Transvascular Intracardiac Applications of a Miniaturized Phased-Array Ultrasonic Endoscope

Initial Experience With Intracardiac Imaging in Piglets

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Background. Recent advances in miniaturization of phased-array and mechanical ultrasound devices have resulted in exploration of alternative approaches to cardiac and vascular imaging in the form of transesophageal or intravascular imaging. Preliminary efforts in adapting phased-array endoscopes designed for transesophageal use to a transvascular approach have used full-sized phased-array devices introduced directly into the right atrium in open-chested animals. The purpose of this study was to assess the feasibility of using a custom-made, very small phased-array endoscope for intracardiac imaging introduced intravascularly through a jugular venous approach in young piglets.

Methods and Results. Experimental atrial septal defects created in four piglets (3–4 weeks old) had been closed with a buttoned atrial septal defect closure device consisting of an occluder in the left atrium and a counteroccluder in the right atrium. Five to 15 days after atrial septal defect closure, the piglets were returned to the experimental laboratory, where a 6.3-mm, 17-element, 5-MHz phased-array probe mounted on a 4-mm endoscope was introduced through a cutdown incision of the external jugular vein and advanced to the right atrium. From the right atrium all four cardiac chambers, their inflows and outflows, and all four valves were well imaged with minimal superior and inferior rotation. High-resolution imaging of the atrial septum defined with anatomical accuracy, later verified by autopsy, the exact placement of both the occluder and counteroccluder in the left and right sides of the atrial septal defects and the absence of any shunting across the atrial septum in any of the four animals.

Conclusions. Our efforts indicate that transvascular passage of small phased-array probes can be easily accomplished and is a promising technique for detailed visualization of cardiac structures. This approach may provide an alternative to transesophageal echocardiography, particularly for guiding interventional procedures such as placement of transcatheter closure devices in pediatric patients. (Circulation 1991;83:1023–1027)

Recent advances in miniaturization of both phased-array and mechanical ultrasound devices has resulted in exploration of alternative approaches to cardiac and vascular imaging and has led to an increasing interest in the potentials of “invasive” echocardiography, that is, transesophageal and intravascular windows for echocardiographic and Doppler interrogation.1–4 Although intracoronary imaging has been viewed as an important aid to making decisions about modes of treatment for coronary disease and can provide guidance during or after coronary balloon angioplasties or performance of other atherotomy techniques, pediatric cardiologists have been more interested in exploring imaging technologies that would be more feasible in the guidance of interventional catheterization procedures such as balloon valvuloplasties, dilatations of aortic coarctations or other central vascular stenoses, and placement of transcatheter devices used for closing patent ductus arteriosus and atrial and ventricular septal defects. To assess its use for intracardiac imag-
ing and for monitoring the position of previously placed atrial septal defect closure devices, we used a custom-made very small phased-array endoscope introduced intravascularly through a jugular vein in young piglets.

Methods

Animal Model

As part of an ongoing protocol to test a transvascular method for closing atrial septal defects, four piglets (3–4 weeks old) had an atrial septal defect created by balloon dilatation of the fossa ovalis. The defects had been closed with a “buttoned” device that consisted of an occluder advanced into the left atrium, a counteroccluder in the right atrium, and a buttoning mechanism that attached both components. The piglets were then allowed to recover and were sent back to the farm. Five to 15 days later, the piglets (8–11 kg) were returned to the laboratory, where transesophageal and transvascular imaging were performed to judge the adequacy of device placement and defect closure before postmortem pathologic examination.

Transvascular Imaging Methods

Transvascular intracardiac imaging was performed using a 6.3-mm–diameter, 17-element, 5-MHz phased-array probe mounted on a 4-mm endoscope (with scanning performed on an Aloka model 870, Aloka Co. Ltd., Tokyo). The probe scanned in a single transverse plane and could be angled superiorly and inferiorly using a cable mechanism. It had capabilities for two-dimensional imaging and pulsed wave Doppler and color Doppler flow mapping at 5 MHz.

Results

Studies were performed in close-chest piglets that lay on their backs while anesthetized with ketamine (10–20 mg/kg); breathing was spontaneous, without endotracheal intubation or mechanical ventilation.

The imaging probe was advanced through a cutdown incision of the external jugular vein and into the right atrium without difficulty. Once in the right atrium, the probe required minimal rotation superiorly and inferiorly to visualize all intracardiac structures and flows with excellent resolution.

Both atria, atrioventricular valves, and ventricles were imaged in detail. Flows were recorded from the vena cava and the pulmonary veins, across both atrioventricular valves, and through both ventricular outflows and great vessels (Figure 1).

In all four piglets, the atrial septal defect closure devices were identified, and the position of each within the atrial septum was defined easily. The device was positioned well in three of the four piglets (Figure 2A). Flow was recorded with color Doppler mapping around the tips of both the occluder and counteroccluder in two of the piglets (Figures 2B and 2C). In the fourth piglet, the occluder was partially pulled through the defect into the right atrium, and a small clot was seen at the bottom of the device just above the tricuspid valve. No residual flow through the atrial septal defects was recorded in any of the four piglets.

All findings related to device placement were confirmed by fluoroscopy and postmortem examination of the heart. No damage was found in the heart or veins as a result of the probe.

Discussion

Our efforts indicate that transvascular passage of small phased-array probes is an easily accomplished and promising technique for detailed visualization of
FIGURE 2. Panel A: Four-chamber view of the heart obtained from an intracardiac right atrial (RA) view. The atrial septal defect closure device is seen as an unusually thick interatrial septum. The occluder positioned in the left atrium (LA) is not distinguishable from the counteroccluder in the RA. At postmortem, both parts of the device, placed 2 weeks before this study, were completely endothelialized and barely differentiated from the surrounding atrial tissue. RV, right ventricle; LV, left ventricle. Panels B, C, and D: Two-dimensional image, color flow image, and diagram, respectively, of an expanded view of the atria. The occluder (OCC) is seen in the LA side of the septum attached firmly to the atrial wall. On the right side of the septum the counteroccluder (COC) is seen with its superior end still not completely endothelialized onto the atrial septal tissue. Flow is seen around the COC tip on the color flow image; however, no residual atrial shunt was detected.

Intracardiac Imaging structures; this technique should serve to guide interventional catheterization procedures with great accuracy and ease.

Intravascular imaging catheters to date have been used to obtain high-resolution images of vessel lumina and vessel walls for purposes of guiding
coronary angioplasties and valvuloplasties, for intracoronary imaging and tissue characterization of atherosclerotic plaques, for guiding mechanical and laser atherectomies, and for preventing the complications associated with these invasive procedures. Because their primary applications have been vascular, these catheters have been optimized for the extreme near field, affording only a limited view of intracardiac, valvular, and septal structures. Furthermore, they are mostly strictly imaging catheters without the capability of interrogating flow velocity information.

Transesophageal echocardiography has been suggested for guiding interventional procedures and assessing placement of transcatheter closure devices. The disadvantages of the transesophageal approach include the following: patient discomfort during manipulation of the transesophageal echocardiographic probe, leading to the need for general anesthesia (in children) when patient immobility is required during interventional procedures; the risk of vagal stimulation, which can be a serious complication in the cardiac catheterization setting; and problems with visualization of cardiac structures and flows when overlapping lung structures obscure or limit the echocardiographic window. Further, the orientation of transesophageal scanning may be inadequate for imaging or flow interrogation of specific cardiac structures.

Preliminary efforts in adapting phased-array endoscopes for transvascular use have involved the introduction of full-sized phased-array devices directly into the right atrium in open-chest animals. With the recent success in further miniaturizing these phased-array probes, investigators have turned their attention to assessing the feasibility of introducing these probes transvascularly. Seward et al. described preliminary findings with intracardiac imaging obtained by manipulating a small esophageal echocardiographic transducer within the aorta and the inferior vena cava of normal pigs. Introduction of these catheters through the external jugular venous system would make this procedure somewhat analogous to that used with bioptomes to perform endocardial biopsies, although the sizes of these imaging endoscopes still exceed those of biopsy catheters.

A number of technological advances expected to be available within the near future should facilitate significant miniaturization of these probes. Increasing transducer interrogation frequency to 7.5 and potentially 10 MHz for sector scan–format phased-array technologies would result in a 30% to 50% decrease in array size, even with the same number of elements, such that a 3-mm, 20-element phased array could be built for longitudinal scanning. Efforts in our laboratory on a National Institutes of Health–sponsored technology development program are aimed in that direction. Further, in addition to changes in the configuration of the phased-array scan head itself, there are also new, smaller, more densely packed and shielded coaxial cables that might aid in reducing shaft diameter. For intracardiac scanning from the right atrium, it is still probably advisable to have steerability to aim the array at different areas of the heart, but metallic alloy materials that change shape when temperature varies or when low-voltage electrical current is applied could be used to bend or flex the tip of the probe. This system would be less cumbersome and smaller than the cable system presently used in ultrasonic esophagoscopes. Last, radially arranged arrays or mechanically steered single-crystal catheters are available at 20 MHz and at lower frequencies, but these technologies have not been implemented with the capability of color flow imaging or waveform Doppler. There are technical difficulties related to the coded aperture reconstructions used for radial array catheter scanners that may limit high spatial resolution at larger distances from the transducer or limit their capability for deriving waveform or color Doppler. We expect, however, that miniaturization of probes and increases in frequencies to 7.5–10 MHz should permit the eventual introduction of phased-array devices through a femoral venous approach; these improvements should increase the ease of use of this type of intravascular ultrasonic monitoring in the cardiac catheterization laboratory and allow for human application, eventually even in children.

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**KEY WORDS** • echocardiography, intracardiac • atrial septal defect • congenital heart defects • transcatheter closure devices
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