Nonsurgical closure of patent ductus arteriosus: clinical application of the Rashkind PDA Occluder System

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ABSTRACT The first successful application of a transcatheter closure technique for patent ductus arteriosus (PDA) suitable for use in infants and children was performed by us in 1977. Since that time, there has been continued improvement and simplification of the equipment as well as in the implantation technique. Following a Food and Drug Administration protocol, a multicenter study was conducted to test the safety and effectiveness of this interventional method. The clinical results from three major regional test centers (Philadelphia, Houston, and New Haven) are presented. One hundred forty-six patients from a test population of 156 were treated for PDA with use of the Rashkind PDA Occluder Systems. Successful closure was accomplished in 94 (66%) of the total cases. Ten patients (7%) retained residual ductal murmurs despite correct placement of the occlusion devices; five additional patients (3%) were considered failures due to the presence of abnormal Doppler flow patterns after the procedure. Postrelease embolizations occurred in 19 (15%) instances. One patient required emergency surgical intervention after attempted retrieval of an embolized occluder. With the improvements in the manufacturing of the double-disk occluder systems as well as the perfection of the transvenous delivery technique, the incidences of closure failure and postrelease complications have decreased. Since January 1984, 78% of all transcatheter closure attempts were successful, with 10% embolization. Circulation 75, No. 3, 583-592, 1987.

TRANSCATHETER DUCTUS CLOSURE with use of the Rashkind PDA Occlusion Systems (U.S.C.I., Inc., Billerica, MA) provides an alternative to surgical correction of the lesion. The procedure is suitable for use in both pediatric and adult populations and is recommended for the nonsurgical closure of patent ductus arteriosus (PDA) alone or in combination with other cardiac lesions in patients as small as 6 to 7 kg and as young as 3 months.

In 1976, we developed a transcatheter technique for the nonsurgical closure of PDA that is suitable for use in small children and infants. Two years later, we reported the successful application of this technique in a 3.5 kg infant. Since that initial publication, efforts to improve the equipment and the implantation technique have continued. Two major achievements occurred over the past 10 years that have greatly influenced the successful course of this project. The first of these was the transition from custom-fabricated prototype equipment to premarketed machine-manufactured systems; the second factor involved the expansion of clinical trials. Three major test centers (in Philadelphia, Houston, and New Haven) collectively performed over 146 transcatheter ductus closure procedures; the Houston group alone completed 79 attempts. The overall improving success rate at the three centers supports the feasibility of the use of our transcatheter closure technique by any physician skilled in pediatric cardiac catheterization.

Methods and materials

The transcatheter ductus occluder and delivery system underwent several major design changes since 1978. Many of these were undertaken either because of problems related to the transition in production or as a result of specific complications encountered in the early clinical trials. The implantation technique was also modified to reflect the improvements and ease of handling of the equipment.

The prototype closure system consisted of a single foam disk,
hooked prosthesis connected to a pin-eye-sleeve attachment-release mechanism. Two devices were fabricated in sizes small enough for percutaneous insertion through sheaths varying in size from 5F to 8F. Since the presence of hooks limited manipulation of the prosthesis once it was extruded from the pod, and since complete occlusion of the ductus did not always occur with the single foam disk, the system was redesigned and the no-hook, double-disk system with a pin-eye-sleeve attachment-release mechanism was developed. These modifications are described in the following paragraphs.

It must be noted that the single-disk, hooked prosthesis and delivery system were custom fabricated by the Philadelphia group and are not available for current clinical use. The bulk of the experimental animal work to test the system design and the implantation technique was performed with the single-disk prosthesis. Twenty-five clinical closure procedures in the Philadelphia series were attempted with the use of these prototype single-disk devices.

Rashkind PDA Occluder System. To improve the ease of implantation and the rate of complete occlusion, a hookless, double-disk system was developed. The occluder consists of two polyurethane disks mounted on two opposing, three-arm spring assemblies, resembling two opposing umbrellas. The arms of each side are fashioned from three individual surgical steel wires wound in such a way as to create an opposing spring tension between the two umbrellas. The individual arms are attached to the central spring mechanism in such a way that the individual arms are spaced 120 degrees apart. The arms are designed so that when released from the delivery system they spring open perpendicular to the catheter shaft and thus self seat in the ductus without the need for anchoring hooks. An elliptical loop is built into the center of the more proximal umbrella to serve as a capture/attachment mechanism. Each arm has a tiny "eye" at the distal end to prevent the extended arms from perforating the vessel wall and to allow the attachment of the occluding fabric.

The occluding fabric is a small disk punched from a sheet of medical grade open-pore polyurethane foam to correspond to the diameter of the prosthesis. One disk is sewn securely onto each steel frame with the use of 7-0 cardiovascular suture material to attach the foam to each distal eye and along each arm. The standard double-disk prosthesis (figure 1) measures 12 mm in diameter. The larger occluding device measures 17 mm in diameter and is built with four slightly heavier arms but with the same opposing spring umbrella mechanism.

The delivery catheter system is illustrated in figure 2. The internal mechanism is composed of a fine central core wire enclosed in a coiled spring guide delivery wire. The distal end of the coiled delivery wire ends are welded to a small tubular "capture" sleeve. The central core wire passes through the entire length of the coiled delivery wire and exits through the sleeve. The central core wire ends in a polished b-shaped knuckle that can be retracted back into the tiny sleeve by withdrawing the proximal end of the central core wire. At the proximal end of the system the inner core wire and the outer spring delivery wire are attached to a slide-plunger mechanism that permits the inner wire to be advanced or withdrawn a finite distance so that the distal knuckle can be advanced out of the sleeve or withdrawn back into the sleeve and locked in that position by a spring T clamp that slips into a small slot on the plunger. Sliding the plunger forward, or toward the distal end of the wire, advances the knuckle out of the sleeve and visa versa.

![FIGURE 1. The 12 mm double-disk PDA occluder. On the left, in profile, a bare skeleton and on the right, a prosthesis with the foam disks attached.](image-url)
This entire delivery wire/core wire system is then contained in an 85 cm long No. 8F delivery catheter. The distal end of the delivery catheter is tipped with a thin-walled stainless steel tubular pod that is 1.7 cm long and also 8F in size. (The larger device comes with a No. 11F delivery pod on the same catheter). The proximal end of the catheter is sealed with a back-bleed gasket assembly with a side port for flushing. The delivery wire and contained core wire are 115 cm long and pass the entire length of the delivery catheter with 20 cm to spare. The small sleeve at the distal end of the delivery wire will withdraw into the pod but cannot be pulled further back into the catheter. The delivery wire may be advanced out of the catheter and pod until the proximal attach/release mechanism reaches the proximal end of the catheter. There is a locknut on the delivery wire that when tightened will prevent the delivery wire from being advanced any further out of the distal end of the catheter.

Figure 3 illustrates the attachment and loading sequence of the double-disk system. Each occluding umbrella comes with a suture passed through the three tiny “eyes” of the distal disk and in turn through the central lumen of a special Lucite loader. When the disk is pulled into the loader, it acts as a funnel to collapse the two opposing umbrellas in opposite directions and compress them so they can be drawn into the metal pod at the end of the delivery catheter.

To attach the device to the delivery system the small elliptical loop at the center of the proximal disk is placed over the extended knuckle at the end of the central core wire so that the disks are aligned perpendicular to the long axis of the catheter. The slide plunger at the proximal end of the delivery wire is withdrawn, drawing the knuckle and the encircling loop of the device into the tiny sleeve until the T clamp slides into the locking slot. The precisely machined internal diameter of the sleeve holds the loop and knuckle securely together until the T clamp is purposefully released and the plunger is advanced.

To load the device, traction is applied to the sutures passing through the opposite end of the loader from the device. This pulls the distal arms toward the loader and as more traction is applied, folds them distally into the funnel of the loader. As the device is pulled further into the loader the following proximal legs fold backward and eventually as the device is pulled all the way to the distal end of the loader, folds the device compactly enough to fit inside of the 8F pod. The pod then is advanced over the wire into the loader until it seats firmly and then the delivery wire is withdrawn from the proximal end of the catheter, in turn drawing the folded device into the pod. When the device is completely within the pod, the locknut on the delivery wire is positioned against the back-bleed gasket and tightened to keep the device in this position. The pod is withdrawn from the loader and the suture is cut and removed from the device and the system is ready for delivery.

Experimental testing. All experimental studies involving animals conformed to the guiding principles established by the American Physiologic Society. Forty-nine calves and nine swine 5 to 9 days old, were anesthetized with 30 mg/kg iv sodium pentobarbital. After a local infusion of 1% lidocaine hydrochloride, the right femoral artery was exposed, and a No. 7F standard cardiac catheter was passed retrograde across the ductus and into the pulmonary artery. (The aortic route was initially used since it provided much easier access to the ductus in the calf than the venous route.) Cineangiography was performed to confirm the size and location of the ductus. After proving the patency of the ductus, the occlusion system was introduced and advanced in the same manner, via the aorta, through the ductus and into the pulmonary artery. When the single-disk system was used, the prosthesis was extruded from the pod precisely in the ductus. The hooks were anchored into the wall of the ductus, the release mechanism was activated, and the delivery system was removed. When the double-disk system
in the vessel wall, and endothelialization began. Neither the lumen of the artery distal to the prosthesis nor those of any of the branches were affected in any manner. In the final stage of this study, 19 consecutive successful implants were performed. A typical postmortem specimen of an occluded ductus is illustrated in figure 5. The aortic (figure 5, A) and pulmonic ends (figure 5, B) of the ductus were sealed and the appearance of the prosthesis was intact. Heavy tissue ingrowth was also present (figure 5, C).

Clinical implantation. All clinical transcatheter closure procedures were conducted in accordance with the Federal Drug Administration regulations for the protection of human subjects. The candidates for closure (or their guardians) were informed of the safety and efficacy of surgical closure as well as the experimental nature of the transcatheter technique. Individual investigators were approved by their corresponding Institutional Review Boards before participating in this study.

All candidates for transcatheter ductus closure underwent routine cardiac catheterization. Patients were sedated in accordance with each test center’s catheterization protocol. General anesthesia was not used. Emphasis was placed on obtaining high-quality biplane aortograms in the posteroanterior and lateral views to clearly demonstrate the location, size, and shape of the ductus. In the true lateral view, the narrowest portion of the ductus was frequently superimposed over the tracheal shadow. (This was not the case, however, when the ductus was long, tortuous, or extremely narrow.) Initially, all patients were he-

Figure 3. Diagram of the attachment and loading sequence for the double-disk PDA occluder. The four-step process is as follows: (1) The occluder eye is placed over the pin knuckle, the slide tumbler is retracted, and the pin/eye is withdrawn and locked inside the sleeve. (2) The “forward” disk arms are compressed by gentle traction on the loading string. With continued traction on the string and using the spring guidewire to push, the attached/occluder is advanced into the narrowest portion of the Lucite loader. (3) The delivery catheter is next advanced over the spring guidewire, positioning the pod inside the loader. (4) While firm pressure is maintained on the delivery catheter, the spring guidewire is retracted and the collapsed prosthesis is “loaded” into the pod.

Figure 4. Postmortem specimen of an embolized 12 mm double-disk occluder in a swine right pulmonary artery (RPA) 2 weeks after implantation. The lumen of the RPA and those of the branches are unaffected by the presence of the prosthesis. The prosthesis is already partially covered by fine tissue matrix.
FIGURE 5. Postmortem specimen of a calf ductus 3 months after implantation. The aortic (A) and the pulmonic (B) ends of the ductus are completely sealed. A longitudinal section into the ductus (C) shows the condition of the prosthesis — the skeleton is intact and the foam matrix is incorporated into the endothelium.
parinized (50 mg/kg) before the introduction of either occlusion system. As the implantation technique was refined, however, the time required to complete the entire procedure was shortened and the routine use of heparin was discontinued.

The clinical implantation sequence for the single-disk occlusion system has been previously described.\(^1\)\(^,\)\(^3\)\(^,\)\(^4\) In all patients treated with these devices procedures were attempted transarterially, initially by cutdown and later via a percutaneous approach. The double-disk implantation sequence, as outlined in the following section, was developed to permit the percutaneous introduction of the device into either the femoral vein or the femoral artery.

Figure 6, A, outlines the transvenous implantation sequence. After placement of a percutaneous sheath, the delivery system is

![Diagram of implantation sequence](image_url)

**FIGURE 6.** Diagram of the two approaches used to place the double-disk PDA occluder. A, The transvenous implant sequence; B, the transarterial route.
introduced into the femoral vein, passed antegrade into the pulmonary artery, and manipulated across the ductus. The lateral aortogram is simultaneously projected at this time to confirm the exact location and shape of the ductus. The prosthesis is slowly extruded from the pod until the distal disk springs open in the aorta. Gentle traction is applied both to the delivery catheter and central delivery wire mechanism, retracting the system into the ductus until the distal disk ribs appear to flex or “funnel” in the ductus. The central delivery wire is held rigidly in this position as the pod is retracted and the proximal disk springs open. The device is now anchored onto both sides of the ductus. It is important at this point not to advance the central wire since any forward motion could result in an incomplete seal or possible embolization. The sleeve is retracted from the knuckle, releasing the prosthesis. All parts are withdrawn into the pod and the delivery system is removed.

For the transarterial approach (Figure 6, B) the system is introduced into the femoral artery and manipulated retrograde through the ductus into the pulmonary artery. The prosthesis is slowly extruded from the pod until the distal disk springs open in the pulmonary artery. Gentle traction is applied to the system until the distal disk firmly abuts against the pulmonic side of the ductus. The pod is then retracted from the proximal disk, which springs open either in or at the aortic end of the ductus. When the physician is convinced that the prosthesis is properly seated, the release mechanism is activated and the delivery system is removed. With either the transvenous or the transarterial technique and before removing all lines, an angiogram is recorded to confirm the location of the occluder in the ductus and the degree of occlusion of the ductus.

Portable anteroposterior and lateral chest films are obtained immediately after the patient leaves the cardiac catheterization laboratory and again the next morning. Complete bed rest is required for 10 to 12 hr. Early in the study, patients were observed in the hospital for 2 to 4 days after transcatheter ductus closure, but currently patients are discharged within 48 hr of the procedure.

Transarterial closure was attempted in 30 of the 57 patients in the Philadelphia series and in nine of the 18 patients in the Philadelphia series and in nine of the 18 patients deemed for transcatheter closure due to incomplete deployment. Postrelease embolizations occurred in 19 (13%) instances; one of these patients required emergency surgical intervention, and the others underwent elective closure of their ductus with removal of the stray device.

During the last 5 years of this investigation, several other design changes to the occluder and the delivery apparatus were implemented and tested. The Mullins sheath technique was introduced during this time and incorporated into the clinical protocol. Eighty-two ductus closure procedures were attempted between January 1984 and December 1985, after the completion of these modifications. Successful occlusion was
TABLE 1
Transcatheter closure of PDA: clinical application from July 1976 through January 1986

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<tr>
<td></td>
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<td>Incom clo</td>
<td>6 (4)</td>
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<td>Success</td>
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<td>Success</td>
<td>13</td>
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Values in parentheses indicate use of single-disk, hooked devices.

Dbl disk = double-disk prosthesis; pin & eye = pin and eye attach mechanism; knuc & eye = knuckle and eye attach mechanism; Non deliv = device unable to be delivered or implanted; Incom clo = device seated but incompletely sealed ductus.

achieved in 64 (76%) cases. Some of the patients in whom the attempt was unsuccessful underwent elective surgical ductal repair, while others have preferred to wait for a repeat nonsurgical procedure.

Clinical studies in Philadelphia. Since July 1976, 59 patients have been included in the study. No attempt was made in 10 patients. Sizing methods indicated that nine ductus were either too large or too small to close by this method. One patient experienced an episode of respiratory arrest before implantation, necessitating termination of the attempt. Twenty attempts are considered failures; there were six instances of incomplete closure, six embolized prostheses, and eight cases in which the occluder could not be seated in the ductus. Fourteen patients in this group had uneventful surgical closure of their defect. One patient in this test population required emergency surgical intervention when, during the attempted retrieval of an embolized occluder from the lung, the device became entangled in the tricuspid valve chordae. The patient was immediately transported to the operating room where the prosthesis was removed and the ductus was ligated. There was no damage to the valve apparatus. Four patients in this series are being followed clinically with residual murmurs. Twenty-nine of the 49 patients deemed suitable for transcatheter closure had complete occlusion of their ductus; 14 were successfully treated with the single-disk system and 15 with the double-disk devices. The patients ranged in age from 1 month to 17 years and their weights ranged from 2.4 to 75 kg.

Clinical studies in Houston. From July 1981 through January 1986, 79 attempts were made at transvenous occlusion of PDA. Between July 1981 and December 1983, 13 (43%) of 30 patients were successfully treated. In the group in which procedures were considered failures, seven devices embolized from the ductus, six to the lung and one to the descending aorta. From January 1984 through January 1986, 49 occlusion procedures were attempted. Successful implantation was achieved in 45 patients in this series, with complete closure in 41 (84%). Four patients retained residual murmurs; in two of these, the residual leaks were subsequently reoccluded. Two patients without residual murmurs are being followed as unsuccessful closures because of the presence of abnormal pulmonary arterial flow patterns on Doppler study. Patients’ ages ranged from 3 months to 42 years, and their weights ranged from 4.2 to 100 kg. The ductus at its narrowest diameter varied from 2 to 9 mm. Two cases of embolization occurred in this latest series.
Clinical studies in New Haven. Eighteen patients were treated between January 1984 and December 1985. In the first nine patients the procedure was by the arterial approach, with good results. With the incorporation of the Mullins technique, transvenous closure has become the method of choice. In 13 patients (72%) complete closure was achieved. One patient in this series required a second prosthesis to effect closure, the first having embolized to the left lung where it was allowed to remain. Embolization occurred in four (22%) instances. Three embolized occluders were retrieved uneventfully from the left lung, two at the time of cardiac catheterization and one during surgical ligation of the ductus. One patient has a residual murmur despite correction placement of the prosthesis in the ductus. Patients' ages ranged from 4 months to 18 years; their weights ranged from 4.3 to 80 kg.

Discussion

In most instances, surgical ligation of a PDA is a safe procedure with low morbidity and low mortality.6-8 The ability to close this defect as part of the cardiac catheterization procedure obviates the need for general anesthesia, a thoracotomy, an extended hospital stay, or a prolonged convalescent period.9-11 Nonsurgical closure of patent ductus in patients with additional cardiac lesions such as atroventricular cunnunis, subaortic stenosis, atrial septal defect, large ventricular septal defects, etc., simplifies the definitive surgical procedure. Also, there are noncardiac conditions frequently associated with PDA, such as bronchopulmonary dysplasia and respiratory distress syndrome, in which the avoidance of general anesthesia and a thoracotomy can be lifesaving.12 The transcatheter closure procedure provides an alternative for those patients with a severe psychological fear of surgery or a religious objection to the use of blood products. In general, all patients presenting with the clinical features typical of PDA are considered candidates for this procedure. Because of the size of the delivery systems, the procedure is recommended only for infants and children over 7 to 8 kg or, when the larger device is used, only for patients over 10 to 12 kg. The limiting factor for transcatheter closure is not only the size of the patient's femoral vessels relative to the size of the required delivery system, but also the difficulty in making the tighter curves through the right heart with the larger tubular sheaths.

Two obvious concerns remain regarding this technique: the risk of the embolization of occluder and residual ductal leaks. Embolization has occurred as a result of incorrect placement of the prosthesis in the ductus in cases in which the actual defect diameter exceeded the occluder size and as a result of postrelease snaring by the central wire attachment mechanism. With our current experience, these three circumstances can be eliminated. Platinum marker wires on the distal disk ribs enhance the visibility of the device under fluoroscopy and the "funneling" of the distal disk arms can be clearly seen. Larger diameter occluders (17 mm) are available to seal defects over 5 mm. The substitution of a highly polished knuckle with a stop flange on the central core wire release mechanism prevents any postrelease snagging or dislodgment of the prosthesis. These changes have reduced the incidence of embolization from 16% to 3.6% in the two centers with experience with both old and new systems.

In the event of embolization, the prosthesis can be removed, either during catheterization with a snare (multipurpose basket and multipurpose forceps; Meditech, Cooper Scientific Corporation, Watertown, MA), or surgically at the time of operative closure. As an added safety measure, the snare catheters are introduced through a large Mullins sheath to protect valvular structures during the retrieval of open-armed devices. (If neither option is possible, however, there is ample evidence from animal studies that complete endothelialization of the prosthesis would occur without significant change in the caliber of any major vessel in which it might lodge.)

The other potential complication is a residual ductal leak despite proper implantation. It is essential to open the occluder squarely in the defect. Again, the forward arm markers enhance visibility and confirm the location of the prosthesis. Maintenance of gentle traction on the central wire, especially after the prosthesis is extruded from the pod or sheath, reduces unanticipated movement and a slingshot effect during release. Should a residual leak remain after placement, our experience shows that additional devices can be used to successfully reocclude the defect. In the event of failure at repeat closure, the patient may still undergo surgical division and ligation. In fact, the greatest complication of the nonsurgical technique is that the patient could require subsequent "standard" operative repair!

In summary, the transcatheter ductus closure technique provides an alternative to surgical closure of PDA. The method described here is suitable for use in both the pediatric and adult populations and is recommended for the nonsurgical closure of ductus in infants as small as 6 to 7 kg and as young as 3 to 6 months. Any physician skilled in performing diagnostic cardiac

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catheterizations on infants or familiar with other therapeutic procedures, such as balloon atrioseptostomy and dilation angioplasty, could, with training, apply the technique safely and effectively.

References
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