Replicating Livers Through 3D Printing for Surgical Training: a Cost-Effective Approach

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Abstract

This research paper explores a unique approach to medical training and surgical planning using 3D-printed gelatin molds to replicate the liver's anatomy. Traditional methods, such as the use of synthetic materials or cadavers, often fall short. Gelatin presents a promising alternative. In this study, we used Tinkercad, a user-friendly 3D modeling software, to design and render a precise liver model previously rendered in thingiverse. To ensure the models were as realistic as possible, we measured hardness, puncture resistance, and elasticity. These scales helped determine how closely the gelatin models replicated the physical characteristics of an actual liver. We determined if these gelatin molds can serve as realistic and cost-effective tools to improve pre-surgical planning with detailed anatomical models. Our 3D-printed gelatin molds will enhance medical education by offering a more hands-on learning experience, improve surgical precision through better preoperative planning, and advance research by simulating liver properties, because the results show that they can in fact mimic a real pig liver, specifically the 12 gram mold liver showing the most similarities. We hope that our findings will significantly contribute to the fields of medicine and biomedical research, offering a practical and innovative solution to current limitations.

Keywords

Biomedical engineering 3D Printing;surgical training; simulation models; liver mimic; gelatin-based replication

Introduction

Liver diseases, especially liver cancer, cast a long shadow over global health, affecting millions of lives each year. According to the World Health Organization, liver cancer ranks as the third leading cause of cancer-related deaths worldwide. In fact, it holds the unenviable position as the deadliest cancer among men globally.[1] Despite the strides made in medical science, the survival rate for liver cancer remains alarmingly low, often due to late diagnoses and the complex nature of liver surgeries. These challenges highlight the critical need for well-trained medical professionals who can effectively diagnose and treat these conditions.

Traditionally, aspiring liver surgeons have honed their skills on cadaveric livers or animal models. Cadavers offer unparalleled anatomical accuracy, but they're scarce and come with significant ethical and logistical hurdles.[2] Animal models, while more available, don't perfectly mimic the human liver, which can limit the effectiveness of training. Synthetic materials like

silicone or polyurethane have been introduced as alternatives, but they often fall short in replicating the true feel and behavior of human tissues, which is crucial for surgical practice.[3]
In recent years, there's been a push to find training methods that are not only more accessible and cost-effective but also more realistic. This is where gelatin molds have started to shine. Gelatin is a material that's both versatile and biodegradable, and it can be molded to closely replicate the texture and density of human organs. What makes it particularly exciting is that it offers these benefits at a fraction of the cost of traditional methods. For instance, while acquiring a cadaveric liver or a high-end synthetic model can run into the thousands of dollars, a gelatin mold is far more affordable, opening up the possibility for more widespread use in medical training.

Additionally, gelatin molds can be tailored to simulate various liver conditions, like tumors or cysts, through proxy materials such as glycerin and sugar, allowing trainees to practice a range of procedures in a highly realistic environment.[4] This adaptability is a game-changer, offering medical professionals a more comprehensive training experience. With these cost effective alternatives, we want to explore whether gelatin molds can stand in as a viable alternative to real livers for surgical training.

Methods and Materials

The initial phase involved selecting an appropriate liver model from Thingiverse, a popular 3D model repository.[5] This model was then imported into Tinkercad, an online 3D design tool, for modification. To achieve a hollow design, the liver was first divided into two halves. This was done by creating two hollow boxes in Tinkercad, which were perfectly aligned in the center of the liver model. The hollow boxes were carefully positioned to ensure each box contained a symmetrical portion of the liver model. Next, each hollow box was combined with its corresponding half of the liver. Once the liver halves were correctly aligned within the boxes, the two hollow boxes were separated from the combined model.[6] This process effectively split the liver into two symmetrical hollow halves. The hollow boxes were then deleted, leaving behind two perfectly hollowed liver halves, ready for 3D printing.

The modified liver mold was processed using Flashprint 5, a slicer software that prepares 3D models for printing. The mold was scaled down to 50% of its original length and additional supports were added to ensure structural integrity during printing. This was done through the feature "auto-supports." To test the compatibility of the mold with the Adventure 3 Lite 3D printer, a preliminary print of a 20x20 mm calibration cube was conducted. This step ensured the accuracy and precision of the printer settings.

For the final mold, PLA gray filament was used due to its durability and ease of use. After printing, minor imperfections, such as tiny holes, were observed in the model. To prevent gelatin leakage during cooling in a refrigerator, the mold was carefully sealed using duct tape.

Gelatin Preparation: Gelatin molds were prepared using Knox gelatin packets. Various gelatin concentrations were tested to identify the most suitable mixture for mimicking liver tissue. The concentrations included:

- G4: 4 g gelatin/100 mL water + 10 g sugar

- G8: 8 g gelatin/100 mL water + 12.5 g sugar
- G12: 12 g gelatin/100 mL water + 15 g sugar
- G16: 16 g gelatin/100 mL water + 20 g sugar

For each preparation, 50 mL of cold water was poured into a bowl, and the gelatin powder was evenly sprinkled on top, allowing it to bloom for 10 minutes. Separately, 50 mL of water was brought to a boil and added to the gelatin mixture, followed by the appropriate amount of sugar. The mixture was stirred until fully dissolved, then poured into the prepared liver molds. The molds were left to cool for four hours, allowing the gelatin to solidify completely.

To simulate liver tumors within some of the gelatin molds, a glycerol agar mixture was prepared. The composition included 3% agarose, 9% glycerol, and 88% water by weight.[4] This mixture was poured into the gelatin mixture and then later into the mold, creating realistic tumor-like structures.

Firmness Measurement: The firmness of the gelatin molds was evaluated using a 10-point Likert scale. The scale was designed to quantify the material's resistance to compression, with higher values indicating greater firmness:

1. Very Soft: Material compresses easily with minimal pressure, similar to a plush pillow.
2. Soft: Material offers slight resistance, comparable to a worn cushion.
3. Moderately Soft: Material compresses moderately, akin to a soft memory foam mattress.
4. Moderately Firm: Material offers balanced resistance, similar to a firm mattress.
5. Firm: Material holds shape with some resistance, comparable to a new memory foam mattress.
6. Very Firm: Material resists compression strongly, similar to a solid wood surface.
7. Extremely Firm: Material is difficult to compress, akin to hard plastic.
8. Near Rigid: Material offers significant resistance, resembling thin metal.
9. Rigid: Material hardly compresses, similar to thick metal.
10. Very Rigid: Material is nearly incompressible, akin to steel.

Puncture Resistance: Puncture resistance was similarly evaluated using a 10-point Likert scale, focusing on the force required to penetrate the gelatin mold:

1. Very Low Resistance: Easily punctured, similar to a balloon.
2. Low Resistance: Punctured with moderate force, akin to soft plastic.
3. Moderate Resistance: Requires noticeable force, like thick leather.
4. High Resistance: Significant force needed, similar to hard plastic.
5. Very High Resistance: Difficult to puncture, akin to thin metal.
6. Extreme Resistance: Very difficult to puncture, like thick glass.
7. Near Unpuncturable: Requires extreme force, akin to steel.
8. Unpuncturable: Nearly impossible to puncture.
9. Almost Impervious: Comparable to heavy industrial materials.
10. Impervious: Essentially cannot be punctured, similar to reinforced steel.

Elasticity Measurement: The elasticity of the gelatin molds was measured using a homemade force gauge. The gauge consisted of a spring scale connected to the mold, with measurements taken as force was applied to either stretch or compress the gelatin. The process was as follows:

Initial Measurement: The initial length of the gelatin mold was measured using a ruler

Force Application: A controlled force of 2 Newtons was applied using the force gauge.

Deformation Measurement: The change in length (deformation) was recorded after one end was held down, ensuring the force remained within the elastic limit of the gelatin.

Calculation of Young's Modulus: Using the recorded deformation and the applied force, the stress and strain were calculated. The Young's Modulus (E), which indicates the material's elasticity, was then determined using the formula: Stress/Strain. Stress, defined as the internal force per unit area, was calculated using the formula F/A where F is the applied force (2 Newtons), and A is the cross-sectional area of the gelatin mold. The cross-sectional area was determined from the diagonal that was cut along the original mold. Strain was found by using the formula change in L/ initial L, where L is the length of the mold.

Density Measurement: Density was calculated by first measuring the mass of the gelatin mold using a precision scale. The volume was determined by water displacement in a graduated cylinder. The density was then calculated using the formula Density= Mass(g)/Volume(mL).

Results and Discussion

Results

The results of this study provide a comprehensive evaluation of the physical properties of 3D-printed gelatin molds across different concentrations, offering insights into their potential as realistic and cost-effective alternatives for medical training. The analysis focuses on firmness, puncture resistance, elasticity, and density, with trends observed in the data that highlight the effectiveness of various gelatin concentrations.

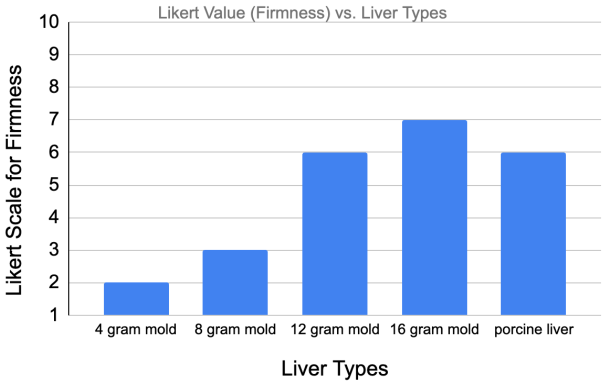

Figure 1: The different gelatin mold concentration's Likert-scale for firmness compared to real pig liver.

Firmness increases with gelatin concentration: Firmness was assessed using a 10-point Likert scale, with a real pig liver scoring a firmness of 6. The 4-gram gelatin mold scored a firmness of 2, corresponding to a "Very Soft" consistency, which means it compressed easily with minimal pressure. The 8-gram gelatin mold, which included a simulated tumor, scored a firmness of 3, falling into the "Soft" category, indicating slight resistance to compression. Because the tumor was towards the center of the mold, it was thought to have not affected the data. The 12-gram gelatin mold scored a firmness of 6, categorized as "Firm," matching the firmness of the real pig liver. The 16-gram gelatin mold scored a firmness of 7, classified as "Very Firm," showing significant resistance akin to a solid wood surface.

As the gelatin concentration increased, so did the firmness of the molds. This trend is consistent with the expectation that higher gelatin concentrations result in greater material density and rigidity. The 12-gram mold, with a firmness score of 6, provided the closest match to the real pig liver, offering a realistic balance of firmness for training purposes. The 8-gram mold, while softer, might serve as a model for less rigid tissue types. The 16-gram mold, being firmer than the real pig liver, may be less ideal for realistic liver simulations due to its higher rigidity.

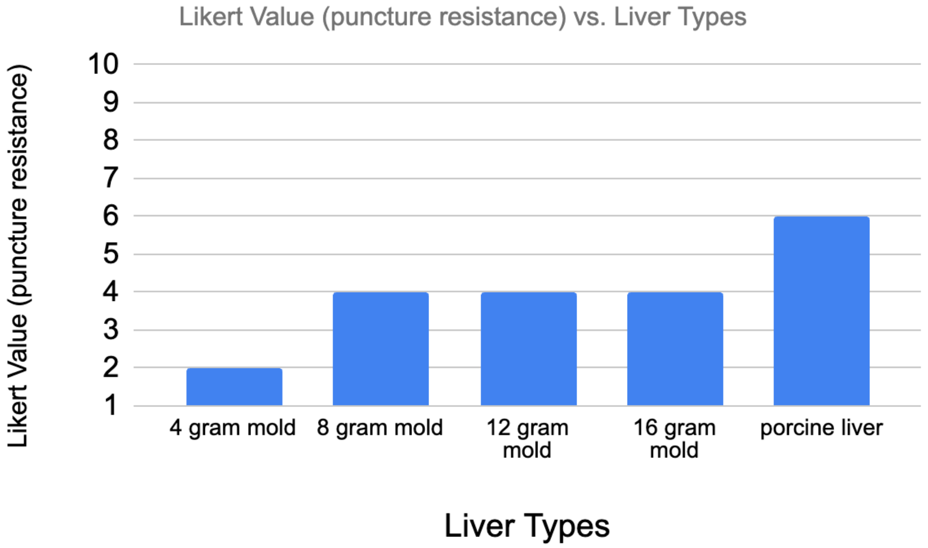

Figure 2: The different gelatin mold concentration’s Likert-scale for puncture resistance compared to real pig liver.

Puncture resistance was also measured using a 10-point Likert scale, with a real pig liver scoring a puncture resistance of 6. The 4-gram gelatin mold scored a puncture resistance of 2, indicating "Very Low Resistance," similar to a balloon. The 8-gram gelatin mold scored a puncture resistance of 4, categorized as "Moderate Resistance," requiring noticeable force to penetrate, comparable to thick leather. This mold also contained a simulated tumor, which did not affect the puncture resistance. Both the 12-gram and 16-gram gelatin molds scored a puncture resistance of 4, maintaining "Moderate Resistance."

The data suggest that gelatin concentration had a minimal effect on puncture resistance, as all tested molds exhibited similar resistance to puncture. The 8-gram and 12-gram molds, while not matching the pig liver's puncture resistance of 6, still offer moderate resistance, making them useful for training in procedures such as suturing or puncture-related tasks. However, further adjustments to gelatin concentration or additives could be explored to bring the puncture resistance closer to that of a real pig liver, enhancing the realism of the model for surgical practice.

Elasticity was evaluated by measuring deformation under a constant force of 2 Newtons, with Young's Modulus calculated for each mold and compared to a real pig liver, which has an elasticity of approximately 246.33 Pa. The 4-gram gelatin mold exhibited a Young's Modulus of 74.78 Pa, indicating lower stiffness and higher elasticity, with a strain of 0.1931, reflecting high deformation under force. The 8-gram gelatin mold demonstrated a Young's Modulus of 124.16 Pa, suggesting moderate stiffness and balanced elasticity, with a strain of 0.1163. The 12-gram gelatin mold had a Young's Modulus of 211.73 Pa, showing increased stiffness and reduced elasticity, with a strain of 0.0682. Finally, the 16-gram gelatin mold exhibited the highest Young's Modulus of 313.91 Pa, indicating the greatest stiffness and least elasticity, with a strain of 0.0460.

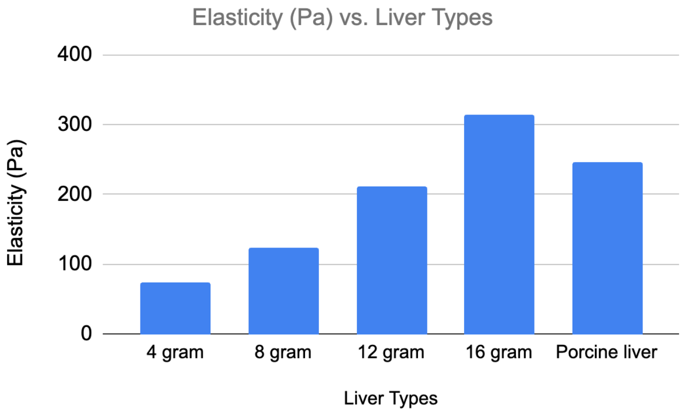

Figure 3: The different gelatin mold concentration’s elasticity compared to real pig liver.

The data reveal a clear trend where increasing gelatin concentration results in higher stiffness and lower elasticity. The 12-gram mold, with a Young's Modulus of 211.73 Pa, comes closest to the elasticity of a real pig liver (246.33 Pa), making it the most suitable for approximating liver tissue properties in a medical training setting. The 8-gram mold, while more elastic than real liver tissue, offers a good balance for simulating softer tissue. In contrast, the 16-gram mold exhibits much greater stiffness than the pig liver, making it less ideal for applications requiring realistic elasticity.

Density measurements were taken to assess the mass-to-volume ratio of the gelatin molds, and these were compared to the density of a real pig liver, which is approximately 1.14 g/mL. The 4-gram gelatin mold had a density of 1.42 g/mL, indicating it is denser than the real liver. The 8-gram gelatin mold measured at 1.53 g/mL, reflecting an even denser material. The 12-gram gelatin mold showed a density of 1.44 g/mL, while the 16-gram gelatin mold had the highest density at 1.56 g/mL.

The results demonstrate a trend where increasing gelatin concentration correlates with greater density, though the values begin to plateau after the 12-gram mold. This suggests that adding more gelatin beyond a certain point does not highly impact the density of the material. While all the molds were denser than the real pig liver, the 8-gram mold offers a balance between density and other physical properties, making it a reasonable choice for simulating liver tissue in medical training. However, for more accurate replication of liver density, further adjustments to the gelatin concentration might be necessary to lower the density and bring it closer to 1.14 g/mL, particularly in scenarios where simulating organ weight and texture is crucial.

Discussion

The findings from our study indicate that 3D-printed gelatin molds offer a promising alternative to traditional liver models used in medical training. The observed trends in firmness, puncture resistance, elasticity, and density reveal that gelatin molds can closely replicate the physical properties of real liver tissues, with certain compositions demonstrating notable similarities.

The firmness measurements showed a clear trend: as the concentration of gelatin increased, the firmness of the molds also increased. For instance, the 12-gram and 16-gram gelatin compositions were rated as "Moderately Firm" to "Firm," reflecting a significant resistance to compression. This characteristic is critical for simulating the tactile experience of handling real liver tissues during surgical training. Realistic firmness helps trainees develop a more accurate sense of the pressures and textures they will encounter in actual procedures, thus enhancing their hands-on learning experience and improving their practical skills.

Puncture resistance data demonstrated that the 8-gram, 12-gram, and 16-gram gelatin molds offered higher resistance compared to the 4-gram gelatin molds. This trend suggests that as gelatin concentration increases, so does the puncture resistance of the molds. This property is particularly valuable for training in techniques such as suturing and needle insertion, where varying levels of resistance can be simulated. Higher puncture resistance in the molds provides a more realistic training scenario, allowing medical professionals to practice and refine their skills in a controlled environment, ultimately contributing to better surgical outcomes and reduced error rates in real procedures.

Elasticity measurements indicated that the 12-gram and 16-gram gelatin molds displayed lower Young's modulus values compared to the 4-gram gelatin mold, suggesting greater flexibility and ability to return to the original shape after deformation. This property is essential for mimicking the dynamic nature of liver tissues, which can stretch and compress during surgical manipulations. Enhanced elasticity in the molds can improve the training experience by offering a more accurate simulation of liver dynamics, thus helping surgeons better prepare for complex procedures.

The density measurements showed that higher gelatin concentrations resulted in increased density values. This trend aligns with the expected outcome that more concentrated gelatin solutions produce denser molds. The density of the molds is a crucial factor in replicating the weight and feel of real liver tissues, which can influence the realism of the training experience. By accurately reflecting the density of liver tissues, the molds ensure that medical professionals can practice with a model that closely approximates the physical characteristics of real organs.

The affordability of 3D-printed gelatin molds offers significant benefits for medical training and surgical planning. Traditional liver models, whether cadaveric or synthetic, are often expensive and less accessible. In contrast, gelatin molds provide a cost-effective alternative that can be produced at a fraction of the cost. This affordability is especially crucial for regions with limited resources, such as third-world countries where liver diseases are prevalent.[7] By providing an accessible and realistic training tool, these molds can enhance medical education and improve surgical preparation in areas where access to high-quality training resources is limited. The ability to produce detailed and accurate anatomical models at a low cost can lead to better-prepared healthcare professionals and potentially improve patient outcomes in underserved regions.

The study's findings highlight the potential of 3D-printed gelatin molds in transforming medical education and surgical training. Future research could explore the scalability of this technology for other organs, the incorporation of additional materials to enhance realism, and the broader applications across various medical disciplines. By continuing to refine and expand the use of gelatin molds, we can further advance medical training practices and address the challenges faced by healthcare systems worldwide. One area for improvement is the longevity of the gelatin molds. Testing whether the molds maintain the same tensile measurements, elasticity, and firmness after being stored for extended periods, such as a month in a refrigerated environment, would provide valuable insight into their durability. This would be crucial for understanding how well these models can withstand repeated use in medical training scenarios. Additionally, subjecting the molds to environmental variations such as humidity, temperature fluctuations, and sterilization methods could provide data on how they perform under real-world conditions, particularly in settings where equipment might not be ideal.

Another enhancement would involve testing the inclusion of different additives, such as plasticizers or cross-linking agents, which could improve the mechanical properties and extend the lifespan of the molds. Furthermore, exploring the impact of more precise anatomical detailing in the molds—such as simulating the vasculature or bile ducts of a liver—would elevate the realism and offer more comprehensive training opportunities. By continuing to refine and expand the use of gelatin molds, we can further advance medical training practices and address the challenges faced by healthcare systems worldwide.

References

1. biotecha_admin. (2024, January 23). *Do surgeons practice on cadavers? training boosts surgeons: Biotech*. biotechanatomy. https://biotechanatomy.co.il/blog/do-surgeons-practice-on-cadavers/#:~:text=Traditional%20formalin%2Dfixed%20cadavers%2C%20while,Tissue%20Texture%2C%20Color%2C%20and%20Consistency
2. Centers for Disease Control and Prevention. (n.d.). *USCS data visualizations - CDC*. Centers for Disease Control and Prevention. https://gis.cdc.gov/Cancer/USCS/#/AtAGlance/
3. Gelatin-agar liver phantom to simulate typical ... (n.d.). https://juniperpublishers.com/argh/pdf/ARGH.MS.ID.555998.pdf
4. Thingiverse.com. (n.d.). *BodyParts3D liver by Lambchops*. Thingiverse. https://www.thingiverse.com/thing:49995
5. World Health Organization. (n.d.). *Liver cancer*. World Health Organization. https://platform.who.int/mortality/themes/theme-details/topics/indicator-groups/indicator-group-details/MDB/liver-cancer
6. Yoshimura, M., Ohura, N., Tanaka, J., Ichimura, S., Kasuya, Y., Hotta, O., Kagaya, Y., Sekiyama, T., Tannba, M., & Suzuki, N. (2018, April). *Soft silicone foam dressing is more effective than polyurethane film dressing for preventing intraoperatively acquired pressure ulcers in spinal surgery patients: The Border Operating Room Spinal Surgery (BOSS) trial in Japan*. International wound journal. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC7950169/
7. YouTube. (n.d.). YouTube. https://www.youtube.com/watch?v=6Nxj4gz2zD0&t=272s