Artificial Intelligence in Cardiovascular Decision Making: A Tool for 3D Heart Modeling and Simulation of Tetralogy of Fallot

Aya Abiya[1], Fatima Bouyahia[1], Mouhcine El Mardouli[2], Drissi Boumzebra[2], Ahmed+

Aamouche[1] [1]Systems Engineering & Applications Laboratory LISA, Cadi Ayyad University-Marrakesh [2]Health & Bioscience Laboratory, Cadi Ayyad University-Marrakesh

Abstract: In this work, a Hybrid 3D modelling is developed to demonstrate how AI can improve the knowledge of heart diseases and facilitate clinical decision-making, especially in cardiology surgery. Using AI for heart modelling significantly impacts medical training and surgery preparation. AI can revolutionise decision-making in cardiology by providing precise, patient-specific tools for heart modelling- This could lead to more accurate diagnoses, more effective treatments, and ultimately, better patient outcomes. The rendering of this research has been corroborated by the positive feedback from doctors, which serves as a testament to the efficacy of this approach. No doubt, the contribution of industrial engineering to solve complex medical issues is notable, including the optimisation process while respecting the principles of the golden triangle. To solve this problem in a structured way, a Define—Measure—Analyze—Design—Verify DMADEV method is adopted as a Six Sigma Framework dedicated to new product or process conception. The potential of AI to transform decision-making in cardiology surgery by providing precise tools for heart modelling is fascinating and opens up a world of possibilities for the future of cardiology.

Keywords: Cardiovascular, Tetralogy of Fallot, artificial intelligence, 3D printing, modelling, simulation, decision making.

INTRODUCTION

This research on artificial intelligence in cardiovascular decision-making, particularly in the context of 3D Heart Modeling and Simulation of Tetralogy of Fallot, represents a significant breakthrough. Traditionally, heart disease diagnosis relied on conventional imaging techniques, which served as diagnostic tools. However, these techniques were inadequate for the complex demands of Structural Heart Disease (SHD) interventions, prompting a shift towards more advanced imaging modalities capable of planning, simulating, and predicting outcomes during procedures.

In transcatheter SHD interventions, the lack of a clear open surgical field poses challenges, depriving physicians of essential tactile feedback and visual verification of cardiac anatomy. As a result, the incorporation of imaging into periprocedural guidance has marked the beginning of a new era in procedural skills, underscoring the importance of visualising the operative field and harnessing technological advancements during the planning phase.

Engineering has been a consistent force in driving medical advancements and enhancing the quality of human life, initially through processes and now through artificial intelligence. AI can potentially revolutionise cardiovascular medicine decision-making by providing precise tools for heart modelling. This work on modelling the heart with Tetralogy of Fallot exemplifies how AI can be leveraged to deepen the understanding of heart diseases and assist physicians in planning and simulating surgical interventions.

Literature Review

The 2020 study by Hon, Hussein, Osamihonjo, and Yoo revealed decreased interest in cardiac surgery among medical students. However, the use of 3D-printed heart models for simulation significantly impacted their career choices, potentially increasing interest in cardiac surgery. [1]

In the research conducted by Anwar & al., (2017), the authors used three-dimensional (3D) printing technology in patients diagnosed with congenital heart disease. Their goal was to represent complex anatomical structures accurately, plan surgical interventions, and educate both medical trainees and patients. The cases examined included individuals of different age groups, from infants to adults, all with congenital heart conditions. Various pathologies were explored, covering intracardiac malformations, vascular anomalies, and airway irregularities. [2]

The 2013 study by D.B.S. Tam & al., illustrates the use of 3D printing to create a replica of an aortic aneurysm. This model helped guide decision-making and device selection for endovascular repair of the aneurysm. 3D printing allowed a detailed analysis of the patient's anatomy, facilitating the selection of appropriate devices. This improved preoperative planning and reduced potential complications. Surgeons can use the 3D model to simulate different treatment scenarios and evaluate their effectiveness. This allows for informed decision-making, minimising risks, and optimising patient outcomes. In sum, 3D printing offers precise and personalised visualisation of the patient's vascular anatomy, facilitating decision-making. [3]

In the same year , The study of Matthew D.B.S. Tam, FRCR; Stephen D. Laycock, ; James R.I. Brown,; and Matthew Jakeways, examines the use of rapid prototyping and 3D printing to enhance decision-making in endovascular aneurysm repair (EVAR) involving complex anatomy. The case of a 75-year-old patient with a 6.6 cm infrarenal aneurysm illustrates the anatomical challenges. Despite tomographic analysis, uncertainties remain, making physical models essential.

The authors highlight the shift toward semi-automated techniques that reduce processing time and facilitate visualization. 3D models improve procedure planning and communication among medical teams.

Finally, the article emphasizes the potential of 3D models to enhance patient outcomes and reduce costs, while calling for further research to validate their clinical use. [4]

The 2014 study by Schmauss & al., evaluates the use of 3D-printing in cardiac surgery and interventional cardiology based on the experience of a single medical center from 2006 to 2013. It demonstrates the use of 3D models for perioperative planning and simulation of cardiovascular procedures. Eight representative cases were selected to show the usefulness of 3D models in accurately visualising cardiovascular anatomy. The study concludes that 3D printing is a feasible and valuable approach to improve planning and simulation in pediatric and adult cardiac surgery and interventional cardiology, paving the way for future studies to quantify its potential benefits better. [5]

The study by Farooqi & al. analysed 3D printing methods, including FDM (Fused Deposition Modeling) and stereolithography. These techniques transform a 3D virtual object into a physical object. FDM printers deposit layers of liquefied thermoplastic material, while stereolithographic printers use a laser to solidify layers of liquid photopolymer. [6]

3D printers, such as FDM, PolyJet, and stereolithographic models, offer a range of capabilities, including multicolour and multi-material printing. FDM printers are more economically accessible, while PolyJet and stereolithographic printers offer finer layer resolution. The choice of the ideal printer depends on cost and specific purpose. Using 3D-printed models with Agilus materials was effective for surgical planning in children with Raghib syndrome. A 2020 study designed a model of complex congenital heart disease to facilitate the simulation of a surgical procedure. Once the 3D virtual file is prepared, it is printed layer by layer. Overhanging parts are generally printed with a support material to maintain their position. [7]

The 2016 study by Crafts & al., highlights that the initial costs of adopting 3D printing are often considered prohibitive, which could hinder its widespread adoption in otolaryngology. However, prices continue to fall, and it has been demonstrated that using 3D-printed materials can result in cost savings. Regarding medical applications, the limited number of materials approved by the Food and Drug Administration results in higher material costs. Although the materials used for 3D-printing of educational models are becoming increasingly accessible, many educators are consistently concerned that there is no proper substitute for human tissues. Nevertheless, the use of 3D-printed models could potentially reduce the need to acquire cadaver bonesfor training.[8]

The research by Yiting & al. (2019) examines the application of 3Dprinting in structural heart diseases. It highlights how this innovative technology improves understanding of anatomy, aids in preoperative planning, and facilitates surgical simulation. The study highlightsthe advantages of 3D printing for customising treatments and reducing surgical risks while discussing future progress and challenges. Despite the potential limitations of 3D printing, such as the quality and precision of printed anatomical models, continuous technological improvement and increasing practitioner expertise offer ways to mitigate these limitations. [9]

In 2018, Lau &Sun studied 3D printing in pediatric and congenital cardiac surgery. Despite the advantages of this technology, such as the creation of precise anatomical models, they also highlight the challenges associated with its implementation, such as the complexity of modelling cardiac structures in pediatric patients, technological constraints, and substantial costs. Thus, despite the potential of 3D printing, its limitations must be carefully considered for optimal use. [10]

This article emphasises the critical role of artificial intelligence (AI) in cardiology decision-making. AI was used to create detailed 3D models of hearts affected by Tetralogy of Fallot, a complex heart disease. These models, evaluated by 125 doctors from 60 nationalities, were praised for their realism and utility in surgical practice. They also enhance medical students' understanding due to their representation of blood circulation and internal details while utilising the DMADV approach, which stands for Define, Measure, Analyze, Design, and Verify. This methodology is a part of the Six Sigma framework and it is used for developing new products or processes or significantly enhancing existing ones.

METODOLOGY

The approach of this study began with identifying the current issue related to congenital cardiovascular diseases, with a particular focus on the Tetralogy of Fallot. This crucial step provided a deep understanding of the challenges and stakes associated with this medical condition.

After clearly defining the problem, a detailed assessment of the current situation was conducted. This involved thoroughly analyzing the existing processes, and examining their strengths and weaknesses. A critical evaluation of the current process was carried out, with pertinent questions raised to determine the feasibility of adopting an alternative industrial approach. Following this analysis, an improvement to the process was proposed. This proposal addressed the challenges identified while assessing the current situation. The proposed improvement was then implemented.

Finally, the work was verified by experts in the field to ensure the effectiveness of the solution. Their expertise and feedback were invaluable in validating the approach and confirming that the right track was being followed to address the identified problem.

In summary, this achievement results from a rigorous methodology and close collaboration with domain experts. This approach will allow to make a significant difference in the fight against congenital cardiovascular diseases.

Problem identified

Based on the information and articles discussed, the problem statement could be formulated as follows:

"How can Artificial Intelligence and 3D printing technology be leveraged to improve the understanding and treatment of complex heart diseases like Tetralogy of Fallot, while overcoming limitations such as the rigidity of models, high costs, the need for continuous technological progress, and increasing practitioner expertise?"

This problem statement encapsulates the key challenges and opportunities in integrating AI and 3D printing in cardiac surgery. It focuses on enhancing medical training, surgical planning, and decision-making in treating complex heart diseases. It also acknowledges the need to address these technologies' limitations and challenges for optimal utilisation.

Measuring the impact

Based on the articles mentioned in the Literature Survey section, the key points that have been highlighted are:

- 3D heart models reduce the need to acquire cadaver hearts for training.
- 3D heart models aid and facilitate student understanding.
- 3D heart models are beneficial for perioperative planning and simulation of cardiovascular procedures.

In addition to these points, it's important to note that using 3D-printed heart models has been shown to significantly impact medical students' career choices, potentially increasing interest in cardiac surgery. These models provide a precise and personalised visualisation of the patient's vascular anatomy, facilitating decision-making and reducing surgical risks. However, despite the potential of 3D printing, its limitations must be carefully considered for optimal use. One such limitation is the rigidity of the models produced by 3D printing. This could hinder the accurate replication of intricate cardiac structures, especially in pediatric patients. Therefore, continuous technological progress and increasing practitioner expertise are needed to mitigate these limitations and fully harness the potential of 3D printing in cardiac surgery.

Analysis

According to the literature review, most 3D printing process outputs tend to be rigid. However, the industry offers a variety of methods, each with advantages and disadvantages. Injection moulding is one such process that could be relevant in your case.

Table 1.3D printing vs Injection moulding

3D printing		Injection Moulding	
Advantage	**Disadvantages**	**Advantage**	**Disadvantages**
-Rapid prototyping: 3D printing allows quick designiterations. -Customization: High design flexibility. -No need for moulds: A 3Dfile suffices.	**-Material losses: Some support structures can leadto material waste. -Slower production: Slower than injection moulding for mass production.**	**-Efficiency: Injection moulding uses exactly the required amount of material to fill the mould, minimising waste. -Mass production: It offers superior scalability once the moulds are ready. -Professional quality: Historically used for high-quality parts.**	**-Process complexity: Calibration, sensitivity to conditions (temperature, humidity, vibrations). -Need for moulds: Expensive upfront mould creation.**

Both techniques boast commendable precision, yet they entail intricate technology and extensive manufacturing durations, particularly 3D printing, given its reliance on industrial processes. While 3D modelling of the heart holds promise for educational purposes and simulating cardiac surgeries, the demand from faculties and hospitals surpasses what 3D printing can efficiently provide in terms of time and pace despite printer redundancy, which escalates costs. On the other hand, opting for moulding could accelerate production rates and decrease turnaround times, albeit at the expense of requiring a steel mould, thereby adding to the overall costs.

Design

Artificial Intelligence (AI) played a significant role in this work, particularly in the field of cardiology. AI was utilised to integrate two types of data: radiological data, including images and scans of the heart, and patient-specific information, such as medical history and genetic factors. This integration enabled the creation of highly accurate 3D models of hearts affected by Tetralogy of Fallot, a complex congenital heart defect. (Fig 1).

The use of AI aims also to enhance the rendering of these 3D models. This involved refining the visual representation of the models to make them as realistic and detailed as possible. The goal was to create a rendering that was not only accurate but also flexible and malleable, much like the actual

human heart.

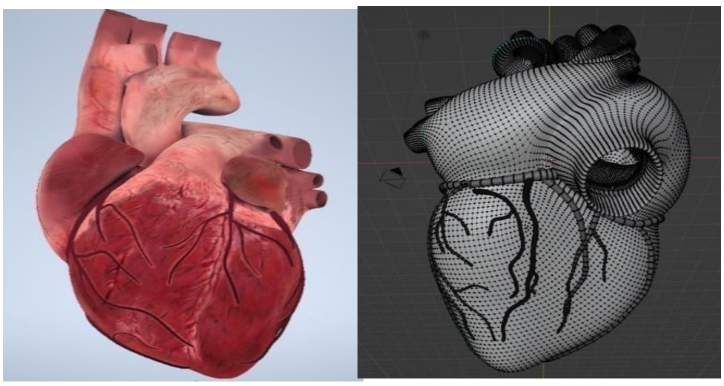

Figure 1 ♦3D modeling of the heart with a TOF.

To achieve this, AI was combined with another industrial process. This combination allowed to overcome the limitations and drawbacks inherent in these two methods when used separately. The result was the successful creation of detailed and flexible heart models (Fig. 2, Fig 3.).

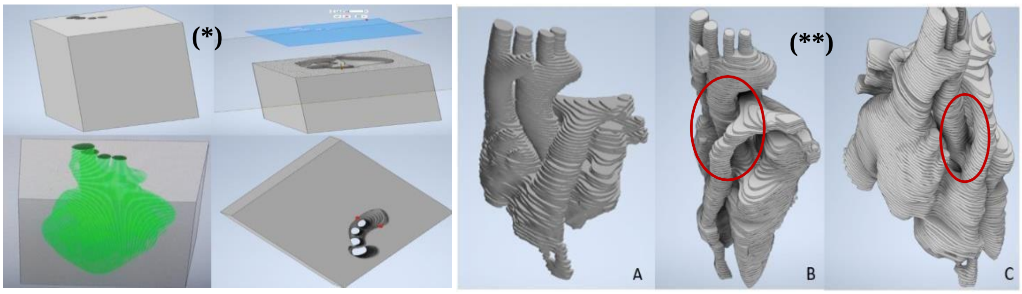

Figure 2 ♦ *(*) Mould and sub-moulds to facilitate demoulding(**) Internal shell before smoothing, A: shell of a healthy heart, B: diseased heart with shrinkage (Stenosis), C: (VSD).*

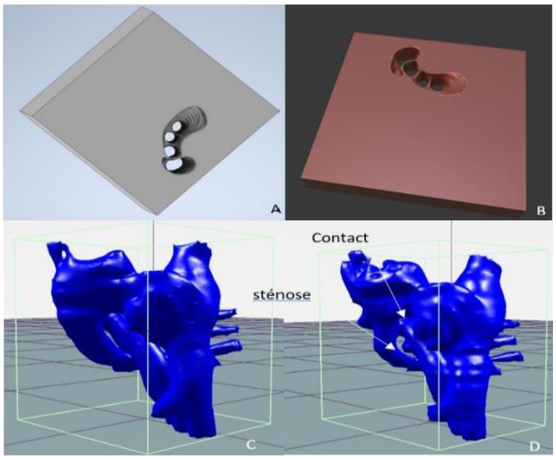

Figure 3 ♦ *A, B: Under external mould before and after smoothing, C: Holy shell and D: Shell of the diseased heart.*

These 3D heart models have proven extremely useful in the medical field. They have been used to assist doctors in making informed decisions about surgical interventions for patients with Tetralogy of Fallot. By providing a detailed and accurate visual representation of the affected heart, these models allow doctors to understand the specificities of each case better and plan the surgical interventions more effectively.

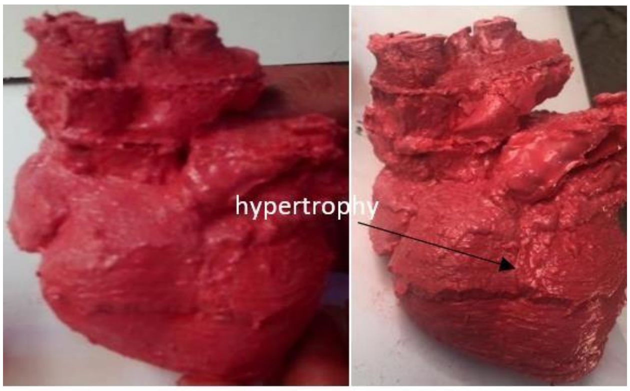

Figure 4 ♦ *Heart in 3d with tetralogy of Fallot (Result of the method).*

In conclusion, integrating AI in this study (Fig. 4) has transformed decision-making in cardiovascular medicine and also improved medical training and surgery preparation. This analysis has demonstrated that the integration of AI with other industrial processes can yield precise and valuable tools in the medical field. This multidisciplinary approach has the potential to revolutionize the understanding and treatment of complex cardiac diseases such as Tetralogy of Fallot.

Process of Implementation

Reception of a patient's X-rays

↓

Import the X-rays into the Radiant software

↓

Export as an STL file format

↓

Import the STL file into Inventor software to eliminate noise

↓

Export as an OBJ file

↓

Open the OBJ file in Blender to smooth the rough angles of the slices

↓

Design the mould (external detail of the heart) and the counter-mould (internal detail of the heart) using the smoothed version of the heart

↓

Assemble the mould and counter-mould to ensure the result

↓

Export the entire assembly as an STL file

↓

Import the assembly into Repetier-Host software

↓

Start printing the assembly

↓

Assemble the complete set (the mould and the counter-mould)

↓

Carry out the moulding

↓

Malleable heart with tetralogy of Fallot

RESULT

Artificial Intelligence (AI) plays a crucial role in this work, particularly in decision-making in cardiology. Through the application of AI, detailed 3D models of hearts affected by Tetralogy of Fallot, a complex structural heart disease, have been generated. These models have served as a valuable guide for doctors in making clinical decisions. By providing a detailed visual representation of Tetralogy of Fallot, these models have allowed doctors to understand the disease and more effectively plan surgical interventions.

Integrating industrial processes into this work has been essential for optimising the realisation of these models. By combining 3D printing with silicone moulding, a heart model has been created that closely resembles real heart tissue in terms of flexible and malleable texture, while also achieving greater accuracy and detail than models produced by traditional methods.

Using these industrial processes has also allowed us to optimise the time and cost of realisation. By using a permanent mould for silicone casting, we have been able to lessen the time required to produce each model significantly. Moreover, optimising the production process allows to reduce costs, making this approach more economical.

One hundred twenty-five doctors tested these models from 60 different nationalities at a workshop and congress (Fig 5). The results were highly positive. 82% of participants felt that this 3D heart model resembled a real heart interms of internal details, and 88% felt the same about the external information. Most importantly, 91% of participants believed that this heart model could help doctors practice operations. In addition, 75% of participants found that the heart material was similar to natural heart tissue. Finally, 100% of participants noted that the blood circulation model and internal details enhance understanding for medical students.

Figure 5 ♦ 3D heart test of more than 125 doctors from 60 nationalities.

In sum, this work illustrates how of integrating artificial intelligence in heart modelling can transform decision-making in cardiovascular medicine while improving medical training and surgery preparation. The positive feedback from doctors at the workshop and Congress demonstrates the effectiveness of this approach.

In conclusion, AI can transform decision-making in cardiology by providing precise tools for heart modelling. Moreover, industrial engineering can contribute to medicine through its industrial processes, which have allowed for the optimisation of the creation of these computer models, respecting the principles of the golden triangle.

REFERENCES

1. Hon, N.W.L., Hussein, N., Honjo, O., Yoo, S.-J.,.Evaluating the Impact of Medical Student Inclusion Into Hands-On Surgical Simulation in Congenital Heart Surgery. Journal of Surgical Education 78, 207–213. (2021). https://doi.org/10.1016/j.jsurg.2020.06.023
2. Anwar, S., Singh, G.K., Varughese, J., Nguyen, H., Billadello, J.J., Sheybani, E.F., Woodard, P.K., Manning, P., Eghtesady, P. 3D Printing in Complex Congenital Heart Disease. JACC: Cardiovascular Imaging 10, 953–956. (2017). https://doi.org/10.1016/j.jcmg.2016.03.013
3. Tam, M.D.B.S., Laycock, S.D., Brown, J.R.I., Jakeways, M. 3D Printing of an Aortic Aneurysm to Facilitate Decision Making and Device Selection for Endovascular Aneurysm Repair in Complex Neck Anatomy. Journal of Endovascular Therapy 20, 863–867. (2013). https://doi.org/10.1583/13-4450MR.1
4. Matthew D.B.S. Tam, FRCR1,2; Stephen D. Laycock, PhD3 james R.I. Brown, FRCS4;and Matthew Jakeways, FRCS. 3D Printing of an Aortic Aneurysm to Facilitate Decision Making and Device Selection for Endovascular Aneurysm Repair in Complex Neck Anatomy. J ENDOVASC THER.2013. https://doi.org/10.1583/13-4450M
5. Schmauss, D., Haeberle, S., Hagl, C., Sodian, R. Three-dimensional printing in cardiac surgery and interventional cardiology: a single-centre experience. European Journal of Cardio-Thoracic Surgery 47, 1044–1052. (2015). https://doi.org/10.1093/ejcts/ezu310
6. Farooqi, K.M., Saeed, O., Zaidi, A., Sanz, J. Nielsen, J.C., Hsu, D.T., Jorde, U.P., 3D Printing to Guide Ventricular Assist Device Placement in Adults With Congenital Heart Disease and Heart Failure. JACC: Heart Failure 4, 301–311. (2016). https://doi.org/10.1016/j.jchf.2016.01.012
7. McGovern, E.M., Tretter, J.T., Moore, R.A., Goldstein, B.H. Simulation to Success. JACC: Case Reports 2, 486–487. (2020). https://doi.org/10.1016/j.jaccas.2019.11.078
8. Crafts, T.D., Ellsperman, S.E., Wannemuehler, T.J., Bellicchi, T.D., Shipchandler, T.Z., Mantravadi, A.V.Three-Dimensional Printing and Its Applications in Otorhinolaryngology–Head and Neck Surgery. Otolaryngol.--head neck surg. 156, 999–1010. (2017). https://doi.org/10.1177/0194599816678372
9. Fan, Y., Wong, R.H.L., Lee, A.P.-W. Three-dimensional printing in structural heart disease and intervention. Ann. Transl. Med. 7, 579–579. (2019). https://doi.org/10.21037/atm.2019.09.73
10. Lau, I., Sun, Z., Three-dimensional printing in congenital heart disease: A systematic review. J of Medical Radiation Sci 65, 226–236. (2018). https://doi.org/10.1002/jmrs.268