

Marcus Granegger, Philipp Aigner*, Erwin Kitzmüller, Martin Stoiber, Francesco Moscato, Ina Michel-Behnke and Heinrich Schima

A passive beating heart setup for interventional cardiology training

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Abstract: Realistic training of cardiologic interventions in a heart catheter laboratory is hardly achievable with simple tools and requires animal experiments. Therefore, first a simple mock circuit connected to a porcine heart mimicking the natural heart motion was developed. In a second step the setup was duplicated to drive both sides of the heart independently to generate motion and physiologic pressures and flows. Using this simple setup cardiologic interventions (arterial and ventricular septal defects ASD/VSD closure) were performed successfully and allowed realistic training under the C-arm, echocardiography, placement of catheters and repair of ASD/VSD. With the second setup flows of up to 4 l/min were achieved in both sides of the heart at maximum left and right ventricular pressures of 80 mm Hg and 30 mm Hg respectively. This method is inexpensive and represents a realistic alternative to training in animal experiments.

Keywords: cardiologic interventions; patent foramen ovale; radiology training; transcatheter closure.

1 Introduction

Extensive training of interventional procedures in cardiology and cardiac surgery is crucial to achieve optimal learning of the physicians and minimize the risk for

the patients. Therefore, numerous approaches have been developed to simulate clinical situations and to provide realistic conditions for a relevant technical training [1]. Whereas various models are available for training of (cardiac) surgeons, only few models have been reported for training of interventional cardiology [2]. Animal models provide a comprehensive setting, however they require a complex infrastructure, are expensive and allow only a limited number of procedure iterations within one animal. Additionally they are usually not accepted in the clinical environment, where the technical equipment for training would be available. Therefore, and also to reduce animal experiments for ethical reasons, *in-vitro* models are strongly desired. Additionally to already existing *in vitro* training setups, integration of anatomical structures as the valve apparatus or even the entire heart with an isolated *ex-vivo* setup could certainly increase the potential for interventional training purposes. However, the setup for experiments with isolated organs is sophisticated and requires an advanced hydraulic circuit and well-trained personnel [3–5]. Recently, passively beating large animal hearts were reported to visualize internal heart structures [6, 7]. In such a setup the hearts are artificially driven by pumps to achieve physiologic pressure and/or flow conditions. Aim of this work was to establish a training setup to allow cardiologists to practice their skills in a realistic model before attempting the technique in the clinic. This setup should be kept compact to allow a simple use in the heart catheter lab. Therefore, we developed a pneumatic driven mock circuit for a passively beating porcine heart from the slaughterhouse.

2 Methods

2.1 Preparation of the heart

Porcine hearts for this training setup were obtained from a slaughterhouse, following the standard slaughtering procedure. During the slaughtering procedure special care was taken to not injure the hearts when the chest was

***Corresponding author: Philipp Aigner**, Ludwig Boltzmann Cluster for Cardiovascular Research, Vienna, Austria; and Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, AKH-4L, Währinger Gürtel 18-20, 1090 Vienna, Austria, E-mail: philipp.aigner@meduniwien.ac.at

Marcus Granegger, Martin Stoiber and Francesco Moscato: Ludwig Boltzmann Cluster for Cardiovascular Research, Vienna, Austria; and Center for Medical Physics and Biomedical Engineering, Medical University of Vienna, AKH-4L, Währinger Gürtel 18-20, 1090 Vienna, Austria

Erwin Kitzmüller and Ina Michel-Behnke: Department for Paediatric Cardiology, Medical University of Vienna, Austria

Heinrich Schima: Department of Cardiac Surgery, Medical University of Vienna, Austria

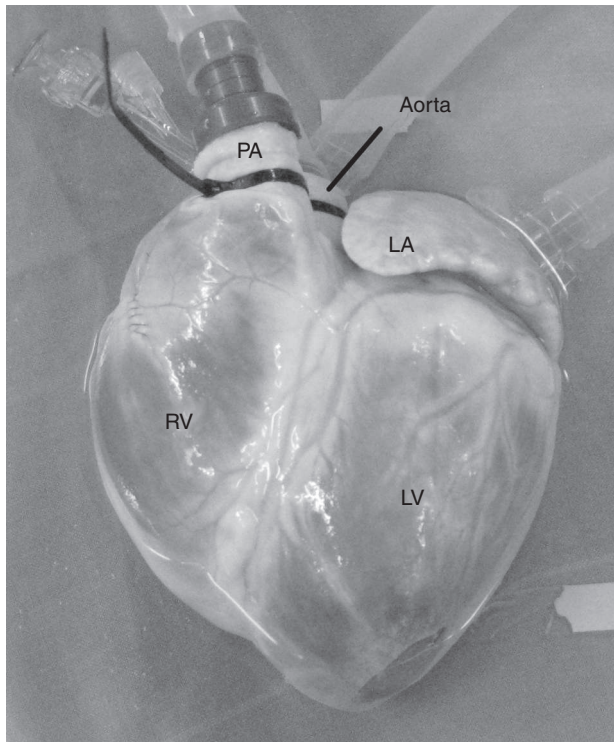


Figure 1: Porcine heart with all connectors in place. LA, left atrium; LV, left ventricle; PA, pulmonary artery; RV, right ventricle.

opened. The hearts were then kept in a refrigerator at 8°C for 2 days to ensure that the rigor mortis did not influence the mechanical properties of the heart. The inferior vena cava as well as the vena azygos, which discharges in the coronary sinus in pigs, were ligated using 4-0 RB1 Prolene (Ethicon, Inc., Somerville, NJ, USA) sutures. In the left atrium, all but one pulmonary vein were closed, the remaining pulmonary vein had a diameter of approximately 1.2 cm. A tourniquet suture was placed around the remaining pulmonary vein and the vena cava superior. Tubing adapters with 1.2 cm outer diameter were inserted and fixed by the tourniquet suture. The aorta and pulmonary artery were cut to a length of 5 cm. A 1.6 cm (outer diameter) tubing connector was inserted in the pulmonary artery and another 2.5 cm connector was inserted into the aorta. Both connectors were positioned and fixed with a zip tie. The heart with all connectors in place is shown in Figure 1.

Additionally to the connections for the mock circuits, defects of the heart can be easily created during preparation for interventional training. E.g. ventricular or atrial septal defects (VSD/ ASD) were generated by perforating the septum to the desired degree, but also other congenital or acquired heart and valve defects can be easily done.

2.2 Mock circuits

Two different mock circuits targeting different aims were developed: The first aimed at a realistic movement of the heart with a very simple setup that allowed placement under a conventional C-arm system. Mimicking realistic physiologic pressures and flows in the heart was not required. The second approach should reproduce physiologic pressures and flows in both ventricles additionally to the heart motion.

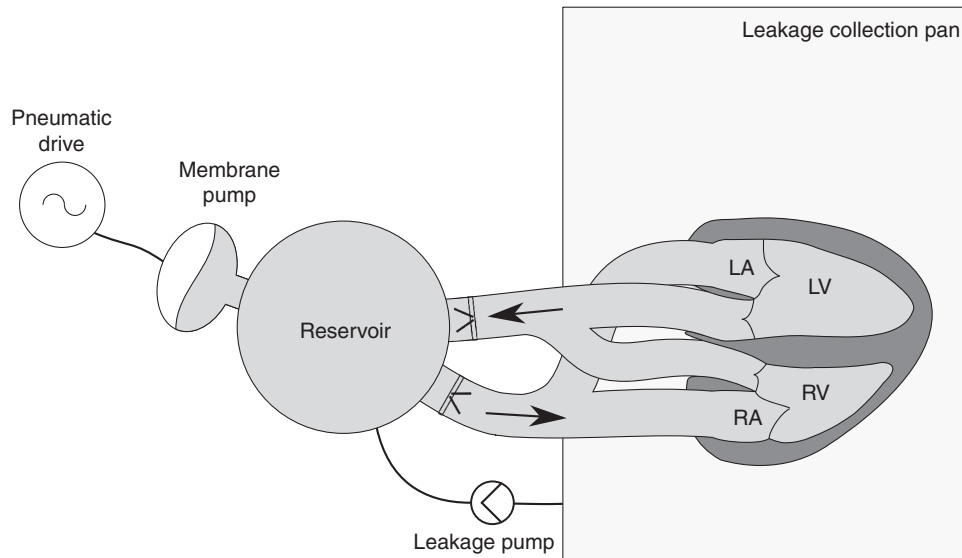
The employed mock circuit consisted of a closed fluid filled reservoir, two mechanical bileaflet heart valves (23 mm St. Jude Medical Standard bileaflet valve, St. Jude Medical Inc., St. Paul, MN, USA) and a membrane displacement pump [8] driven by a self-built pneumatic driving unit, able to generate positive and negative pressures. A schematic diagram of this circuit is shown in Figure 2A.

The mechanical valves were mounted on the reservoir, one in the outflow, the other one in the inflow direction to ensure unidirectional blood flow independently of heart valve insufficiencies and compliant structures. The reservoir was connected to the pulsatile membrane displacement pump for dividing the fluid from the pneumatic side to prevent fluid discharge from the mock circuit to the pneumatic driver. Both atria were connected to the outflow of the reservoir, the pulmonary artery and the aorta were connected to the inflow. Therefore, in case of a positive pressure in the reservoir, fluid was pumped into the heart via the atria; in case of negative pressure the fluid flowed back or was sucked out of the heart via the pulmonary artery and the aorta. In the presented case pressures at the pneumatic drive were set to ± 50 mm Hg at a heart rate of 70 bpm with a time-ratio of 60% positive pressure and 40% negative pressure. The entire mock circuit and the connected heart was placed in a large collection pan with a centrifugal pump delivering potential leakage flow from the pan back into the fluid filled closed reservoir and maintained a defined positive pressure level.

For realistic pressure and flow conditions inside the heart a different modified setup was required and established. For this purpose exactly the mock circuit as described above was duplicated to allow independent pressure and flow generation in each side of the heart: the left atrium and the aorta were connected to one of the reservoirs, the right atrium and the pulmonary artery to the other one. Both reservoirs were driven by two membrane displacement pumps connected to separate pneumatic drivers (see Figure 2B).

The synchronized pneumatic drives for both sides allowed simultaneous pressurization of both ventricles with independent pressure levels. In the presented case both

A



B

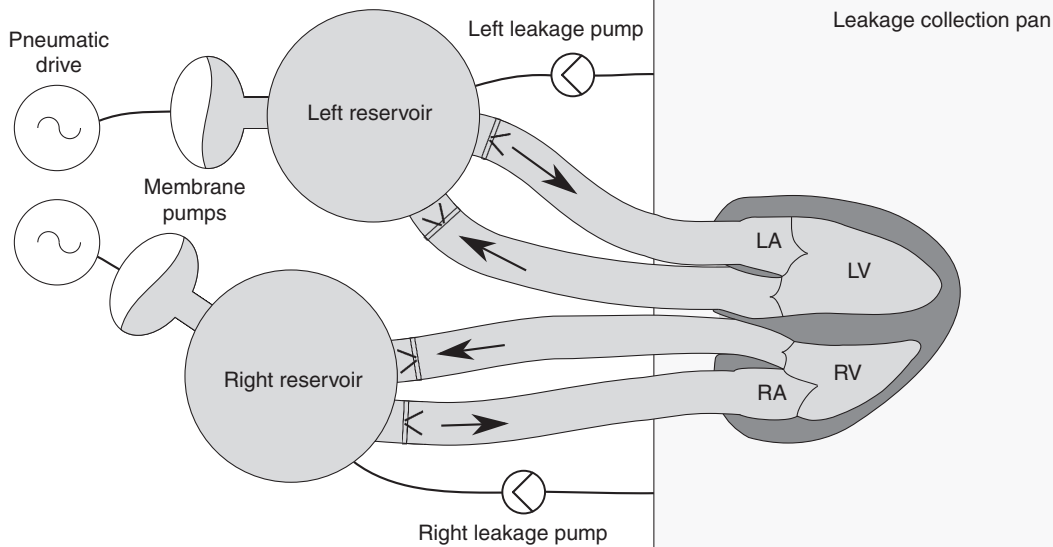


Figure 2: Schematic diagrams of the simple mock circuit for cardiac motion simulation (A) and for generation of realistic hemodynamics in both sides of the heart (B). LA, left atrium; LV, left ventricle; RA, right atrium; RV, right ventricle.

sides of the heart were pressurized at a rate of 70 bpm with a time-ratio of 60% positive pressure and 40% negative pressure. The two centrifugal pumps delivered potential leakage flow from the pan back into the reservoirs and maintained a positive pressure level in each of the reservoirs and consequently the two sides of the heart.

3 Results

All hearts connected to the setup moved realistically. In both atria and ventricles, the same pressures were applied,

generating a flow of 5 l/min through the pulmonary artery and a flow through the aorta of 1 l/min. The reason for the higher flow in the right ventricle was the higher distensibility at the same pressure levels compared to the left ventricle. Nevertheless, the described setup was compact and allowed placement under a conventional C-arm system. The established configuration enabled a simple use and adjustment of heart movement. The generated septal defects were visualized using contrast agents and successfully repaired by making use of ductal occluders and ASD/VSD occluders inserted via the atrium and the ventricular wall, respectively. For ASD closure a standard 15 Fr heart catheter sheath was fixed in the vena cava

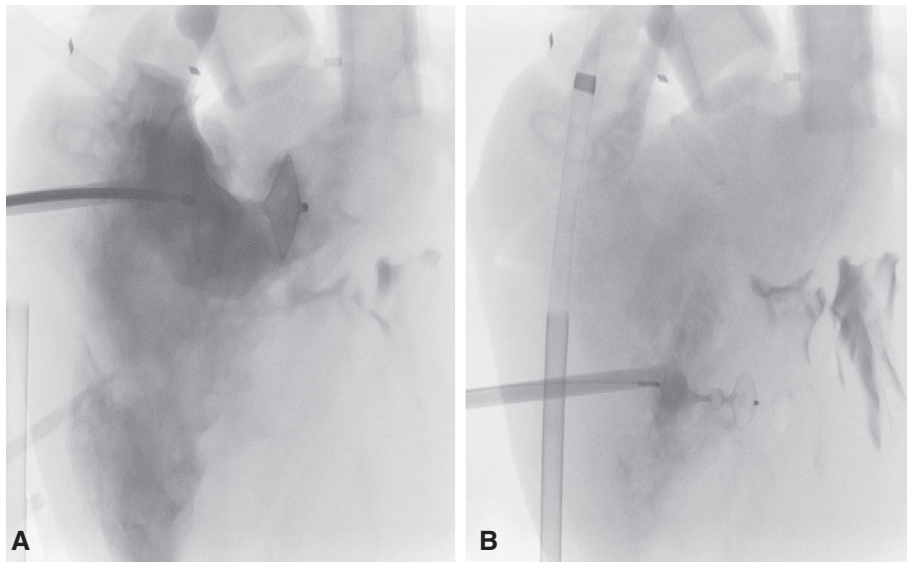


Figure 3: Atrial septal defect (ASD) closure using an ASD occluder (A) and hybrid closure of a ventricular septal defect (VSD) using a ductus occluder for neonates/infants and small children (B).

inferior with a tourniquet suture, the defect was crossed with a multipurpose catheter, a guidewire was placed in the left atrium and a second long sheath was advanced over the wire in the left atrium. Then the device was placed in the atrial septal defect within the septum as shown in Figure 3A.

Due to the small size of the created ASD this procedure, especially crossing the ASD, was not easy to perform (as it is sometimes in real life). To train device deployment in a faster manner the right atrial appendage was punctured and a sheath fixed, so that the course through the ASD became much easier. Figure 3B shows the hybrid closure of a VSD by employing a ductus occluder, which is used for closing a large VSD in infants. The free right ventricular wall was punctured with a needle, a guide wire was placed through the defect in the left ventricle; after removing the needle, a sheath was placed over the guidewire in the left ventricle. Through this sheath the device was implanted. The hearts was kept passively beating for several hours and allowed training of several physicians on only one heart.

Using the duplicated mock circuit physiologic pressures and flows in each side of the heart could be generated: in the left ventricle a pressure between 10 mm Hg (diastole) and 80 mm Hg (systole) at mean flow rates of 3–4 l/min were achieved. In the right heart pressures between 10 mm Hg (diastole) and 30 mm Hg (systole) at a mean flow of 3–4 l/min were generated (see Figure 4).

Pressures and flows could be easily adjusted by adapting the pulsatile driving pressures and the speed of the centrifugal pumps which maintained certain positive

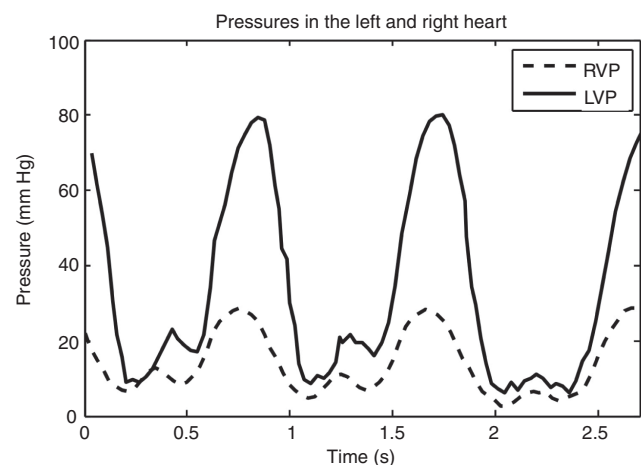


Figure 4: Typical left and right ventricular pressure (LVP and RVP) traces and mean flows of 3.5 l/min in both sides of the heart.

pressure levels inside the reservoirs and consequently in the ventricles.

4 Discussion

A simple and cost effective setup for the training of cardiologic visualization and interventions is presented based on passively beating heart. This allows the training of established and new [9, 10] cardiac interventions in a realistic environment with a contracting heart. As a general instrument for training of interventional cardiac procedures it is not limited to training of ASD/VSD closures. Since the

animal hearts used for this purpose were obtained from the slaughterhouse this method is not only cost effective but also reduces the amount of required animal experiments. The supply of these hearts from the slaughterhouse is potentially unlimited and the preparation and connection of the heart to the mock circuit is simple and fast. Therefore, this setup allows fast exchange of the hearts and consequently represents a tool also for large trainee groups. In contrast to other passively beating heart setups [6, 7] where visualization of cardiac structures and valve repair procedures was the goal, our setup primarily aimed at realistic motion of the heart. Therefore, in the first step, the right as well as the left heart was pressurized with the same pressures. Although this does not result in physiologic pressure and flow conditions, it provides the opportunity to apply interventional cardiology procedures at a moving heart inside a realistic environment including the whole intracardiac structures and valve apparatus. It must be noted that all passively beating hearts which are driven either from the apex or by pneumatic drivers as presented in this setup do not represent the physiologic pressure-volume relationship inside a heart. Whereas in beating hearts the pressure increases during systole and volume decreases at the same time, in passively beating hearts the volume increases with increasing pressures. This might be a considerable limitation for studies aiming at investigation of internal heart structures as heart valves. However, for the performed transvenous and percutaneous ASD/VSD closure interventions, experienced cardiologists reported a similar haptic perception, visualization using the C-arm and washout of contrast agents compared to *in vivo* interventions. For the reproduction of hemodynamics the presented setup can be adapted to pressurize the left and right side of the heart independently from each other to achieve physiologic pressures and flows. Although the mock circuit needs to be duplicated for both sides of the heart it remains still simple, easy to handle and can be placed inside a standard C-arm environment. Although the ventricular pressure-volume relationship in such a setup is inverse, physiologic pressures in and flows through both sides of the heart were achieved. This setup would also allow visualization of anatomical structure and surgical/cardiology interventions at realistic pressures and flows as proposed in [6, 7]. Due to the compact size, the possibility to build the mock circuit without any metal parts and the external pneumatic drive unit, this setup could also be used for training and research in imaging techniques like CT and MRI.

5 Conclusion

A compact and simple passive beating heart setup was developed which allows training of cardiologists in the heart catheter lab or surgical hybrid suite in a realistic cardiac environment including the geometric complexity of the human heart.

Author's Statement

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