Development of a high-fidelity coronary artery bypass graft training platform using 3-dimensional printing and hydrogel molding

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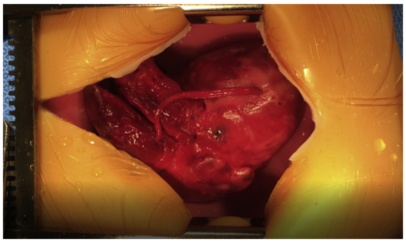


Hydrogel heart model after completion of simulated coronary artery bypass procedure.

CENTRAL MESSAGE

A simulation platform, using 3D-printing and hydrogel injection molding, demonstrates high realism and promising educational effectiveness for cardiothoracic resident training.

See Commentaries on pages e295 and e296.

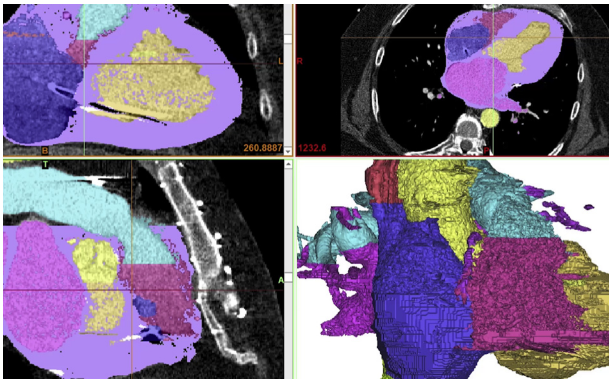
▶ Video clip is available online.

The introduction of integrated cardiothoracic residency programs creates the challenge of instructing residents through complex operations without the 5-year background of general surgery training. While simulation will never replace intraoperative experience, it may provide an important training tool to develop the skills and procedural experience necessary to optimize intraoperative learning.[1,2]

Porcine and cadaver models are considered the gold standard for simulation training. Both achieve realistic tactile and visual feedback. However, specialized spaces required for handling biohazardous tissues create logistical and financial challenges that limit their use.[1] Alternatively, low-fidelity, table-top models offer more accessible training platforms, but their poor organoleptic properties limit their clinical utility.[3]

We sought to create a simulation platform that combines the benefits of high-fidelity tissue with the accessibility of non-biohazardous simulators (Video 1). Previous reports have demonstrated the educational potential of 3-dimensional (3D)-printed models but were limited by unrealistic materials with poor tactile feedback.[3,4] We developed a technique that uses 3D-printed molds and polyvinyl alcohol hydrogel to produce highly realistic, non-biohazardous tissues that can be dissected, cauterized, and sutured.[5] The tissues are the basis for a highly customizable simulation platform that is realistic and easy to use.

Following institutional review board approval (approval: STUDY00003725 on March 20, 2017—the Research Subjects Review Board reviewed this study and determined that it meets federal and university criteria for exemption; thus, informed written consent was not required), a computed tomography scan was segmented into a 3D computer-aided design file using Mimics software (Materialize, Leuven, Belgium). The desired anatomy was used to create negative molds, which were 3D-printed (Ultimaker, Utrecht, Netherlands), filled with polyvinyl alcohol hydrogel, and processed to replicate the mechanical properties of porcine myocardial and aortic tissue (Figure 1). Fabrication takes approximately 2 hours of labor spread over 5 days and requires $15 of raw materials, $15 of supplies, a commercial 3D printer, and freezer. Multiple models can be manufactured simultaneously, and molds can be reused



VIDEO 1. Production steps, full procedure simulation, and questionnaire results of a high-fidelity coronary artery bypass simulation platform made using 3D printing and hydrogel injection molding technology. Video available at: https://www.jtcvs.org/article/S0022-5223(20)31548-8/fulltext.

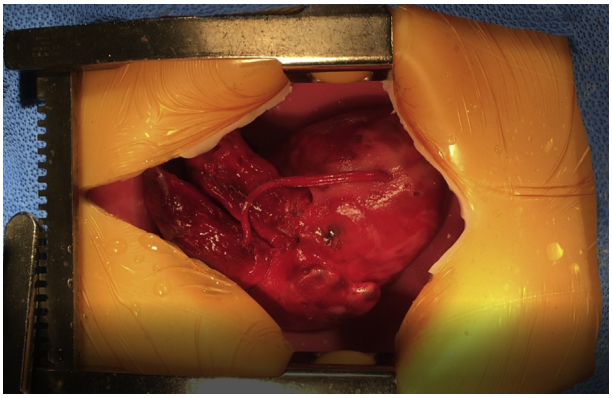


FIGURE 1. Hydrogel heart model after completion of simulated left anterior descending coronary artery bypass procedure.

indefinitely, increasing economies of scale and shorter production times to reproduce established models.

The utility of the platform in simulating a left anterior descending bypass was assessed by 3 cardiac attendings and 5 integrated cardiothoracic residents (postgraduate years 1-6). Each participant performed a left anterior descending bypass using a hydrogel conduit with proximal anastomosis to the aorta (Figure 1). Postoperatively, all participants completed a 5-point Likert scale survey to evaluate the model as a training tool.

Both novices and experts rated the model highly for overall realism (Table 1) and educational effectiveness (Table 2). Realism was high regarding both relevant human anatomy (average 4.7 ± 0.5) and tactile feedback (4.1 ± 0.3). Participants felt strongly about the educational effectiveness of the model in its usefulness as a training tool (4.8 ± 0.4), capability to assess technical ability (4.6 ± 0.5), and utility to improve technical skills (5 ± 0.0). All residents stated they would like this model incorporated into their curriculum.

Our model has several potential benefits compared with current simulation options. First, the model has increased accessibility due to its non-biohazardous properties. Whereas live tissue models require extensive time and planning to coordinate a simulation, our model can be stored directly in call rooms, offices, or even resident's homes, drastically decreasing the barriers to use within clinical schedules and work hour mandates. Second, incorporation into an anatomical simulated chest cavity allows for practice of more nuanced surgical steps such as positioning of the heart to properly expose target vessels and refining difficult needle angles for multiple anastomosis sites. Lastly, while this proof-of-concept replicates a straightforward case, the platform allows for customization in reproducing patient-specific anatomy and pathology to practice challenges that cannot be readily simulated by porcine. Ultimately, this platform allows for the potential to create multiple models with increasing levels of difficulty that can be incorporated into a robust simulation curriculum specific for each year of training.

Although these results are promising, limitations must be acknowledged, including a small sample size and subjective assessments of utility. Further study using direct comparisons with porcine and objective assessments of performance are needed. Ideally, multicenter cohorts will be used. We have the capacity for large-scale production, and the biggest barrier is multicenter recruitment and coordination. Lastly, the use of the simulators still requires supervised instruction by experienced surgeons and will require faculty support. Further research is needed to determine how best to use the increased accessibility of the non-biohazardous simulator to promote faculty involvement in simulation-based learning.

TABLE 1. Assessment of the high-fidelity, hydrogel heart model's realism by participants after completing of a full coronary artery bypass hydrogel simulation

Realism	Overall model	Coronary artery	Conduit	Aorta	Thoracic cavity anatomy	Overall realism
Resident (n = 5)	4.0 ± 0.0	2.8 ± 0.8	4.0 ± 0.0	4.0 ± 0.0	4.5 ± 0.5	3.9 ± 0.7
Attending (n = 3)	4.3 ± 0.5	4.5 ± 0.5	5.0 ± 0.0	4.0 ± 0.8	5.0 ± 0.0	4.6 ± 0.6
Overall (n = 8)	4.1 ± 0.3	3.3 ± 1.1	4.5 ± 0.5	4.0 ± 0.5	4.7 ± 0.5	4.1 ± 0.8

TABLE 2. Assessment of the high-fidelity, hydrogel heart model's educational effectiveness by participants after completing of a full coronary artery bypass hydrogel simulation

Educational effectiveness	Overall model	Provides opportunity to adequately practice distal anastomosis	Provides opportunity to adequately practice proximal anastomosis	Useful tool for teaching this procedure	Useful for assessing the user's ability to perform this procedure	Useful for improving technical skills	Overall educational effectiveness
Resident (n = 5)	4.6 ± 0.5	4.2 ± 1.0	4.8 ± 0.4	4.8 ± 0.4	4.4 ± 0.5	5.0 ± 0.0	4.4 ± 1.0
Attending (n = 3)	5.0 ± 0.0	4.3 ± 0.5	4.7 ± 0.5	4.7 ± 0.5	5.0 ± 0.0	5.0 ± 0.0	4.5 ± 0.9
Overall (n = 8)	4.8 ± 0.4	4.3 ± 0.8	4.8 ± 0.4	4.8 ± 0.4	4.6 ± 0.5	5.0 ± 0.0	4.4 ± 0.9

In conclusion, our simulation platform offers a non-biohazardous, high-fidelity training tool for bypass procedures. The platform addresses many of the logistical and safety limitations of current simulations while also providing the foundation for future harder-to-replicate procedures. Further validation is warranted to assess incorporation of this model into cardiothoracic programs as a supplement to current training modalities.

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