New Cardioscope-Based Platform for Minimally Invasive and Percutaneous Beating Heart Interventions

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With heart disease increasing worldwide, demand for new minimally invasive techniques and transcatheter technologies to treat structural heart disease is rising. Cardioscopy has long been considered desirable, as it allows direct tissue visualization and intervention to deliver therapy via a closed chest, with real-time fiber-optic imaging of intracardiac structures. Herein, the feasibility of the advanced cardioscopic platform, allowing both transapical and fully percutaneous access is reported. The latter technique, in particular, is believed to represent a milestone in the development of the cardioscope. Cardioscope prototypes were used in 7 bovine models (77.2−101.1 kg) for transapical or percutaneous insertion. Miniature custom-built, water-sealed cameras (diameters: Storz, 7 Fr; Medigus, 1.2 mm) were used. For percutaneous cardiopulmonary bypass, the pulmonary artery was occluded by a balloon catheter (Intraclude, 10.5 Fr, 100 cm) and perfused with a crystalloid solution. Cameras were inserted transapically ($n = 4$) through the left ventricular apex or percutaneously ($n = 5$) via the carotid artery. Insertion of the optimized cardioscope devices was feasible via either approach. Intracardiac structures (left ventricle, mitral valve opening/closure, chordal apparatus, aortic valve leaflets, and regurgitation) were visualized clearly and without deformation. Catheter tips were successfully bent >180° inside the left ventricle; rotation and navigation to view various intracardiac structures were feasible in all cases. This study showed the technical feasibility of direct cardioscopic visualization using transapical and percutaneous approaches. This advanced cardioscopic instrumentarium represents a promising platform for future interventions and surgery under direct visualization of the beating heart.

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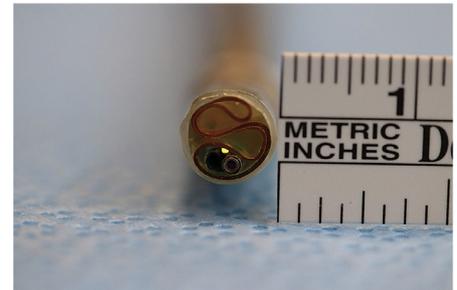
Cleveland clinic cardioscope tip.

Central Message

In vivo studies demonstrated the technical feasibility of direct intracardiac visualization via transapical and fully percutaneous approaches of our latest prototype cardioscope with us.

Perspective Statement

Insertion of the optimized cardioscope devices was feasible via transapical or percutaneous approaches. The achievement of this important project milestone suggests that our improved cardioscopic device holds significant potential for development into a valid minimally invasive clinical option to deliver intracardiac therapies without the need for open-chest surgery or cardiopulmonary bypass.

INTRODUCTION

Intracardiac visualization represents a significant area of interest in the cardiovascular field and has achieved landmarks in cardiovascular innovation in the past several decades. Years ago, before successful interventional procedures had been introduced and sophisticated technologies to conduct cardiac surgical procedures had not yet been invented, surgeons and engineers foresaw the major advantage offered by direct visual identification of lesions. They developed innovative means for intracardiac visualization, and several concepts have been proposed since early in the twentieth century. The first records of cardioscope concepts were in publications by Rhea and Walker in 1913 and Allen and Graham in 1922, and several other ideas were developed afterward.[1-4] To facilitate visualization of the blood-filled organ, these early concepts primarily focused on direct introduction of variously designed endoscopes through the cardiac wall, after which the interior of the heart could be inspected.

Today, developments in transcatheter solutions and imaging techniques have evolved dramatically. Through miniaturization and seamless catheter connection solutions, as well as improved cardiac perfusion techniques, the development of intracardiac imaging technologies has been significantly facilitated. Various teams report their intracardiac visualization tools and device evaluations with differing criteria for success.[5-8]

We previously developed a cardioscopic platform for intracardiac visualization and simulated the intracardiac procedure in an open-chest condition.[9] This report will present the latest developments of 2 cardioscopic platforms (transapical and fully percutaneous) that underwent optimizations and have recently been evaluated in vivo at our institution.

MATERIALS AND METHODS

The cardioscope studies were performed in 7 calves (Jersey calves; weight range, 77.2−101.1 kg); devices were inserted via thoracotomy for transapical cardioscope placement ($n = 4$) or via carotid artery for percutaneous insertion ($n = 5$). Both insertion techniques were tested in animals ($n = 2$) when feasible.

The study protocol was approved by Cleveland Clinic's Institutional Animal Care and Use Committee, and all animals received humane care in compliance with the "Guide for the Care and Use of Laboratory Animals" (Institute of Laboratory Animal Resources, Commission on Life Sciences, National Research Council, National Academy Press, Washington, DC, 2011) and institutional guidelines.

Technology

Two separate cardioscopic systems were fabricated, 1 for transapical and 1 for fully percutaneous insertion (Fig. 1).
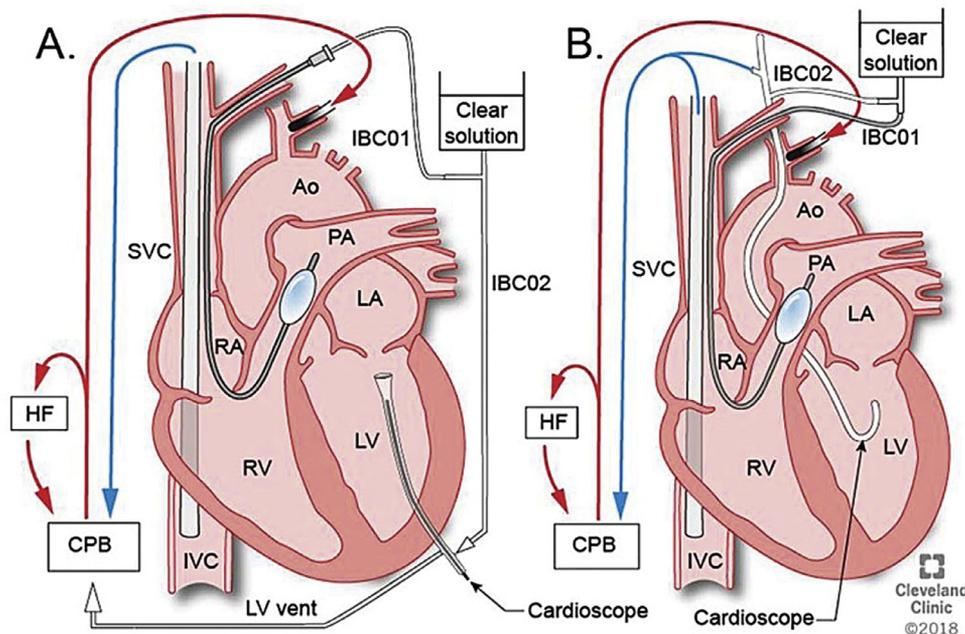

Figure 1. (A) Less invasive (transapical) LV imaging and CPB circuits; (B) percutaneous LV imaging and CPB circuits. Ao, aorta; CPB, cardiopulmonary bypass; HF, hemofiltration; IBCO, imaging bypass circuit output; IVC, inferior vena cava; LA, left atrium; LV, left ventricle; PA, pulmonary artery; RA, right atrium; RV, right ventricle; SVC, superior vena cava.
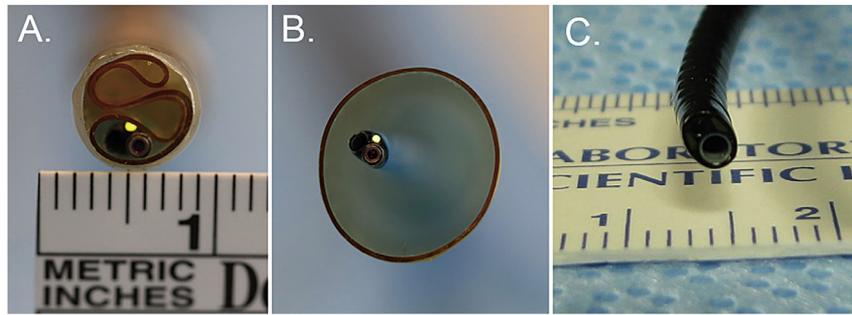
Figure 2. The miniaturized cardioscope cameras. (A) The catheter hood with contained Medigus camera and fiber-optics is crimped into the percutaneous sheath; (B) open hood; (C) Storz camera tip.

Additionally, 2 different image-processing systems were designed and custom built for this study; both systems and the catheters for cardioscopy were designed to be used with either camera or device insertion options.

The Medigus camera (1.2-mm-diameter; frame size—704 × 720 (W × H); frame rate—25 fps; bitrate—3229 kbps; pixel aspect ratio—1.0; IntroSpicio, Medigus, Omer, Israel) is mounted on the tip of the cardioscope, with an external fiber-optic light source and a channel for lens flushing (Fig. 2A and B). Proximal ends of these components were integrated using a 3D-printed adapter intended for user-friendly catheter connection. A high-definition camera (7-Fr. diameter; Karl Storz, GmbH & Co. KG, Tuttlingen, Germany) was designed with an image sensor positioned distally from the catheter tip, incorporated into the image-processing unit (Fig. 2C).

Figure 3. Custom-made cardioscope sheath. (A) Catheter for percutaneous insertion; (B) control handle; (C) catheters for transapical insertion.

A custom-made flexible catheter (16-Fr diameter) with incorporated cardioscope hoods was mounted onto a Dexterity (100 cm long) 180° steerable introducer (Cardiosolutions, West Bridgewater, MA) (Fig. 3A and B). An Intraclude balloon catheter (10.5-Fr diameter, 100 cm; formerly known as Endo-clamp; Edwards Lifesciences, Irvine) was used for pulmonary artery occlusion. The cardioscopes were designed with different stiffnesses (harder and softer catheter materials) for trans-apical and percutaneous use, respectively. The transcapical cardioscope sheath was made of rigid plastic (Fig. 3C). Each device iteration and the optimized device components were tested in vitro using a proprietary heart model prior to all acute animal experiments.

Anesthesia and Surgical Techniques

Each calf was sedated with ketamine (10 mg/kg) intramuscularly, then atropine (0.15 mg/kg) was administered intramuscularly. After being anesthetized by isoflurane inhalation (5%) via mask, endotracheal intubation was performed, and a venous infusion line was inserted into the right jugular vein (distal insertion). The anesthetized animal was situated using an Olympic Vac-Pac (Natus Medical Inc., San Carlos, CA) in the supine position. Lidocaine (1 mg/kg/h intravenously) was started.

A neck incision was performed to isolate the jugular veins and carotid arteries. Heparin (300 U/kg) was administered for systemic anticoagulation. A 23-Fr-diameter sheath (EndoReturn arterial cannula, Edwards Lifesciences) was inserted into the right jugular vein with a purse-string suture for the insertion of the 10.5-Fr-diameter pulmonary arterial perfusion catheter (Intraclude aortic catheter, Edwards Lifesciences). A 24-Fr-diameter arterial cannula was inserted into the left carotid artery for cardiopulmonary bypass (CPB). A 25-Fr-diameter venous cannula (QuickDraw, Edwards Lifesciences) was inserted into the left external jugular vein and advanced to the right atrium, and its position was confirmed via fluoroscopy.

CPB was started. The cardioscope hood was retracted into the sheath and introduced into the left ventricle (LV) along the standard (0.035 inch) guidewire placed within the carotid artery.

The main pulmonary artery was occluded by inflating a balloon (filled with a contrast solution), and the irrigation solution was delivered at 1 L/min to flush blood from the lungs. Once the cardioscope sheath was advanced, the irrigation
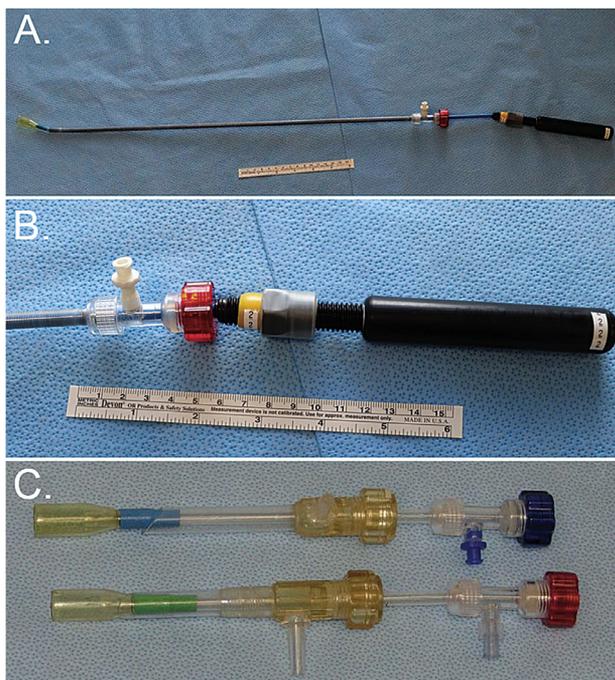
solution rate was reduced to 500 mL/min or less. Blood drainage from the LV was established via a percutaneous sheath connected to the CPB device. Hemoconcentration was used, and the retrieved imaging fluid was returned for reperfusion via the secondary imaging circuit.

Once intracardiac images were obtained, the experiments were terminated by bolus injection of heparin (500 U/kg) followed by potassium chloride (3 mEq/kg).

RESULTS

Both transapical and percutaneous cardioscope visualization systems were successfully developed and tested. The insertion of all catheters went smoothly, and no resistance or mechanical/anatomical difficulties were encountered during insertion. Navigation of the cardioscope tip was easy, and tactile feedback was present during insertion and handling. The maneuverability of the catheter sheath was deemed improved over the previous version.

From the transapical access point, the visualization of mitral chordal apparatus and mitral and aortic valves (MVs/AVs), and other anatomical structures was successfully performed (Fig. 4). Using the percutaneous approach, in a first attempt to observe

surrounding structures, the LV apex, free wall, and subvalvular MV apparatus were visualized. With this entirely percutaneous approach, several clear close-up images of the LV chamber and AV cusps (Fig. 5) were obtained. Then the catheter tip was turned 180°, and enabled visualization of the MV and AV (at a 180–190° turn). Occasionally, the image on the screen became unclear, but this difficulty was managed by increasing the cardioscope cannula perfusion flow up to 1 L/min.

Pulling and pushing of the percutaneous cardioscope was easy. Also, the "U-turn" with the cardioscope hood was successful every time. However, we realized that after MV visualization, the U-turn to see the AV would make the catheter tip abut the atrioventricular groove, as the distal portion of the catheter would be too long. Therefore, before aortic visualization, the catheter was pushed toward the LV apex, which turned the tip such that it made a 140–150° turn. After that was achieved, catheter was withdrawn while still turning the scope up to 180°. After that, the distance between the catheter tip and AV leaflets was adjusted. By adjusting the distance between the camera tip and the exit orifice at the center of the hood, all structures were visualized. The catheter was
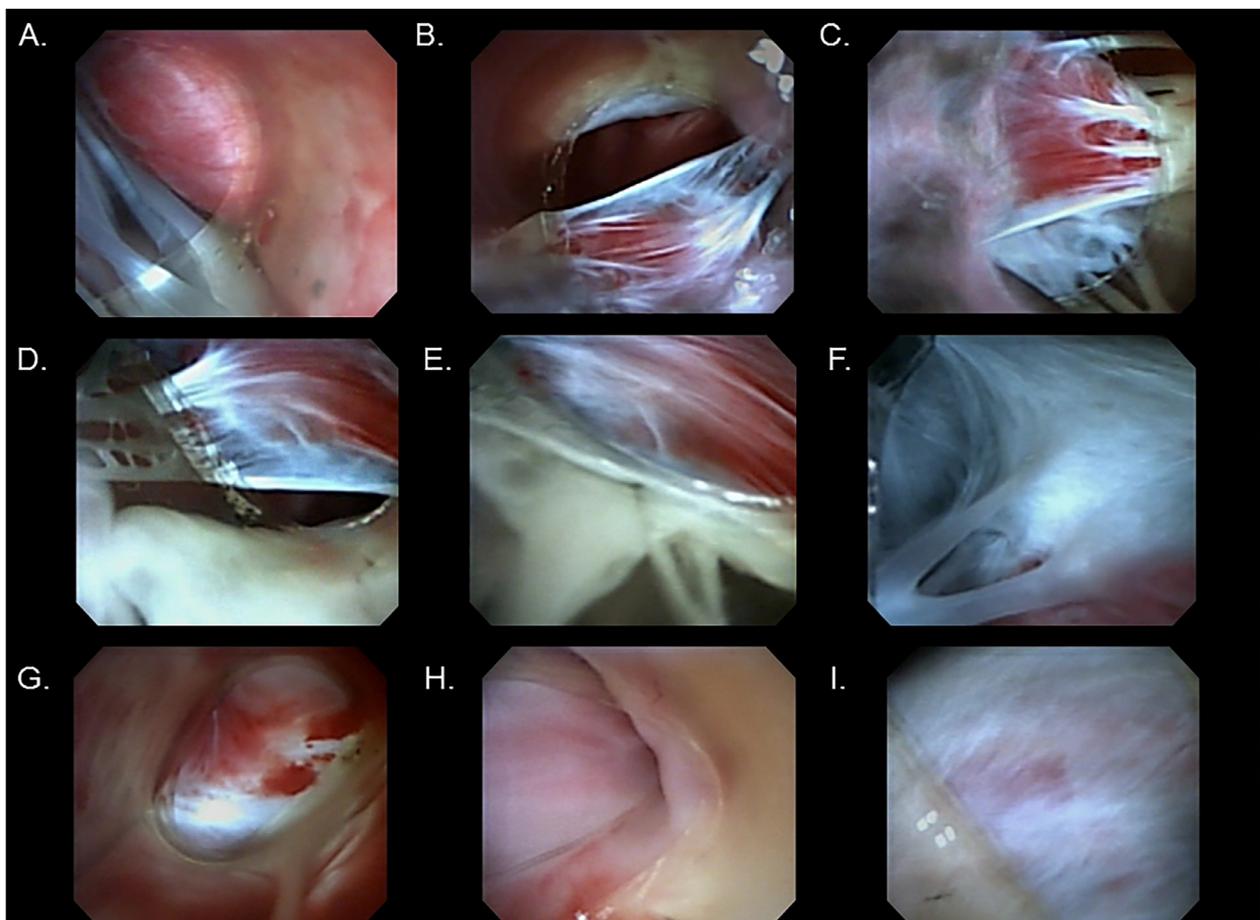

Figure 4. Images from transapical Cardioscope. (A) Mitral valve (MV) chordae (toward apex); (B) MV (both leaflets); (C) subvalvular chordae tendineae; (D) ventricular MV view; (E) MV during closure; (F) direct ventricular MV view, (G) LV wall (ventricular view); (H) pulmonary vein orifice; (I) left atrium view.
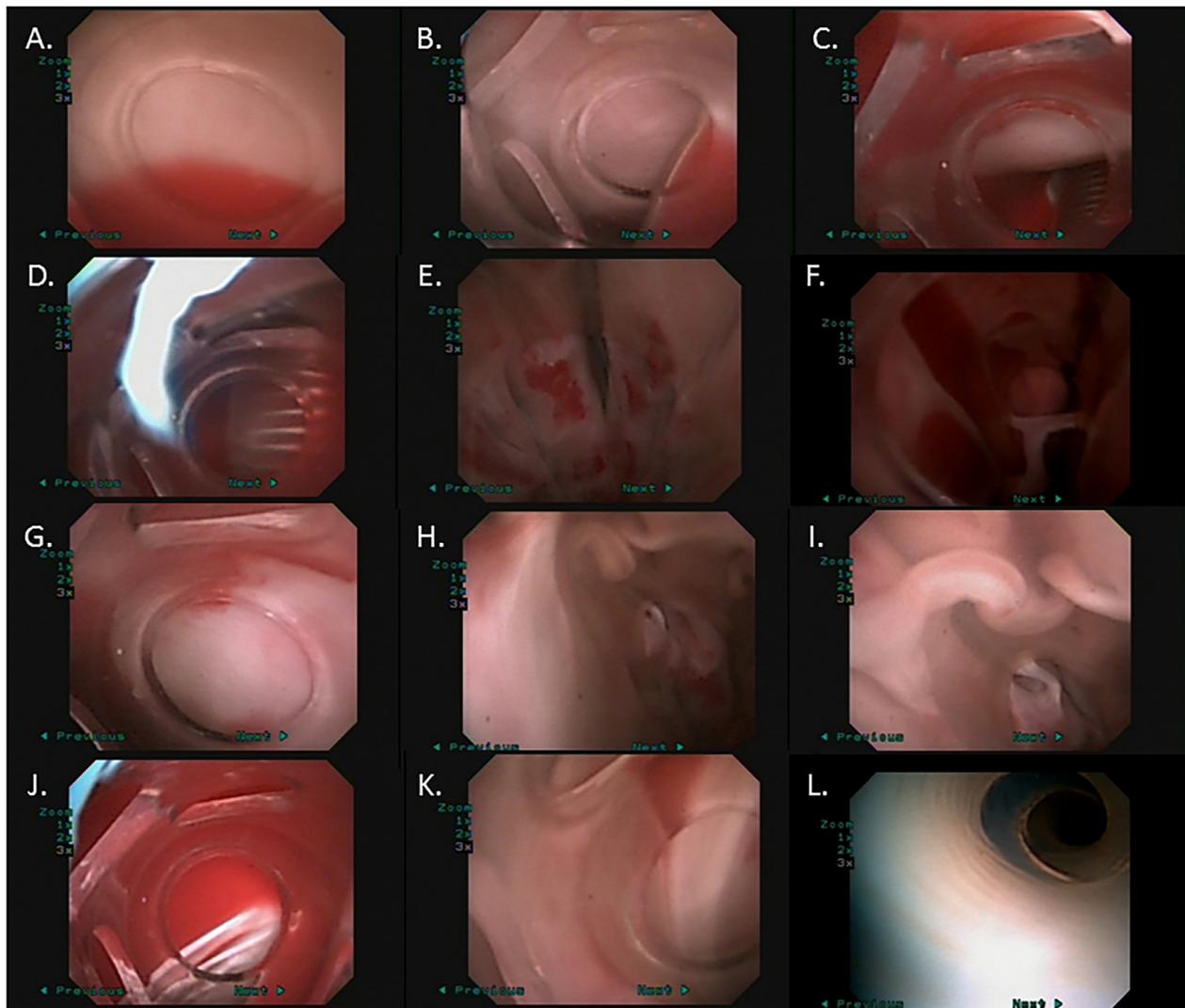
Figure 5. Images from percutaneous cardioscope. (A) Aortic valve (AV) and regurgitation area; (B) aortic leaflet; (C) aortic regurgitation due to the catheter; (D) cardioscope U-turn; (E) papillary muscle; (F) in the middle of MV leaflets; (G) AV; (H) mitral leaflet and chordae; (I) chorda attached to the leaflet; (J) mitral chordae and regurgitation; (K) mitral leaflet compressed with the device hood; (L) twisted cardioscope sheath.

successfully bent >180° inside the LV; thus the catheter body, as it exited from the AV, and valve's regurgitated backflow caused by the catheter positioned within it was observed.

The catheter steerability perfusion/drainage abilities were not affected by the degree of bending. The hood could be easily folded into the outer sheath during device delivery for an atraumatic insertion. After delivery, the hood could be pushed out and released to its original shape in all cases. The cardioscope was rotated to see different intracardiac structures, with variable results. The camera rotations were stiff in all cases and created deformation of the sheath (Fig. 5L).

Both miniature cameras performed well. The Medigus camera began to lose image quality due to the low-emission light-emitting diode light that came through the sheath fiber-optics. Therefore, the image quality was not always adequate to the original camera capacity, but allowed to complete the

visualization assessment. The Storz camera showed very clear image quality in all modalities.

The newer cardioscope handle hosted most of the control units, including catheter steering, perfusion inlet, drainage outlet, camera channel, etc. The scope's ergonomic design allows one-handed operation to achieve most functional positions.

DISCUSSION

For these advanced cardioscopic tools, the major undertakings have been device design optimization and in vivo evaluation of prototypes in large animal models, comparing transapical with fully percutaneous access. Both systems were tested; however, the main emphasis was given to the percutaneous approach.

Several cardioscopy concepts have been tested previously by various groups.[10] In 1950, Murray[3] reported another cardioscopic cannula concept requiring direct contact between the

cannula tip and cardiac wall. Carlens and Silander described use of an inflatable rubber balloon (5−10 mL) mounted on a 7-mm-diameter telescopic cannula tip and placed in the right atrium.[11] Bolton et al[2] reported using a simple Lucite tubing used to transmit external light into the heart. Device (length: 9−12 cm; diameter: 0.75−2 cm) placed through a purse-string suture on selected atrial appendage was used for intracardiac assessment and photography.

Various cardioscopy methods presented in the literature have several features in common: the need to bring the optical end of the tool close to endocardial territory and direct contact for proper visualization and displacement of blood in front of the lens by clear fluid under pressure.[10] Early cardioscopy concepts were primarily based on using a translucent, transparent, or optical window, without major optical magnification, and recording options. Today, the use of high-definition imaging technologies packed into miniaturized catheters makes possible imaging and recording of images for any duration. As described early by Carlens and Silander[11], specific difficulties, such as the chamber filling with opaque viscid fluid, temporary interruption of blood flow, and avoidance of arrhythmias, still make cardiac endoscopy distinct from other existing endoscopic applications. More recently, Reuthebuch et al[5] reported cardioscopic placement through atria or ventricles in 100 patients. Either rigid (5 mm) or flexible (4 mm) scopes were used along with elongated surgical tools for intracardiac interventions such as resection or evaluation of hypertrophied or fibrous interventricular tissue (15%), aortic stenosis (12%), foreign body (13%), ventricular septal defects (8%), paravalvular leaks (8%), diagnostic (4%), and education (40%) through full median sternotomy. Ohtsuka et al[6] reported cardioscopy-assisted transseptal cryoablation in 11 patients using a 3-mm, 30° angle-view endoscope through partial sternotomy. Padala et al[7] reported use of a blunt convex Plexiglass tip that enabled intracardiac tissue visualization in 80-kg porcine models ($n = 5$) through sternotomy and minithoracotomy incisions. Recently, Rosa et al[8] described cardioscope fitted with a silicone optical window for detecting paravalvular leaks in porcine models ($n = 3$) through median sternotomy.

The imaging technology used in our study was based on different technological solutions and methods of image processing. Therefore, the quality was variable. Placement of the image sensor at the catheter tip saved a good deal of cross-sectional space. However, this configuration would require effective delivery of light, perhaps through the catheter body. For disposable devices, this may be a more effective measure to reduce costs vs incorporating more costly imaging optics. The Storz camera designs are intended for multiple uses, which explain the superb quality of sealing and packaging. The imaging quality could be considerably enhanced by image-stabilization software, which is particularly important due to the pulsatile environment.

The limitations of this study can be attributed to the animal model, since the ascending aorta in calves is extremely short, and the LV chamber can appear as hypertrophic, limiting the navigation of the cardioscope's tip. Miniaturization of the catheter is feasible, and testing of several scaled-down versions could be beneficial to evaluate the image quality at lower infusion fluid rates.

Another important aspect of this and other existing cardioscope solutions is the necessity of using CPB. The true value for these technologies could be achieved by eliminating CPB, thus making the procedure even less invasive and accomplished more quickly.

The key results of this study show a successful development of the catheters and sheaths for both apical and percutaneous cardioscopic approaches. This first report on application of a totally percutaneous approach suggested the feasibility and reproducibility of the approach, and the cardioscopic platform opens up further possibilities for intracardiac surgical procedures. The inevitable limitations encountered in the natural cardiac environment, such as a blood-filled chamber and only temporary flow interruptions, seem to persist and provide challenges for any technologies that are yet to come. Future adoption of cardioscopic technology will depend on how easily it can fit into existing well-established procedures.

CONCLUSIONS

During the course of this study, both transapical and percutaneous cardioscopic visualization systems were successfully developed and tested in vivo. The quality of visualization overall was superb, and the imaging catheter navigated toward the intracardiac areas of interest proved feasible in all cases. Each type of cardioscope system may serve as a dedicated platform intended for a specific procedure range.

The implementation of this in vivo feasibility testing showed that cardioscope-based platform can provide the quality intracardiac visualization to enhance the known surgical and some of the evolving interventional repair techniques. Additional development will be necessary to incorporate these techniques and catheter delivery systems into a single state-of-the-art toolkit.

SUPPLEMENTARY MATERIAL

The following is the supplementary data to this article:

Catheter withdrawal

Video 1. This video documents the feasibility of the transapical, but more importantly, the fully percutaneous technique for visualizing cardiac structures with the latest cardioscope prototype.

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