Transcatheter Closure of Atrial Septal Defects

Experimental Studies

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Recent experience with the spring-loaded patent ductus arteriosus (PDA) occluder has demonstrated several advantages of this device in the closure of intracardiac defects compared with previously described techniques. Pathologic and animal model studies were performed to identify which atrial septal defects (ASDs) might be suitable for device closure and to test a new septal closure double umbrella. Fifty specimens from the Cardiac Registry with unrepaired ASD secundum (2') were analyzed. Mean ASD size was 8x10 mm (range, 3x4 to 30x30 mm); 80% (n=40) of ASDs were judged closable with the new device. ASD closure was attempted in four lambs with the Rashkind (hooked single umbrella) ASD occluder. One of four umbrellas was correctly positioned; no ASDs were closed. A new double-hinged ("clamshell") umbrella device was designed: eight ASD closures were attempted with this device (defects ranged from 8 to 20 mm in diameter). Six of eight umbrellas were correctly positioned; four of four animals observed more than 1 day appeared to have complete closure on postmortem examination with endothelialization of the device. We conclude that 1) most ASD 2' are far enough from vital structures to permit closure, 2) initial placement of hooked umbrellas is often incorrect and cannot be altered, 3) clamshell double umbrellas were successfully placed in six of eight attempts, and 4) endothelialization of closed ASDs appears complete within weeks of implantation. These preliminary studies appear promising and support testing the clamshell ASD device in clinical trials. (Circulation 1989;79:1091-1099)

Atrial septal defects (ASDs) have been closed with a variety of catheter methods.1-3 The double-disk technique of Mills and King1,2 was successful in selected patients, but the delivery system was 23F, and only defects less than 20 mm could be closed. Rashkind developed a single-umbrella technique, with "fishhooks" at the end of three of the six arms. The occlusive material was collapsible foam, but the catheter size had to be 15F to accommodate the hooks. Because the hooks might snare the foam when the device was collapsed, several millimeters of space were required between the foam and the hooks, thus limiting the size of defect that could be closed. Finally, the arms were opened in the left atrium, and then pulled back against the septum: any initial misplacement of any one of the fishhooks would prevent correct seating of the device. Thus, methods to ensure accurate placement of each hook are required to permit the successful use of this device.

Recently, we adapted the use of the spring-loaded Rashkind patent ductus arteriosus (PDA) double umbrella to close a variety of intracardiac defects, including small interatrial defects4 and ventricular septal defects.5 Such an approach had several potential advantages, including the use of smaller delivery systems and the avoidance of hooks. However, these clinical trials indicated that the Rashkind PDA device itself was too small for the closure of most atrial septal defects and might partly protrude into the atrial chambers. Furthermore, the anatomic types of atrial defects that might be suited for transcatheter closure have not been defined. We, therefore, undertook a number of anatomic, pathologic, and experimental studies to test a new type of septal closure umbrella and to further understand the processes of transcatheter ASD closure.

Pathologic Studies of Human Secundum Atrial Septal Defects

Methods

We reviewed the Cardiac Registry files of cases with unrepaired secundum ASDs (ASD 2') to iden-
tify 50 specimens for analysis. All specimens with ASD 2° without associated cardiac malformations were analyzed (n=32). Eighteen specimens with associated cardiac malformations were identified for analysis by sequential review of the most recent registry files. Specimens with other forms of ASD or anomalies of venous drainage were excluded.

We measured the size of each defect (mm) in its longest and shortest diameter and the distances of the defect from superior vena cava, inferior vena cava, tricuspid valve anulus, coronary sinus ostium, closest pulmonary vein ostium, and paraseptal segment of the mitral anulus. The morphology of ASDs was classified regarding the number of ASDs and their relation to the fossa ovalis and septum primum (valve of foramen ovale). Finally, each specimen was looked at with regard to suitability for umbrella closure.

### Results

Death occurred at a mean of 2.8 years (range, 1 day to 36 years). The causes of death were varied: only two patients died as a result of complications relating to the atrial defect (pulmonary vascular obstructive disease and brain abscess). Defects ranged in size from 3 x 4 to 30 x 30 mm with an average size of 8 x 10 mm. Although few defects were perfectly round, the longest and shortest diameters were similar: on average the ratio of short to long dimension was 0.8 ± 0.1 (range, 0.5 - 1.0). In 17 of 50 specimens, it was not possible to measure distances between the ASD and all atrial structures. In the remaining 33 specimens, the closest cardiac structure on the right atrial side was most frequently the coronary sinus (48%), often the superior vena cava (18%) or inferior vena cava (18%), and occasionally the tricuspid valve (15%). From the left side, the pulmonary vein ostia were closer than the mitral valve in the large majority (Table 1); the right pulmonary vein ostia were always closer than the left. At least 3 mm separated the defect from the nearest cardiac structure in 70% of the specimens.

All the defects analyzed fit into one of four morphologic categories: 1) virtual absence of septum primum such that the ASD was the entire fossa ovalis (n=19, 38%; see Figure 1); 2) deficiency of septum primum (n=16, 32%); 3) fenestrated septum primum—multiple ASDs (n=2, 4%); and 4) fenestrations in a deficient septum primum—multiple ASDs (n=13, 26%; Figure 2). In all cases with multiple ASDs (categories 3 and 4), an umbrella that covered the fossa ovalis would close all of the defects.

Finally, we made a subjective assessment of the suitability of each ASD for transcatheter closure. Defects judged not cokable were either too large (>25 mm in diameter) or lacked a complete circumferential rim of atrial septum (>2 mm). We determined that 10 of 50 ASDs (20%) were not cokable with the device: in three cases, the defects were too large; in the other seven, there was an incomplete septal rim for anchoring an umbrella. Of the remaining cases, 23 (46%) appeared ideal for closure and 17 (34%) could probably be closed with correct umbrella sizing and placement.

### Transcatheter Creation of Atrial Septal Defects in Lambs

#### Methods

Although animal models are available for the PDA and the ventricular septal defect, an animal model of long-standing secundum atrial septal defects has not to our knowledge been described. ASDs have been created clinically in the catheterization laboratory for more than a decade, and we applied some of these transcatheter techniques to create large atrial defects in the immature lamb.

The method for transseptal puncture in the lamb was developed after a process of trial and error. The atrial septum is relatively small, and the fossa ovalis is located at the end of a shallow funnel (bound anteriorly by the aorta and limbus, and posteriorly by the back wall of the heart) when viewed from the right side of the septum. The standard Brockenbrough needle was manually reshaped to create a steeper angle of curvature, such that the tip points at a right angle to the shaft over a radius of about 5 - 7 cm. A long sheath and dilator (6 - 7F) was advanced from the femoral vein to the superior vena cava, and the Brockenbrough needle advanced to the tip of the dilator. The entire unit was withdrawn into

### Table 1. Anatomic Measurements of Atrial Septal Defect Location

<table>
<thead>
<tr>
<th>Distance from ASD</th>
<th>Right atrium</th>
<th>Left atrium</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CS</td>
<td>SVC</td>
</tr>
<tr>
<td>Average</td>
<td>8</td>
<td>9</td>
</tr>
<tr>
<td>Minimum</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Maximum</td>
<td>38</td>
<td>40</td>
</tr>
<tr>
<td>Number closest to ASD</td>
<td>16</td>
<td>6</td>
</tr>
<tr>
<td>%</td>
<td>48</td>
<td>18</td>
</tr>
</tbody>
</table>

ASD, atrial septal defect; CS, coronary sinus; SVC, superior vena cava; IVC, inferior vena cava; TV, tricuspid valve; MV, mitral valve; PV, pulmonary vein.

n=33.

Distances are in millimeters.
FIGURE 1. Photograph of the right atrial and ventricular view of a 10-month-old patient (PMN, A56-271) with a secundum-type of atrial septal defect (ASD). The septum primum (valve of the foramen ovale) is extremely deficient; only its attachments on septum secundum are preserved. ASD 2°, atrial septal defect secundum; CoS, coronary sinus; IVC, inferior vena cava; SVC, superior vena cava; TV, tricuspid valve.

Transcatheter Closure of Lamb ASD With the Rashkind-USCI Single Umbrella

Methods

The Rashkind atrial septal defect occluder is a single-umbrella device that has a set of six spring-loaded equidistant arms. A foam pad is sewn to the arms and is considerably smaller than the total length of the arms. A 2-mm fishhook is attached to the ends of three of the arms, and these hooks are used to secure the device to the septum. The umbrella is loaded into a 15F metal pod, with the center of the umbrella at the tip and the arms folded backward; care must be taken during loading to ensure that each of the fishhooks is aligned in the same direction (either clockwise or counterclockwise) around a central triangular shaft. After Rashkind’s initial clinical experience with this device, a set of three centering arms were attached to the loading system, to attempt to keep the umbrella near the center of the atrial septal defect during the time of device attachment to the septum.

Vascular access to each of four lambs was attained percutaneously from the femoral vein, and the position of the atrial septum and its defect were the heart, with the needle tip directed in a straight leftward direction, until the needle popped leftward just below the center of the anteroposterior cardiac silhouette (Figure 3). Unlike in the human heart where the left atrium is posterior, the left atrium lies at the midleft border of the lamb cardiac silhouette, with the left atrial appendage forming most of the left border. Once the septum is engaged with the Brockenbrough needle tip, a small amount of contrast (0.3 ml) is injected to confirm septal position, and the needle-sheath-dilator unit is advanced through the septum into the left atrium with a short but firm jerk. Catheter position is confirmed by both contrast injection and aspirating red blood.

Although blade septostomy will create a reasonable atrial defect acutely, we were unable to create large defects that remained patent for more than a few days using the blade catheter in lambs. Accordingly, we used two 18-mm angioplasty balloons inflated simultaneously across the atrial septum to create an atrial defect. This technique was well tolerated and resulted in large secundum atrial septal defects with smooth edges after 2–8 weeks of follow-up (Figure 4).
determined by both angiography and passage of an inflated balloon. The lambs were positioned in the anteroposterior view, allowing the septum to be aligned parallel to the radiographic beam. Device opening, fixation, and release were recorded on cineangiographic film to allow subsequent reconstruction of events surrounding placement.

**Results**

We attempted to close defects in four lambs; one of the four umbrellas was correctly positioned, but none of the defects was closed.

In the first two lambs, we passed the pod directly into the left atrium and advanced the control wire so that the umbrella arm tips were first opened in the center of the left atrium. We then retracted the umbrella against the atrial septum (one lamb) or the delivery pod (one lamb) to cause full arm extension. With the arms fully opened in the left atrium, the device was withdrawn to the left atrial side of the septum, and then the umbrella was jerked to fix the fishhooks into the septum. In both of these lambs, the most cephalad hook attached prematurely into the posterior portion of the left atrium, near the orifice of the right pulmonary veins. This hook

**FIGURE 3.** Diagram of a posteroanterior roentgenogram in a 2-month-old lamb during transseptal puncture. The atrial septum is more vertical than in humans, necessitating a steeper curve on the Brockenbrough needle, and is lower and more anterior (i.e., straight leftward) in the cardiac silhouette.
predetermined the location of all the other hooks, as it remained attached to the left atrial wall, causing the umbrella to be displaced posteriorly. Because the umbrella did not center on the septum, one of the three hooks could not be set in both cases, and the umbrella eventually became dislodged and floated free in the left atrium without causing acute hemodynamic compromise.

Based on the above experience, in the next two lambs we attempted to open the umbrella arms as close to the atrial septum as possible (e.g., 1–3 mm) while still being on the left atrial side. In one lamb, one or more arms actually opened in the right atrium, presumably because the catheter shaft itself displaced the atrial septum toward the left. Incorrect arm opening was difficult to recognize, as the septal position became quite distorted by the opened umbrella. In one lamb, the umbrella was positioned “correctly,” although the relatively small foam size in comparison to the arm diameters resulted in incomplete ASD closure.

**Transcatheter Closure of Lamb ASD With the Clamshell Double-Umbrella Occluder**

**Methods**

Based on the above noted experience, we surmised that hooked devices would suffer from several drawbacks. 1) The placement of the initial hook predetermined the placement of all subsequent hooks, thus eliminating the possibility of device
FIGURE 6. Diagram of progressive delivery of clamshell device, in which the left atrial arms are opened in midchamber, retracted against the septum so that the arms flex to a right angle position, and the right atrial arms are opened by withdrawing the long sheath.
repositioning. 2) Hooks by necessity limit the size of the foam or cloth pad that is actually used to close the defect. 3) If the foam reaches the tips of the arms, it will become enmeshed in the hooks during device loading, and the use of a safe hook-foam distance leaves little room for less-than-perfect device placement. Although the PDA double-umbrella system was designed as a plug for a tube, our prior experience using the larger-sized umbrellas to close a wide variety of intracardiac and extracardiac defects suggested an alternative approach.

A new double-umbrella device was designed to allow the arms to fold back against each other, thus using spring tension rather than hooks to fix the device on the septum. Because the tension in the arms could be manually overcome, the clam-shell configuration of the distal arms could be everted during device placement, thus creating a "cone" that would self-center and allow easy device repositioning. These performance criteria were accomplished by the placement of a second spring in the center of the 0.007-in. arms (Figure 5). With the above configuration, the need for small foam pads, centering arms, and triangular rods were eliminated, allowing the size of the pod to be reduced to 11F.

Based on our previous experience, the ASD occlusion technique was similar for all animals: animal ASDs were first sized with a balloon catheter, and device sizes were 1.5-fold to twofold the defect size. The distal arms were opened in the midleft atrium, the entire umbrella-delivery system was withdrawn until the arms were seen to flex inward, and the
umbrella was held constant as the long 11F sheath was withdrawn to allow the proximal arms to open (Figure 6). The position on the septum was noted fluoroscopically, and the device was released. As before, each lamb was positioned in the anteroposterior view, and device opening, positioning, and release were recorded with cineangiography.

Results

We attempted eight ASD closures with prototype (clamshell) occluders. The defect sizes ranged from 8 to 20 mm. Umbrella sizes were 17, 23, and 33 mm. Six of eight umbrellas were correctly positioned: one was released in the left atrium, and one in the right atrium. Each of four lambs observed for more than 1 day had what appeared to be complete ASD closure, with endothelialization of the Dacron observable after 1 and 2 months.

Two devices were incorrectly positioned. Each device embolized (to the descending thoracic aorta and pulmonary artery respectively) without producing hemodynamic instability. With the first device, the cephalad arms were seen to flex inward during device placement, although the caudal arms did not flex. The umbrella was held in that position, and the sheath was withdrawn to allow the proximal arms to open. When the device was released, it "bobbed" for a few minutes as if poorly seated and then was swept into the descending aorta. Review of the anatomy and angiograms indicate that the cephalad arms flexed against the prominent "septum" that separated the left and right common pulmonary
vein orifice in this animal, a mistake that was not recognized because the septal position was poorly defined and was not in profile. In the next animal, we placed somewhat more downward traction (to be certain that we were against the atrial septum and away from the pulmonary venous origins) on the distal arms before releasing the proximal arms. This device was also poorly seated and then swept into the pulmonary artery, where it was nonocclusive. Review of the developed angiograms indicated that just before delivery of the right atrial arms, two of the four left atrial arms popped across the septum to the right atrium. Thus, provided that atrial septal position was well defined and that a moderate amount of traction was placed during device seating, each of six devices was successfully placed. One device, which was securely positioned, did become dislodged when an angiographic catheter was seen to pass between the septum and one of the arms; even then, the device only dislodged when a long sheath was passed over the trapped catheter.

**Late Follow-up and Pathologic Observations**

Four animals were observed for periods of 3, 10, 30, and 60 days. There were no signs of cardiac disability. Each umbrella was well positioned across the atrial septum, with what appeared to be complete septal closure (Figure 7). In one defect, part of an arm straddles the septum, such that the tip of one left atrial arm could be seen from the right side of the heart. Review of the cineangiogram of the delivery and repeat cineangiography of the specimen with the umbrella in situ revealed that the arm tip migrated through the specimen some time after delivery, presumably due to too much spring tension in that arm.

Microscopically, one umbrella (from the lamb whose septum had been closed 30 days previously) was sectioned such that wedge-shaped sections were obtained from the umbrella device into the adjacent myocardium. Hematoxylin and eosin sections demonstrated that the fabric was enmeshed in fibrous tissue and fused with the myocardium. The device was, therefore, densely adherent to the atrial wall, with complete endothelialization of the surface (Figure 8). There was no histologic evidence of endocarditis or hemorrhage.

**Discussion**

These preliminary studies appear to support several tentative conclusions. 1) Although the anatomy of secundum atrial defects can be highly variable, most are located in the center of the septum, most are round or nearly so, and most are far enough from vital structures to permit transcatheter umbrella closure, provided that the cloth reaches the ends of the metal arms. 2) The use of a modified Brockenborough needle and two 18-mm angioplasty balloons in lambs more than 1 month old can produce a long-lasting, relatively large secundum atrial septal defect. 3) Although single umbrellas whose position is secured by hooks can, with experience, be correctly positioned in the mid atrial septum, incorrect placement cannot be corrected. 4) A clamshell configuration double umbrella was successfully positioned in six of eight attempts, despite unfamiliar atrial anatomy in the lamb and very little experience. 5) Healing appears complete, including endothelialization, within a few weeks of implantation.

Given our own previous experiences with initial animal trials in interventional cardiology, these results appear promising. Incorrect positioning of two devices might be averted by increased experience or slightly more robust arms. Several potential problems may reduce the clinical usefulness of this double umbrella in routine atrial septal defects; the incidences of late embolization, thrombosis formation, arrhythmias, migration of metal arms through cardiac tissue, and endocarditis will be determined only with a larger amount of clinical experience. Nonetheless, these preliminary studies appear promising and would support the institution of clinical trials.

**References**


**KEY WORDS** atrial septal defect heart defect, congenital catheterization, heart
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