

The teaching of human anatomy is one of the fundamental pillars in the training of healthcare professionals, as it provides the structural foundation necessary to understand the pathophysiology of diseases and support clinical reasoning. For decades, this learning has relied on cadaveric dissection, the study of preserved anatomical specimens, and the use of two-dimensional atlases (1). However, factors such as the scarcity of cadavers for teaching purposes, the costs of preserving biological material, and the increasing biosafety requirements in anatomy laboratories have progressively limited students' access to real specimens (2). Faced with these restrictions, the development of digital modeling and three-dimensional (3D) printing technologies has opened a complementary avenue for anatomical teaching. 3D printing allows the transformation of digital anatomical data, usually derived from segmented DICOM images, into manipulable physical objects that faithfully reproduce the morphology of a specific structure and can be multiplied without damaging the original specimen (3,4). International evidence consistently supports its didactic value; thus, a systematic review with meta-analysis of randomized controlled trials concludes that 3D printed models facilitate spatial visualization, improve the understanding of anatomical relationships and are associated with higher academic performance compared to exclusively two-dimensional methods, without any study having been identified that reports its inferiority as a didactic resource (5).

The application of these technologies to pathological anatomy is of particular interest because, unlike normal anatomy, the study of pathological lesions requires interpreting heterogeneous morphological variations: a cirrhotic liver, for example, does not present the same nodular surface or consistency in all patients, which makes its faithful representation through photographs or diagrams difficult (1). Studies focused on hepatic, renal, pelvic, and cardiac specimens agree that the manipulation of printed replicas improves the understanding of procedures, clinical confidence, and equitable access to specimens with a full spectrum of pathology, regardless of the size or resources of the training program (6-9).

The adoption of a technology, however, does not in itself guarantee its pedagogical benefit. The TAM, formulated by Davis, postulates that the intention to use a tool depends on the perceived usefulness and ease of use perceived by the user (10). Recent studies applying the TAM and its extensions to digital anatomical environments show that these perceptions predict the intention to use relatively independently of the technical quality of the resource, which introduces the possibility that technological acceptance acts as a variable partially dissociated from the effective improvement of academic performance (11).

The methodological component of the strategy applied in this study is Problem-Based Learning (PBL), which has its own independent evidence base regarding its positive effect on learning, beyond its synergy with 3D biomodels. Since its original characterization as a family of methods organized around the clinical problem, and not the prior presentation of content (12), recent systematic reviews associate PBL with improvements in critical thinking and clinical reasoning among health science students (13), and qualitative experiences in medical programs in the region identify student motivation as its main contribution to achieving meaningful learning (14). This dual evidence base, technological on the one hand and methodological on the other, is relevant for correctly interpreting the scope of the present study, in which both components were applied together and cannot be statistically separated (see section 2.4).

In Latin America, the integration of 3D printing into medical programs is in a phase of uneven consolidation. Recent systematic reviews confirm higher scores with three-dimensional models than with equivalent two-dimensional resources (15,16), and experiences described from medical programs in the region document a growing adoption of digital resources and printed models in anatomical training (17). Based on the literature reviewed for this study, which did not constitute an exhaustive systematic review, no publications were identified that specifically evaluated the effect of 3D-printed hepatobiliary pathological biomodels, applied through problem-based learning (PBL), on academic performance in pathology courses within the Ecuadorian medical curriculum. This observation indicates a gap relative to that specific context and should not be interpreted as an absolute assertion of non-existence.

Within this framework, the present study aimed to evaluate the effect of a combined strategy—the design, development, and didactic application of 3D-printed liver biomodels using Problem-Based Learning (PBL)—on the academic performance and technological acceptance of medical students at the National University of Chimborazo (UNACH), using liver cirrhosis as a case study. Since the intervention integrates two components that vary simultaneously between groups (the three-dimensional resource and the active learning methodology), the study did not aim to isolate the specific effect of each component, but rather to evaluate their combined effect compared to traditional lecture-based teaching supported by two-dimensional images.

2. Methods

2.1. Design and participants

An empirical study was conducted using a quantitative, descriptive-correlational approach and a quasi-experimental pretest-intervention-posttest design. Participants were from two intact groups (parallels) of fourth-semester medical students at the National University of Chimborazo (UNACH, Riobamba, Ecuador), enrolled in the Pathological Anatomy course during the 2026-1S semester. A non-probabilistic, census-type convenience sampling method was used: all students from both parallels who met the inclusion criteria (regular enrollment, attendance at the corresponding sessions, and signed informed consent) were included, with no exclusions due to course repetition. The final sample consisted of 72 students: 40 in the experimental group (parallel A) and 32 in the control group (parallel B). Since these are intact groups and not an individual random assignment, the design favors ecological validity but does not allow for the complete exclusion of confounding variables associated with the original parallel, a limitation that is addressed in the discussion.

2.2. Instruments and variables

Two instruments were used. The Knowledge Test, consisting of 13 items on normal and pathological hepatobiliary anatomy (dichotomous scoring for each item, with the total score transformed to a scale of 0 to 10), was administered in pretest and posttest to both groups, with randomization of the order of items and options between the two administrations to reduce the memorization effect. The instrument underwent content validity testing, established through expert judgment in the health and education fields, achieving an Aiken's V coefficient of 0.953 (very high validity)(18), and its reliability, estimated using KR-20 in a pilot test, was 0.971(19).

The second instrument was a questionnaire adapted from the Technology Acceptance Model (TAM), originally formulated by Davis and expanded by Davis, Bagozzi, and Warshaw with the subscales of perceived ease of use (PEOU) and perceived usefulness (PU) (20). The version used in this study was translated and adapted into Spanish, with the content of both subscales expanded to 8 items each (16 items in total) on a 7-point Likert scale, with a possible range of 8 to 56 points per subscale. Unlike other studies, the questionnaire was designed to specifically assess students' perceptions of the digital design and 3D biomodel creation process described in section 2.3, and not their subsequent application in the classroom. The questionnaire was administered only to the experimental group at the end of this process, as it assesses perceptions of an experience to which only this group was exposed. Its reliability in this sample, as measured by Cronbach's alpha, was 0.987 (21). Regarding the second instrument based on the TAM, a new construct validity analysis was not performed, given that its validity has been previously corroborated in multiple studies that support its theoretical and psychometric soundness (10,20). However, the internal consistency of the instrument was evaluated in the analyzed sample to ensure the reliability of the scores obtained.

Regarding the study variables, the independent variable was the combined teaching strategy (3D biomodels designed and manufactured by the students and applied through PBL, versus traditional teaching with two-dimensional images); academic performance was the dependent variable; and technological acceptance towards the design and elaboration process, the exploratory association variable.

2.3. Design and development of 3D biomodels by students

The study began with a contrast-enhanced abdominal computed tomography scan of a patient with a confirmed diagnosis of liver cirrhosis, obtained with authorization for academic use and prior anonymization of the DICOM metadata. Under the direct guidance of the supervising professor, the students in the experimental group, working in small teams, processed the images using 3D Slicer

software. They segmented the pathological liver parenchyma using intensity thresholding and manual slice-by-slice correction. The segmented structure was exported in STL format and refined with Meshmixer (surface smoothing, mesh repair, and wall thickness adjustment), resulting in a biomodel of the cirrhotic liver. The healthy liver biomodel was not derived from an independent DICOM study or a pre-designed generic template. Instead, the students themselves generated it through digital post-processing of the segmented mesh of the cirrhotic case. Under faculty supervision, they smoothed the nodular surface, regularized the contour, and normalized the parenchymal thickness to approximate the reference liver morphology described in the anatomical literature. This ensured that both configurations shared the same baseline size and shape, and that the comparison between them was attributable to the pathological morphological difference rather than individual anatomical differences between patients. The students fabricated both models at a 1:1 scale using FDM printing with PLA filament, with a layer height of 0.2 mm, an infill density of 15%, a textured bed surface, and a reduced speed for the initial layer—parameters designed to faithfully reproduce the nodular texture characteristic of cirrhosis. After printing, the pieces were subjected to sanding and differentiated coloring by structure, also carried out by the students, to facilitate their visual identification during the subsequent teaching sessions (Figure 1).

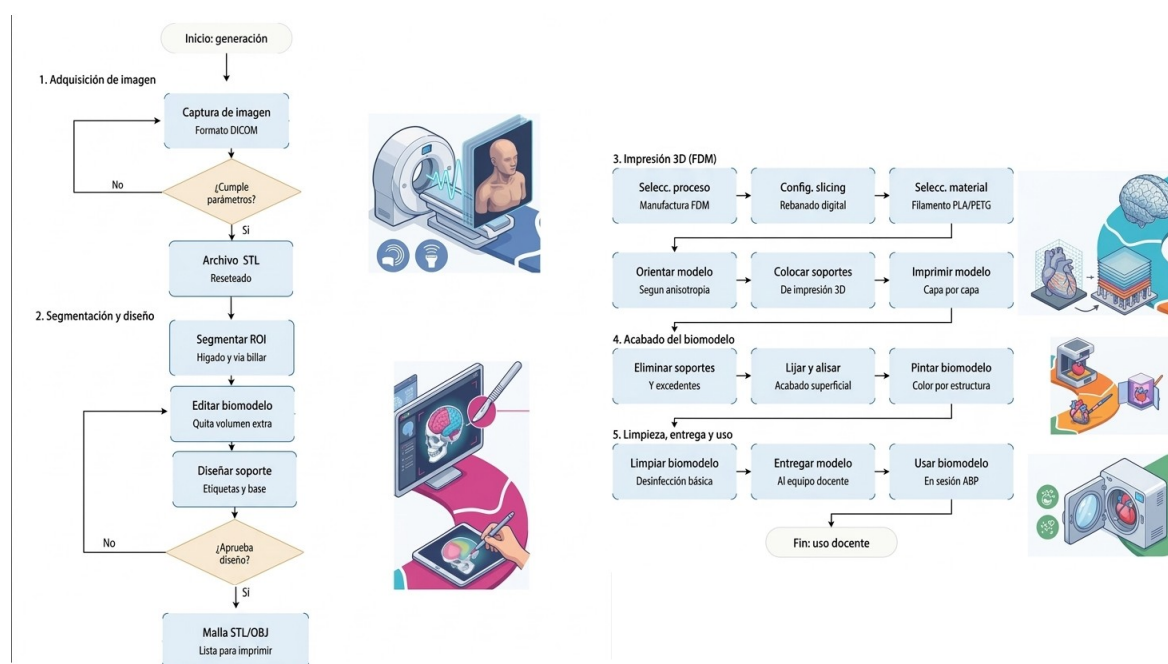


Figure 1. Workflow followed by students, under faculty guidance, for the digital design and production of hepatic biomodels via 3D printing—from the DICOM image to their use in the teaching session.

It should be noted that no independent, objective evaluation of the morphological fidelity of the resulting 3D biomodels was performed (e.g., validation by a panel of experts in pathology, geometric metrics of overlap with the source image, or other quantitative verification procedures). The procedure described in this section therefore corresponds to the technical objective of the modeling process and not to an empirically validated morphological fidelity result; this distinction is consistently maintained in the study's results and conclusions.

2.4. Didactic intervention

Once the 3D biomodels were manufactured, the experimental group participated in four 60-minute sessions using a Problem-Based Learning strategy. In these sessions, students worked in small

groups, directly manipulating the healthy and cirrhotic liver models they had designed and created themselves, to solve clinical cases of hepatobiliary disease. During the same period, the control group received the same content through lectures supported by two-dimensional images, without access to the printed models or the active small-group work methodology. At the end of the session, both groups completed the Knowledge Test (post-test), and the experimental group also answered the TAM questionnaire related to the design process described in section 2.3.

It is necessary to clarify here the main methodological limitation of the study. Between the two groups (control and experimental), two components change simultaneously: the teaching resource (3D biomodels versus 2D images) and the teaching methodology (Problem-Based Learning with active work in small groups versus traditional lectures). This is called intervention confound, as these components vary together in the educational application; that is, no difference between groups can be attributed solely to 3D printing. This difference could depend on the 3D biomodel, the active methodology, or the interaction between the two. The present study evaluated the combined effect of the two components (3D biomodels and PBL) compared to traditional teaching, and not the specific effect of either one separately. This limitation is addressed in the discussion and is consistently reflected in the interpretation of the results and the conclusions.

2.5. Statistical analysis

Data were processed using IBM SPSS Statistics v.25. Descriptive statistics (mean, standard deviation, median, quartiles, minimum, and maximum) were calculated for the Knowledge Test and the TAM subscales. The assumption of normality was verified using the Shapiro-Wilk test, recommended for sample sizes of less than 50 per group; its widespread violation led to the use of nonparametric statistics in all comparisons (23). Initial equivalence between groups and the comparison of posttest performance and learning gain (posttest minus pretest) were assessed using the Mann-Whitney U test; the pretest-posttest change within each group was assessed using the Wilcoxon test; and the relationship between technological acceptance (total TAM, PEOU, and PU) and the posttest academic performance of the experimental group was assessed using Spearman's rank correlation coefficient. To complement the statistical significance values with a measure of effect size, the biserial rank correlation coefficient (r) was calculated for the Mann-Whitney and Wilcoxon tests, following the simple difference formula (22), and 95% confidence intervals for r and ρ were estimated using Fisher's z -transform. A p -value greater than 0.05 was interpreted as a lack of evidence of a statistically significant difference between the groups, although this does not in itself imply proof of substantive equivalence between them. A two-tailed significance level of $\alpha = 0.05$ was set for all tests.

2.6. Ethical aspects

The study adhered to the principles of the World Medical Association's Declaration of Helsinki (24) and the Council for International Organizations of Medical Sciences (CIOMS) International Ethical Guidelines (25). Informed consent was obtained from each participant by research support staff not involved in the formal assessment of the course, and not by the instructors directly responsible for grading students, in order to reduce the risk of perceived coercion. The consent form guaranteed voluntary participation, the right to withdraw from the study at any time without academic penalty, and data confidentiality through alphanumeric coding. Both the Knowledge Test and the TAM questionnaire were administered exclusively for research purposes: their scores were not included in the official course grade records, which were assessed independently using the regular course instruments. For reasons of academic fairness, the control group was given access to the printed biomodels after data collection was completed. The research was approved by the institutional ethics committee, according to resolution No. 47-CEISH-UNACH.

3. Results

In the pretest, both groups started from a low and similar level of hepatobiliary knowledge, with no statistically significant difference between them according to the Mann-Whitney U test. This result indicates an absence of evidence of difference between the groups at baseline, but does not, in itself, constitute proof of substantive equivalence between them (Table 1). In the posttest, the experimental group achieved a mean of 9.75 points, with more than half of the students at the maximum possible score on the scale, while the control group averaged 7.57 points, with a notably greater dispersion (Table 1, Figure 2).

Both groups showed statistically significant improvement compared to their own pretest (Wilcoxon, $W=0.0$; $p<0.001$ in both groups; pairwise rank-biserial $r=1.00$ in both cases, indicating that all students in each group increased their score), suggesting that both teaching strategies were associated with learning. The direct comparison of posttest scores between groups significantly favored the experimental group, as did the learning gain between posttest and pretest. This correlation, taken together, supports the consistency of the finding from two different perspectives (Table 2). Since the intervention applied to the experimental group was inextricably linked to the use of 3D biomodels and the PBL strategy (see section 2.4), these differences should be interpreted as the combined effect of both components compared to traditional teaching, and not as isolated evidence of the specific contribution of 3D printing.

Regarding the technological acceptance of the 3D biomodel design and development process, the medians for perceived ease of use (PEOU=54.00, range 8-56) and perceived usefulness (PU=55.00, range 8-56) were close to the maximum value on the scale, suggesting an overall favorable assessment by the experimental group (Table 1). However, the standard deviation was high in both subscales (14.73 and 15.53, respectively), with a minimum value of 8, indicating that, alongside a majority with a very positive perception, there was a small group of students with a clearly negative assessment.

Table 1. Descriptive statistics of the Knowledge Test (pretest-posttest) and the TAM questionnaire (posttest, experimental group).

Instrument	Cluster	Moment	M $\pm$ OF	Mdn (Q1-Q3)	Min-Max
Knowledge Test	Experimental (n=40)	Pretest	1.96 $\pm$ 1.33	1.54 (0.77-2.50)	0.00-5.38
Knowledge Test	Experimental (n=40)	Posttest	9.75 $\pm$ 0.53	10.00 (10.00-10.00)	7.69-10.00
Knowledge Test	Control (n=32)	Pretest	2.00 $\pm$ 1.42	1.54 (0.77-3.08)	0.00-5.38
Knowledge Test	Control (n=32)	Posttest	7.57 $\pm$ 1.22	8.08 (6.92-8.46)	3.85-9.23
TAM - PEOU	Experimental (n=40)	Posttest	46.88 $\pm$ 14.73	54.00 (47.75-56.00)	8.00-56.00
TAM - PU	Experimental (n=40)	Posttest	46.38 $\pm$ 15.53	55.00 (48.00-56.00)	8.00-56.00
TAM total	Experimental (n=40)	Posttest	93.25 $\pm$ 29.91	107.00 (94.50-112.00)	16.00-112.00

Note: M: mean; SD: standard deviation; Mdn: median; Q1-Q3: quartiles 1 and 3; PEOU: perceived ease of use; PU: perceived usefulness.

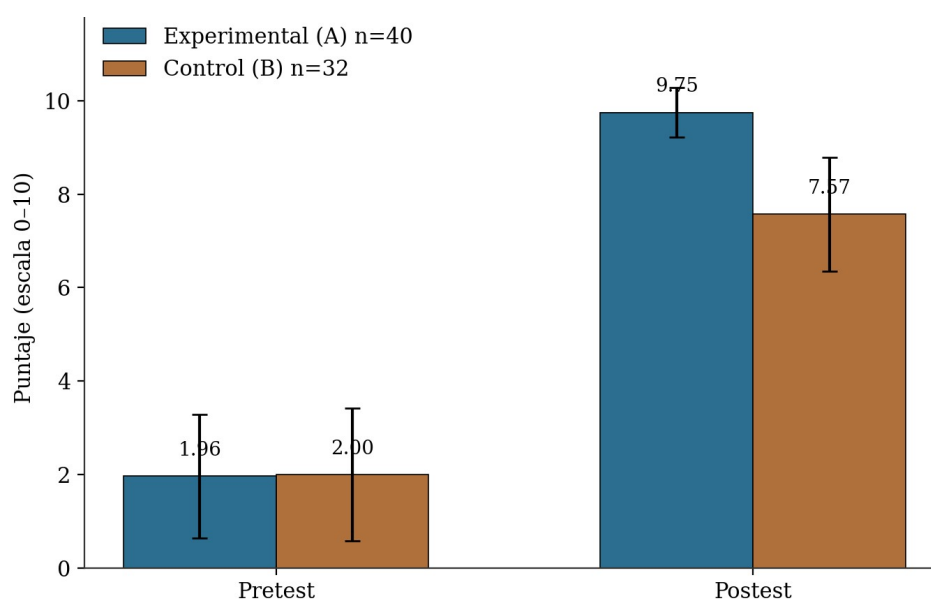


Figura 2. Comparación de los puntajes de la Prueba de Conocimientos en pretest y posttest, por grupo. Las barras de error representan la desviación estándar.

Table 2. Summary of statistical contrasts, with effect size and 95% confidence interval.

Contrast	Proof	Statistical	p	r / rho (95% CI)
Initial equivalence (pretest Exp. vs. Control)	Mann-Whitney U	U=629.5	0.908	r=0.02 [-0.22, 0.25]
Pretest-posttest change, experimental group	Wilcoxon	W=0.0	<0.001	r=1.00
Pretest-posttest change, control group	Wilcoxon	W=0.0	<0.001	r=1.00
Posttest between groups (Exp. vs. Control)	Mann-Whitney U	U=1241.5	<0.001	r=0.94 [0.91, 0.96]
Learning gains between groups	Mann-Whitney U	U=1033.5	<0.001	r=0.61 [0.45, 0.74]
Total TAM vs. performance (post-test)	Spearman's rho	rho=0.135	0.408	rho=0.14 [-0.18, 0.43]
PEOU vs. performance (posttest)	Spearman's rho	rho=0.108	0.507	rho=0.11 [-0.21, 0.41]
PU vs. performance (posttest)	Spearman's rho	rho=0.161	0.322	rho=0.16 [-0.16, 0.45]

Note: Exp.: experimental group; U: Mann-Whitney statistic; W: Wilcoxon statistic; rho: Spearman's rank correlation coefficient; r: rank-biserial r coefficient (Mann-Whitney and Wilcoxon tests); CI95%: 95% confidence interval calculated using Fisher's z-transformation.

When analyzing the relationship between technological acceptance and post-test academic performance using Spearman's rho coefficient, no statistically significant associations were identified (Table 2). This lack of correlation could be explained, at least partially, by a ceiling effect in the post-test of the experimental group: since most scores were concentrated at the maximum value of the scale, the variability available for any correlation coefficient to detect a real association was substantially reduced, regardless of the subscale being compared. This explanation is plausible but cannot be confirmed with the available data; additionally, the finding can also be interpreted as a

limitation of the instrument's discriminative capacity at the upper end of the scale, an aspect that is addressed in the discussion.

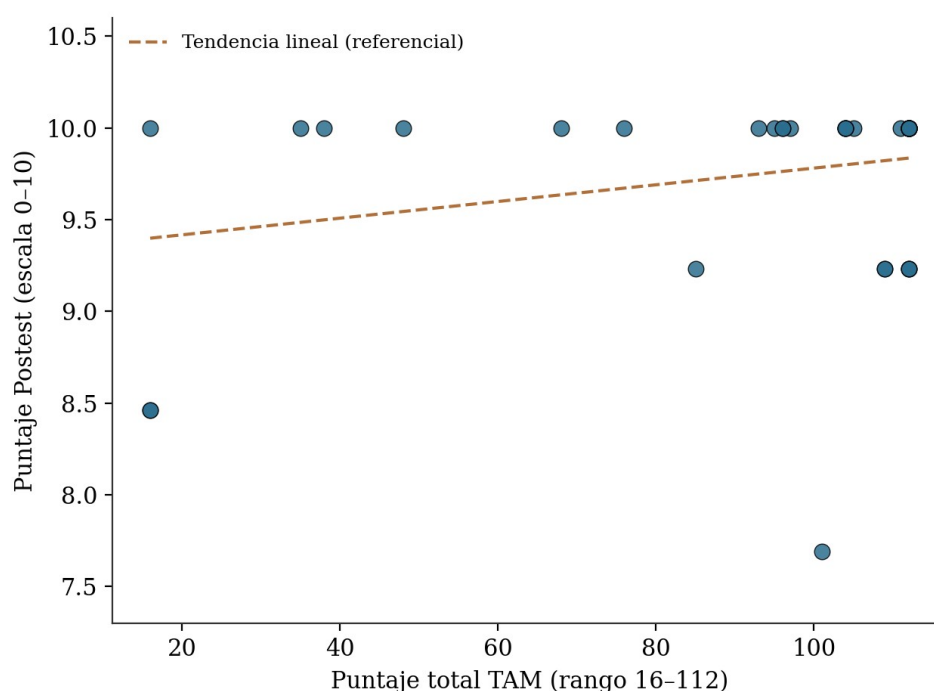


Figura 3. Relación entre aceptación tecnológica (TAM) y rendimiento académico en el grupo experimental (n=40).

Overall, the results are consistent with the research hypothesis regarding academic performance, which posits that the combination of anatomical biomodels designed and manufactured by the students themselves using digital modeling and 3D printing, applied through the PBL (Problem-Based Learning) teaching strategy, was associated with a significantly greater improvement in the learning of hepatobiliary pathological anatomy compared to traditional teaching. Since the study design does not allow for statistically separating the contribution of the three-dimensional resource from the PBL methodology (section 2.4), this conclusion is limited to the combined effect of both components (3D-PBL). Regarding technological acceptance, the hypothesis is only partially supported: while the overall assessment was favorable, there was insufficient statistical evidence of a linear association with the performance achieved.

4. Discussion

The results show that the intervention applied to the experimental group with anatomical biomodels designed and manufactured by students using 3D printing, developed under the PBL (Problem-Based Learning) strategy, was associated with a significantly greater learning gain than traditional lecture-based teaching in the hepatobiliary section of Pathology, with no initial differences between the groups. This finding is broadly consistent with the systematic review with meta-analysis of randomized controlled trials by Xie et al., which concludes that 3D-printed models facilitate spatial visualization and are associated with greater academic performance compared to exclusively two-dimensional methods (5). Specifically in the hepatic field, the observed improvement is compatible with that reported by Bao et al., who documented significant advances in the understanding of hepatic surgical procedures among students who used full-size printed models compared to conventional methods (6). It should be noted, however, that neither the study by Xie et al. nor that of Bao et al. They combined the three-dimensional resource with a Problem-Based Learning methodology applied in this research, so the comparison with the present study is indicative and

cannot be taken as confirmation that the 3D printing component, by itself, explains the magnitude of the observed effect.

Within the Latin American context, these findings are consistent with those reported by Valdez et al. regarding the positive association between three-dimensional visualization and academic performance in medical students in the region (26), and align with recent reviews published in Ibero-American medical education journals that document favorable educational effects of 3D printing and technological tools applied to teaching morphology (15,16), as well as with the growing adoption of digital resources described in regional medical programs (17). This research, in particular, provides a previously undocumented Ecuadorian precedent in this specific area: while UNACH had reported previous positive experiences with related visual technologies, with an overall positive assessment among students who used augmented reality for anatomical learning (27), no publications were identified that specifically evaluated the effect of 3D-printed pathological biomodels, designed by the students themselves and applied through PBL, on academic performance in pathology courses within the medical program. This observation describes a gap relative to that particular context within the reviewed literature, and should not be read as an absolute assertion of the non-existence of similar studies in other settings not covered by this review.

The absence of a statistically significant correlation between technological acceptance and academic performance allows for at least two non-mutually exclusive explanations, neither of which can be definitively confirmed with the available data. The first is statistical and measurement-related: the marked ceiling effect observed in the post-test of the experimental group reduced the available variability for any correlation coefficient to detect a real association, and constitutes, in itself, a limitation of the discriminative capacity of the assessment instrument at the upper end of the scale, rather than necessarily a limitation of the association in the general population. The second is theoretical and finds support within the TAM framework itself: perceived usefulness and perceived ease of use determine the behavioral intention to use a technology, not necessarily the performance obtained when using it (10). Along these lines, Kalinkara and Özdemir, using UTAUT2 to evaluate the acceptance of an anatomy environment in a metaverse, found that performance and effort expectations predicted the intention to use the resource relatively independently of its technical quality, suggesting that technological acceptance and learning outcomes may behave as partially dissociated phenomena (11). Based on this interpretation, it is plausible that the students in the experimental group learned more from the pedagogical value of designing, fabricating, and manipulating a physical replica of a real clinical case within an active Problem-Based Learning methodology, relatively independent of how much they specifically valued the 3D printing technology used to produce the resource. However, this interpretation is post hoc and would require a specific design for verification.

Among the study's limitations, the most relevant for the causal interpretation of the results is methodological rather than statistical: the intervention applied to the experimental group inextricably combined two components—the use of 3D biomodels designed and manufactured by the students and the Problem-Based Learning methodology in small groups—compared to a control intervention that also combined two distinct components—two-dimensional images and the generally expository lecture. This confounding of interventions, by design, prevents us from determining whether the observed difference is due to the three-dimensional resource, the PBL methodology, the active work in small groups, or the interaction between these elements. This should be considered the central limitation when interpreting the results of this study, ahead of the additional limitations described below. The quasi-experimental design, with intact groups not randomly assigned, favors ecological validity but does not allow for the complete elimination of confounding variables associated with the original parallels. The sample consisted of a single cohort from a single institution and a single pathological case (liver cirrhosis), which limits the

generalizability of the findings to other hepatobiliary lesions or other educational contexts. Furthermore, an independent, objective evaluation of the morphological accuracy of the printed biomodels was not performed; therefore, this study's assertions regarding their educational utility do not imply morphometric validation of said accuracy. Future research could experimentally isolate the effect of the 3D resource from that of the corresponding PBL methodology (for example, using a four-arm factorial design), incorporate instruments with a greater range of discrimination at the upper end of the knowledge scale, expand the study to other pathological structures and different institutions, and explore the mediating, rather than directly correlational, role of technological acceptance on academic performance.

5. Conclusions

- Under the guidance of the teacher, the students designed and manufactured biomodels of healthy and cirrhotic livers from the same study of real DICOM images, using 3D Slicer segmentation, post-processing in Meshmixer and FDM printing in PLA; this procedure was aimed at reproducing the nodular texture characteristic of cirrhosis for teaching purposes, without having carried out an independent morphometric validation of the anatomical fidelity achieved.
- The Problem-Based Learning teaching strategy applied with the 3D biomodels designed by the students themselves was implemented in a period of time comparable to that of the control group, without relevant incidents, which supports its operational feasibility in a regular Pathological Anatomy course.
- The technological acceptance of the experimental group towards the process of designing and elaborating the 3D printed biomodels was, in general, high, both in perceived ease of use and in perceived usefulness, although with a minority group of clearly negative assessments.
- No statistically significant relationship was found between technological acceptance and academic performance; this result could be explained, at least partially, by a ceiling effect in the post-test of the experimental group, without allowing us to rule out with certainty a real absence of association under conditions of greater variability.
- The academic performance of the experimental group that worked with 3D biomodels using PBL was significantly higher than that of the group with traditional teaching, both in the final score and in the learning gain, which supports the research hypothesis in its performance component, always referring to the joint effect of both components of the intervention and not only to 3D printing in isolation.
- Since the study design does not allow for statistically separating the contribution of the 3D biomodel resource with the PBL methodology, this limitation should be considered when translating the findings into curricular decisions, and it points to the need for future factorial designs that allow for isolating both components.
- This study provides empirical evidence on the combination of 3D-printed biomodels designed and created by students and their application with the Problem-Based Learning (PBL) strategy for teaching hepatobiliary pathology. The findings contribute to the knowledge of innovative learning strategies within the institutional setting; however, the results should be interpreted within this specific context and not extrapolated as evidence of pioneering work in Ecuadorian medical education.

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Authors' contributions: BGHC: conceptualization and research methodology. MVMR and AGMA participated in data curation, statistical analysis, and drafting of the original manuscript. ATO and WPVA performed the conceptualization, supervision, design, and development of the biomodels, as well as drafting, revision, and editing. All authors have read and accepted the submitted version of the manuscript.

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