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Pediatric and Adult Beating Heart Simulator

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Central Message: The development of a low-cost beating heart simulator may broaden access to cardiac surgery training.

Perspective Statement: A beating heart simulator with high fidelity beating heart simulations was developed at a low cost compared to what exists on the market. The simulator reproduces systole compared to other simulators that only inflate and deflate pig hearts.

Central Picture Legend: Pediatric and adult beating heart simulator
Abstract:

Objectives: The objective was to create a low-cost beating heart simulator for adult and pediatric cardiac surgery training. Such simulators can increase exposure to rare and more complex surgical cases in a patient-safe environment.

Methods: Pediatric and adult beating heart simulators were invented using car parts and other low-cost items in a home garage. The simulator models use porcine heart-lung complexes instead of living animals for surgical training.

Results: A low-cost and high-fidelity beating heart simulator was created that generates airflow and vacuum in a sequence leading to systole and diastole simulation with all blood vessels perfused. The results accurately represent a beating heart ready for any cardiac surgical procedure and complication simulation, and the simulator also includes different speeds and different heart rhythms.

Conclusions: This low-cost simulator can be used for adult and pediatric cardiac surgery training, especially in places with low surgical caseloads or difficulties providing adequate autonomy to residents as operating surgeons.

Keywords: education, cardiac, congenital cardiac, valve disease, heart simulator


**Introduction**

Pediatric and adult cardiac surgery professions have specifics that are not shared with other surgical specialties. Many of these are difficult to learn due to their rarity, the length of training programs, and other essential factors, such as working-hour regulations. Therefore, beating heart simulator-based training is an alternative pathway for advancing surgical training for the next generations of cardiac surgeons and increasing their exposure to rare and more complex surgical cases in a patient-safe environment [2]. A beating heart simulator was developed to reproduce systole using porcine heart-lung complexes and inexpensive parts to offer a low-cost simulator option for cardiac training.

**Background**

A web search to identify different cardiac surgical simulators revealed only a few options. One challenge identified is that it is difficult to invent a high-fidelity cardiac surgical simulator that can be incorporated into cardiac surgical training while remaining low-cost for broad use.

All high-fidelity simulators have one thing in common: they can reproduce a real-case scenario. High-fidelity surgical scenarios can be achieved through use of live tissue, as there is still no material that accurately recapitulates living tissue. Artificial organs used in simulations are far from actual tissues. Even 3D printing is insufficient at producing artificial organs that could substitute living tissues in high-fidelity simulations. While artificial tissues can be used early in resident training, they are not applicable during more advanced training because they simply do not feel real upon handling, dissecting, suturing, or moving. While remaining a good choice for simple demonstrations of surgical case scenarios, artificial tissues should not be used for surgical resident/fellow training.

One difference between operations performed on a beating heart simulator compared to operations performed on a porcine heart-lung complex without using the simulator is the high fidelity of the simulations. For example, one can put a purse-string on a standstill porcine heart atrium but the experiences differs from putting a purse-string on a beating heart simulator when the atrium and the whole heart rapidly move. Beating heart simulators' most crucial advantage is that they create a realistic environment for things like putting purse-strings and canulation on a beating heart, starting cardiopulmonary bypass, performing off-pump CABG, lung transplantation, and other procedures.

Some research papers suggest that cardiothoracic surgical trainees are not allowed to perform complex cardiac surgical cases both in adult and pediatric cardiac surgery, therefore after completion of classical cardiac surgical training in the USA, fellows continue their training in a super fellowship (Non-ACGME accredited fellowship programs in the USA or similar positions as a trainee outside the US) to broaden their operative experience [6,7]. Even after that, exposure to complex cases continues in an apprenticeship model. For example, many trainees in the USA do not perform aortic cases, mitral valve cases, and other complex cardiac surgical cases regularly.

Similarly, it is rare to see a fellow perform the most complex pediatric cardiac surgical cases as an operating surgeon, influencing the trainees' future independent practice. In most cases, both pediatric and adult cardiac surgery fellowship graduates work as junior cardiac surgeons after joining groups of cardiac surgeons and continue their training under the guidance and mentorship of more experienced surgeons. For example, an arterial switch operation for transposition of great arteries is considered a complex procedure, and fellows are often forbidden from performing this procedure as an operating surgeon. However, with a low-cost beating heart simulator, the switch operation steps could be reproduced on the simulator, e.g., coronary artery reimplantation. Coronary artery reimplantation is the most critical step during this complicated procedure, and it can be simulated on
a simulator in a patient-safe environment until a fellow feels comfortable doing it, providing a maximally safe environment for the patient.

Ultimately, repetition is an integral part of surgical training. Beating heart simulator-based training can provide a limitless number of repetitions. Adding simulator-based training into cardiac surgical training may improve the quality of the training and help produce more qualified cardiac surgeons, especially for rare surgical cases mainly performed by attending surgeons during the fellowship/residency. Fellows could perform such surgeries on a simulator repeatedly until they felt comfortable and only then transfer that knowledge/skills to an actual patient. This strategy would decrease the number of surgical mistakes made by the residents/fellows, which is excellent for the patient and the entire team. Conditions are worse outside the USA, where surgical and cardiac surgical training is considered to be more hands-on with more autonomy. Outside the USA, surgical/cardiac surgical training is less hands-on with less autonomy; therefore, beating heart simulator-based training could solve this global problem, potentially leading to more qualified cardiac surgical graduates worldwide.

Methods

Previously, research was conducted regarding simulation-based cardiac surgical training. The simulator training took place at eight thoracic surgical residency programs, the Cardiac Surgery Simulation Consortium was formed, and subsequently, a curriculum was produced, which is available on the website of the Thoracic Surgery Directors Association [TSDA]. Under the Agency for Healthcare Research and Quality grant R18HS020451, the Consortium created a 39-session curriculum to assess whether a simulator curriculum could possibly improve resident training and thereby contribute to surgical patient safety. Training modules were created that used the Ramphal simulator. These modules were: Cardiopulmonary bypass, coronary artery bypass grafting, aortic valve replacement, massive air embolism, acute intraoperative aortic dissection, and sudden deterioration in cardiac function. Twenty-seven residents participated in this simulator Cardiac Surgical Training using the curriculum and modules provided by the Consortium. Residents demonstrated improvement with practice repetitions that resulted in excellent final scores per module. The study mentioned above concluded that overall performance in component tasks and complete surgical procedures improved during simulation-based training. Also, it was mentioned that simulation-based training provides the necessary skill sets for managing adverse events and can help produce safer surgeons.

However, to be most useful in training, high-fidelity simulators should recreate natural movements of the heart, the systole, the diastole, the contraction, and the relaxation while having the properties of real organs. Existing commercial cardiac surgical simulators have challenges meeting these needs.

There are two commercially known cardiac surgical simulators: The Ramphal [1] simulator is now produced by the KindHeart company, and the Chamberlain company produces the other. The KindHeart simulator uses porcine hearts, e.g., organs from vendors and butcher companies; therefore, no animals were sacrificed explicitly for the simulation purposes. Both simulators recreate cardiac activity. Ramphal's simulator uses inflatable balloons placed into the ventricles that simulate systole and diastole. However, the cardiac activity does not look realistic because when the balloon inflates, the heart is stimulated to go into the diastolic phase. Thus, the size of the heart increases. When the balloons then deflate, the heart goes to its starting point regarding the size of the heart,
while a real heart during real systole produces a noticeable contraction, and the heart size decreases during systole.

Rampal’s simulator has no contraction component: it only inflates and deflates. It is a great simulator, but the contractions do not look natural. The Chamberlain simulator uses artificial hearts made from synthetic material unsuitable for high-fidelity simulations and training. One of the problems is the cost of these simulators, which means most cardiac surgical departments cannot purchase them. Thus, they have limited implementation. Both simulators have value, but there is need for a high-fidelity and low-cost cardiac surgical training simulator.

Results
To overcome the challenges exhibited by the commercial models, pediatric and adult beating heart simulators were invented in a home garage using car parts and other low-cost items [1, 6, 7]. The result was a realistic beating heart ready for any cardiac surgical procedure or complication simulation. The simulator has different speeds, and different heart rhythms can be reproduced. It can also be connected to a PC via different computer programs. Real-time cardiovascular monitoring can also be provided. Any pediatric or adult cardiac surgery and its complications can be simulated using specifically written scenarios.

No other pediatric or adult beating heart simulators are currently available that offer such realistic presentations, and there was no information regarding pediatric beating heart simulators that use porcine hearts. Our pediatric version of the simulator will be the first yet reported to use porcine hearts. It uses a specially invented and built mechanism that leads to systole [3],[5] and diastole [2], [4], with a noticeable myocardial contraction; it also uses real live tissue bought from butchers. Low-cost in building and handling, this simulator uses old car parts, simple electrical parts, tubing, valves, and other low-cost items. Because the simulator has no complicated mechanical or electrical parts, it is practical and potentially broadly applicable.

The simulator prototype uses air force to inflate the atriums and the ventricles, simulating diastole, and uses a vacuum to deflate the atriums and the ventricles to the neutral position of the cadaveric heart. These then move beyond the neutral position to recreate a ventricular contraction. Thus, the system needed a source of pressurized air to inflate and a vacuum to forcefully deflate the heart chambers, which was achieved via medical syringes. The air moves in and out of the heart via tubing, and the tubes are placed in the right and left ventricles. There are four main tubing elements: two for inflation and two for deflation. Two pipes were placed into the ventricle—one pipe inflates, and the other deflates the heart, simulating diastole and systole. A car wiper motor was used to move the plunger of the syringe. Because this motor was relatively weak and heated up quickly, a more durable version was created. The electrical supply was 110 and 220-volt inputs tuned to 6-12 volts for the wiper motor. The control panel can regulate the voltage and thus the speed and force of the wiper motor—this simulates faster or slower simulated heartbeats. The simulator also has a one-way valve system such that when the syringe is depressed, the valve opens on one side and closes on the other so that the air escapes from the syringe inflating the heart chambers. When the syringe comes out, the outflow valve opens, and the inflow valve closes, leading to air being withdrawn, thus producing a vacuum in the heart chambers. This action leads to perfect systole and diastole. During the simulations, varying inflation and deflation pressures were experimented with. For example, inflating with more air and pressure caused the diastolic phase to look more rapid; the same applied to air deflation with more vacuum and more air deflated, made the systolic phase more rapid and the contraction more forceful. However, if weaker and slower contractions are needed (for example, as when coming out of cardiopulmonary bypass and noticing the first heart contractions), the inflation
pressure, amount of inflated air, vacuum, and the amount of deflated air, could all be decreased. While wall tensions were not measured, this it could be done in the future for the sake of more information regarding physiology. Simulated systolic and diastolic timing could vary depending on what speed the simulator is chosen. If the engine's speed (in this case, windscreen viper engine) is increased, the mechanism moves faster, so the time to inflate the heart chambers and deflate them decreases, decreasing systolic and diastolic timing. Other than size, there are several specific differences between adult and pediatric cardiac surgical simulations; the mechanism used is the same; however, for the pediatric simulations, smaller diameter tubing is used, less inflated air is needed, and less vacuum force for air suction is needed.

There were some specific challenges while building this simulator. During diastole, the air can escape from the heart through the aortic and pulmonary valves. This was prevented via retrograde simulated blood flow into the aorta and pulmonary artery. These close the aortic and pulmonary valves and simulate aortic and pulmonary artery blood flows. This simulated blood flow is very important if our simulator has an aortic cannulation component; thus, having a pressurized aorta with artificial blood makes aortic work possible—procedures like purse-string placement and cannulation are realistic. Air leakage from the super or inferior vena cava is prevented by isolating the inferior and super vena cava from the right atrium via an internal plug or clamping them.

In addition, during the current simulation runs scenarios, there was not pressure feedback; however, when the simulator is modified and connected to a computer via an Arduino microcontroller, it will be possible to simulate the vital signs or different cardiac rhythms. For example, in case of sudden deterioration of cardiac function, it will be possible to simulate the actual heart behavior and vital signs related to this condition. It was also concluded that more vacuum force is needed for the left ventricle to simulate systolic contraction, and less for the right ventricle, therefore, a stronger source of vacuum will be used next time, and probably larger sized syringes.

It only takes a short time to prepare for a simulation. The simulator is assembled with all the lines, valves, retrograde perfusion system, the computer, and the mannequin chest part ready to put the heart-lung complex into it. It then takes time only to put the simulator lines (inflation and deflation lines) into the heart through the left atrium’s posterior side into the left ventricle and through the SVC or IVC into the right ventricle. Also, two retrogradely perfused lines must be put into the aorta and pulmonary artery. The time needed to prepare for the whole simulation would be less than 30 minutes, and one person is enough for the job to be done.

Because this simulator is meant to be low-cost, where porcine hearts are procured is also important. Porcine hearts, lungs, and heart-lung complex prices may vary depending on country. While fresh porcine hearts are available from multiple online vendors that specialize in supplying living tissues for training purposes, providing certification regarding the absence of animal-borne diseases (often necessary if one is planning to bring living animal tissues to the hospital), these can be costly, while porcine organs purchased from a butcher may not be. The easiest way to preserve organs and make them reusable for a more significant number of residents and fellows to practice on the simulator on multiple occasions is to wash porcine hearts or other parts, like heart-lung complexes, in soap water and then put the tissues into the fridge or freezer until the time needed.

**Discussion**
It is hypothesized that this simulator model can be used for adult and pediatric cardiac surgery training, especially in places with a low caseload or difficulties in providing adequate autonomy to residents as operating surgeons while maintaining a low cost of simulations and a patient-safe training environment. Cardiac surgery trainees may be dissatisfied with their operative experience. One of these reasons could be insufficient time during the training to be exposed to all types of surgical cases. Autonomy may vary based on the site of training. Use of a simulator means critical parts of the surgical procedures could be learned in a patient-safe environment. For example, coronary artery reimplantation during the arterial switch operation for the transposition of the great arteries can be reproduced. The same applies to any pediatric or adult cardiac surgical procedure that requires a high repetition volume to achieve excellence. Learning surgical skills ultimately requires repetition, which is currently deficient due to work hour regulations, less hands-on training, and decreased autonomy. The incorporation of simulator-based training in residency/fellowship programs on a regular basis may lead to more competent cardiac surgical residency graduates which will positively affect cardiac surgical outcomes.

This simulator offers an opportunity to work on internal parts of the heart like valves, cords, and myocardium. Any known cardiac surgical procedure can be performed, e.g., a CABG procedure becomes super high-fidelity because the coronary arteries are perfused retrogradely through the aorta via the simulator’s retrograde aortic perfusion system. Perfusion in this simulator used a simple IV perfusion system: The same system was used for pulmonary artery retrograde perfusion. This simulator has no extra high-cost components, which makes it broadly applicable. The same simulator airflow system can be used for inhalation and exhalation to achieve maximal fidelity of the procedures with the lungs moving, inflating, and deflating. This may be a great addition to cases that do not imply respiratory arrest, e.g., off-pump CABG. All these features make this simulator an excellent candidate for trainees.

After building the simulator, it was used to perform several procedures to access and demonstrate its effectiveness. 2 individuals performed the procedures. The procedures performed using an adult model were blood vessel dissection using electrocautery, scissors while using the beating heart simulator, aortic and atrial purse-strings and subsequent cannulation (aorta and pulmonary artery were retrogradely perfused with artificial blood), and off-pump CABG. Procedures performed using a pediatric model were blood vessel dissection using electrocautery, scissors while using the beating heart simulator, aortic and atrial purse-strings, and subsequent cannulation (aorta and pulmonary artery were retrogradely perfused with artificial blood). This simulator is appropriate for both intra-cardiac and epicardial procedures/repairs.

As of yet, the simulator has not been applied to a broader audience. The next step will be an application of the simulator to a broader audience of pediatric and adult cardiac surgical residents, fellows, attending, and medical students interested in cardiac surgery. Hopefully, the final results will demonstrate the effectiveness of this low-cost beating heart simulator in allowing cardiac surgeons practice in a patient safe environment, impacting cardiac training for the next generation.
References


Legends

Figure 1: Pediatric and adult beating heart simulator
Figure 2: Pediatric beating heart simulator diastole
Figure 3: "Supplemental" Pediatric beating heart simulator systole
Figure 4: "Supplemental" Adult beating heart simulator diastole
Figure 5: "Supplemental" Adult beating heart simulator systole
Figure 6: "Supplemental" Pediatric and adult beating heart simulator (car viper mechanism, syringes, one-way valves, and tubes)
Figure 7: "Supplemental" Syringes with one-way valves and tubes
Video: Pediatric beating heart simulator video