

## Fast sutureless implantation of mechanical aortic valve prostheses using Nitinol attachment rings: Feasibility in acute pig experiments

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**Objective:** There is a need for fast sutureless implantation of valve prostheses with a better outcome than that of current valved stents.

**Methods:** The suture ring of a St Jude mechanical valve prosthesis (St Jude Medical, Minneapolis, Minn) was replaced by a proprietary non-stent-based attachment ring made of Nitinol memory metal (Endosmart, Stutensee, Germany) and covered with textile. In acute pig experiments, the aortic valve was removed and the device was introduced in a temporary stretched shape and activated by removing constrainers and heating to reach its final attachment shape.

**Results:** The devices could be actuated within seconds. Echocardiography showed normal prosthetic valve and heart function. No paravalvular leakage was demonstrated by supravalvular angiography. At autopsy, no abnormalities were found in the surrounding structures or valve prostheses. Pulling tests showed the strong adhesive power of Nitinol attachment rings withstanding up to 5 kg of pulling force.

**Conclusion:** Nitinol memory metal attachment rings, covered with textile, around suture ring-denuded St Jude mechanical aortic valve prostheses enabled fast and strong sutureless implantation in acute pig experiments. Further studies in chronic animal models and humans are needed to determine long-term safety.

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Some parts of the prototypes were provided by St Jude Medical (Minneapolis, Minn), Edwards Lifesciences (Irvine, Calif), and Vas-cutek-Terumo (Renfrewshire, Scotland, UK).

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Hand-suturing is the current standard of attaching a valve prosthesis to the anatomic valve annulus. However, it is time-consuming, particularly in multivalve and combined procedures, and makes minimally invasive valve surgery less favorable. Currently, there is renewed interest in sutureless valve implantation, primarily by mounting a biologic aortic valve into a metal stent and compressing it into a catheter sleeve.<sup>1-3</sup> However, with this technique the diseased valve is not removed, and current valved stents do not result in outcomes comparable to those of surgically removed and replaced heart valves.<sup>4</sup> Our intention was to test the feasibility of a sutureless Nitinol (Endosmart, Stutensee, Germany) attachment device that can be combined with any current suture ring-denuded valve prosthesis, regardless of the position in the heart and type of prosthesis, and that can attach the valve prosthesis to the anatomic valve annulus as solidly as current state of the art hand-suturing. Because durability is an important feature of most available Food and Drug Administration-approved valve prostheses, our intention was not to design a completely new heart valve prosthesis.

### Materials and Methods

#### Devices

The suture ring from standard 21-mm St Jude mechanical valve prostheses (St Jude Medical, Minneapolis, Minn) was removed and replaced by a valve attachment ring (VAR) made of Nitinol memory metal (Figures 1 and 2). This proprietary ring was sinusoidally shaped to match the aortic annulus, with a flexible upper and lower flange. The VAR was fixed around

### Abbreviations and Acronyms

VAR = valve attachment ring

the carbon housing of the bare valve prosthesis, while maintaining its full rotatability. The flanges were composed of separate finger rows that were temporarily stretched to facilitate passage of the device through the aorta and annulus. The ring was maintained in temporary shape by a low temperature and constraining devices, such as a tube or sutures around the fingers and their textile. If the ring was at its desired position, the fingers were activated to expand radially to fit the annulus between them. Actuation of the metal flanges was done by removing the constraining tools and heating. Initially the rings were used without any textile covering. However, to exclude paravalvular leakage and facilitate suture constraining, a textile covering was necessary, as was done by the first author. The development of the VAR started in 1998, and 6 generations of prototypes have been manufactured and tested from 2001 on. Initially the VAR was placed first and then the valve prosthesis was connected to it, but an integrated 1-shot device proved more efficient. The configuration and force of the flange fingers of the VAR went through a number of iterative improvements. The outer diameter of the device as tested and described was approximately 20 mm in stretched cold shape (Figure 1, A) and approximately 24 mm in expanded warm shape (Figure 1, B), whereas the height was approximately 12 mm in stretched cold state (Figure 2, A) and approximately 10 mm in expanded warm shape (Figure 2, B). The textile covering of the particular third-generation device as used in the described acute experiments was redundant, which was corrected in later prototypes and experiments.

### Applicators

Four generations of specific applicators to hold, constrain, navigate, and fire the devices were manufactured (Kiki Ingenieursgesellschaft, Malsch, Germany). The last-generation applicator consisted of 2 arms to hold and release the device, a temporary constraining tube with a tapered end that could be moved up and down to facilitate the introduction of the device, and a hollow channel with perforations at the tip of the applicator for free flow of hot or cold solution as a temperature regulator.

### Testing

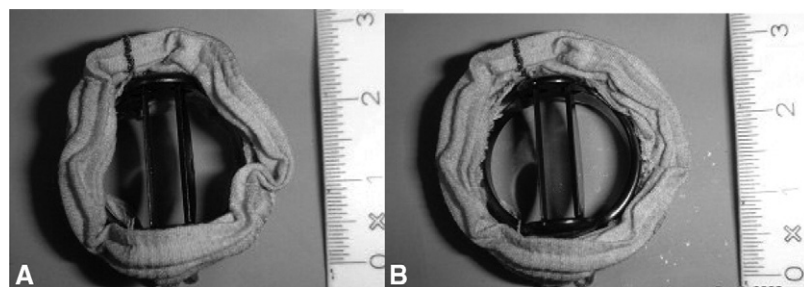
All prototypes of rings and applicators were tested extensively in ex vivo slaughterhouse pig hearts. As part of these ex vivo tests,

pulling tests with a pulling force measurement device (Force Gauge, Lutron, Taipei, Taiwan) were performed in both directions to determine detachment forces. Starting in 2001, 11 acute in vivo pig experiments were performed in 3 different animal laboratories: Dierenlaboratorium Leids Universitair Centrum (LUMC, Leiden, The Netherlands), Animal Laboratory of the Brigham and Woman's Hospital (Harvard, Boston, Mass), and Laboratorium voor Experimentele Cardiale Heelkunde (UZG, Gent, Belgium). In all experiments the animals received human care in compliance with the European Convention on Animal Care and the "Guide for the Care and Use of Laboratory Animals," as published by the US National Institutes of Health (Publication No. 85-23, revised 1996). All experiments were approved and performed in accordance with the Animal Research Ethics regulation of the institution and country where the experiments took place. The last 3 consecutive in vivo experiments, as performed in the Laboratorium voor Experimentele Cardiale Heelkunde, are described in detail.

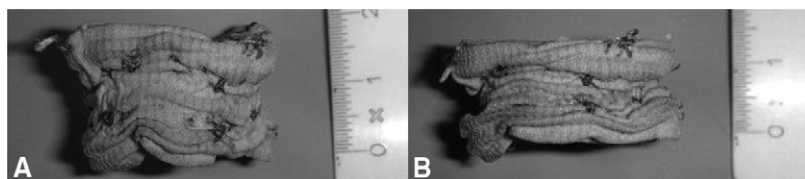
### Surgical Procedures

The VAR-valve device was prepared before the procedure. The flanges were manually stretched in ice water, and the device was placed on the applicator without a constraining tube. Sutures were fixed around the stretched textile-covered rows of the upper and lower fingers and attached proximally to the applicator.

In anesthetized and ventilated female pigs (weighing 65–85 kg), a median sternotomy was performed. After heparinization, the animal was placed on full bypass with arterial cannulation in the ascending aorta and venous cannulation in the right atrium. Left ventricular decompression was achieved, the aorta was cross-clamped, and cold St Thomas' crystalloid cardioplegia solution was administered. The aorta was completely transected a few millimeters above the valve commissures, which were retracted with sutures. The aortic valve was completely removed. A circular annular suture (2-0 Excel, Ethicon, Somerville, NJ) was placed in a rather flat plane following the aortic annulus, but below the commissures, to compensate for mismatch between the diameters of the annulus and the VAR; there was only 1 size of prototype available, and the porcine annulus diameter was variable and flexible in young pigs. Three mattress sutures with pledget (2-0 Excel, Ethicon) were placed in the middle of the sinuses and sutured through the textile covering of the upper row of fingers to guide the VAR to its desired position, because direct view in the relative small aorta was obliterated by the device and applicator. While the guiding sutures were pulled, the VAR valve was introduced into the aorta and positioned at the annular level. The constraining sutures that kept the flanges in temporary stretched position were cut and retracted, and the applicator was removed.



**Figure 1. A, Textile-covered third-generation device in stretched cold shape from below. B, Textile-covered third-generation device in expanded warm shape from below.**



**Figure 2. A, Textile-covered third-generation device in stretched cold shape from aside. B, Textile-covered third-generation device in expanded warm shape from aside.**

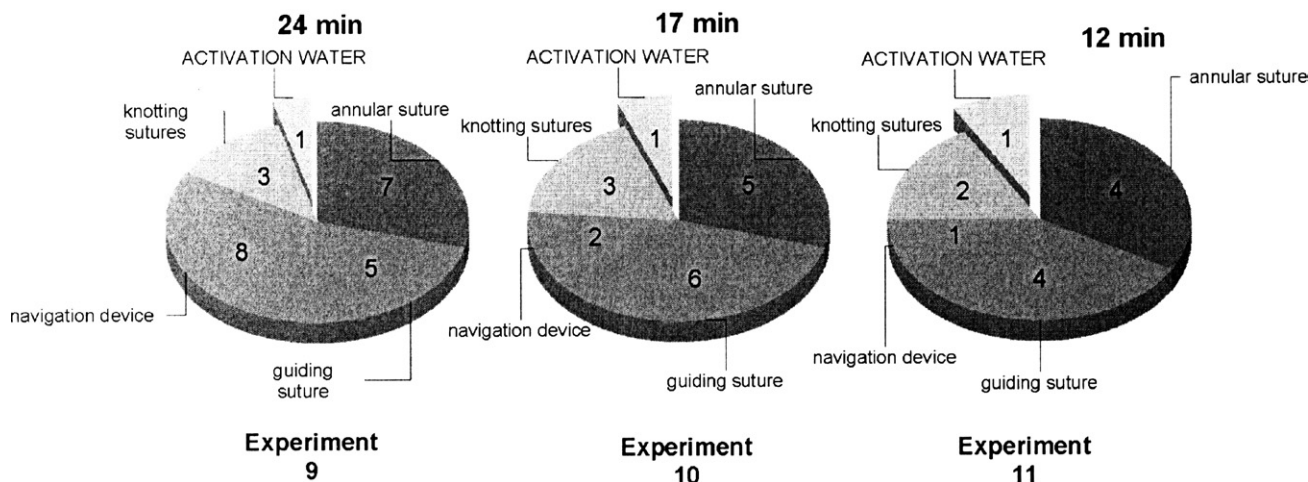
The 3 guiding sutures and the circular annular suture were tied. In these particular cases, no use was made of the fluid holes in the applicator, but the VAR was actuated with warm (45°C) physiologic salt solution that was poured in the pericardium. The aorta was closed, and the animal was weaned from bypass. A calculated dose of protamine was given.

Heart and valve function were evaluated and registered by transesophageal echocardiography before bypass, before weaning from bypass, and after bypass. After bypass, the heart was allowed to beat for another 2 to 3 hours. During this time a supravalvular angiography was performed. After this time, the animals were killed, and the heart with the ascending aorta was taken out for gross examination. The position and function of the VAR valve were determined. Paravalvular leakage was sought using 1-mm probes. Inspection for damages of surrounding structures included removal of the device.

**Results**

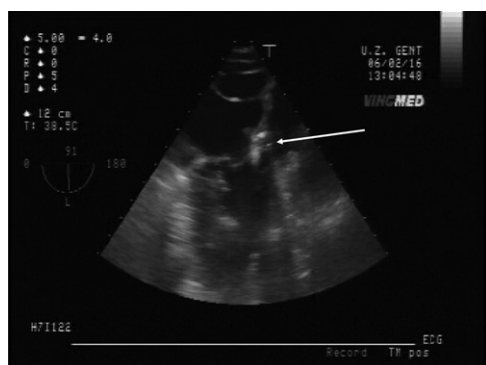
In ex vivo pig heart experiments, it was demonstrated that VAR valves actuated at the aortic annulus in the described fashion could withstand up to 5 kg (the maximum of the used force gauge) of pulling force in the direction of the ascending aorta and left ventricle. In the last 3 consecutive in vivo experiments, the VAR valves were successfully introduced into the aorta, navigated to the annulus, and actuated. Most of the operating time was consumed by closing the ascending aorta, which needed to be transected to enhance exposure. If we define valve replacement time as

the time between the removal of the valve and the closure of the aorta, we observed a 50% reduction of this time with further experience, which was 12 minutes in our last experiment (Figure 3). The time necessary for navigation and actuation of the device was approximately 2 minutes. The device actuation itself lasted less than 5 seconds. The rest of the time was spent on placement and tying the annular and guiding sutures. All animals were removed from bypass, without inotropic support, and remained hemodynamically stable for several hours until intended termination. There were no signs of ischemia or conduction abnormalities. After the procedure there were no signs of paradevice leakage, determined on the basis of diastolic systemic blood pressure, blood pressure curve, transesophageal echo (Figures 4 and 5), supravalvular angiography (Figure 6), and circumference probe of the devices at autopsy. Normal opening and closing of the valve prosthesis were confirmed by transesophageal echo, fluoroscopy, supravalvular angiography, and postmortem examination (Figures 7 and 8). In these particular cases, the textile covering was shown to be redundant; this was corrected in later prototypes. Transesophageal echo revealed no valve gradients, with normal heart contractility and normal mitral valve function. Flow velocity over the valve prosthesis was 1.5 m/sec in 2 experiments and 2.0 m/sec in 1 experiment, which was attributed to too much textile at the upper side of the VAR; this was

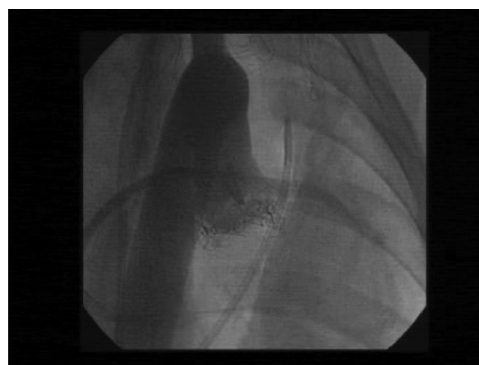


**Figure 3. Valve replacement time in last 3 cases.**





**Figure 4.** Echogram device in situ during systole. Opened valve blade (arrow).



**Figure 6.** Postoperative supravalvular angiogram.

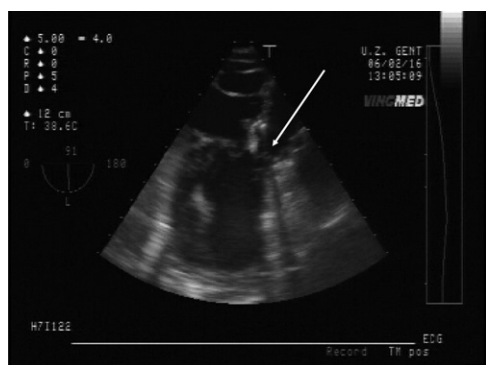
subsequently corrected. Postmortem examination showed a small hematoma at the outside and base of the ascending aorta in some cases, most likely the result of the circular annular suture. All devices were neatly situated at the aortic annulus, with unimpeded coronary ostia and without macroscopic damage to the mitral valve or other surrounding tissues.

## Conclusions

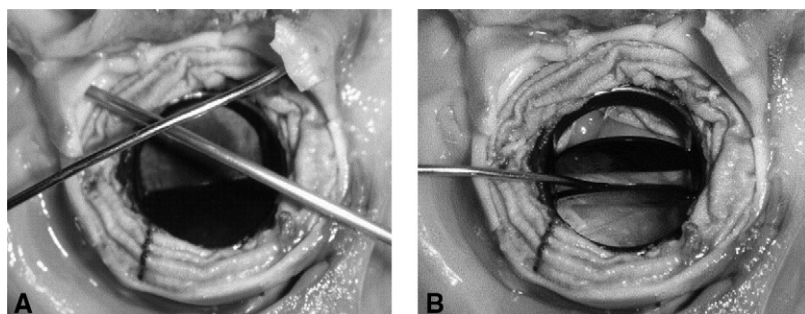
The use of Nitinol memory metal attachment rings to implant mechanical aortic valve prostheses in the acute pig model is fast and feasible. The devices and applicators are relatively easy to handle. VAR valves were firmly attached to the aortic annulus without any aortic insufficiency or stenosis. One can argue that the study was performed in pigs with healthy aortic valves, whereas the devices eventually will be used for diseased calcified aortic valves. However, we are not aware of a pig model with calcified aortic valves, and our philosophy remains that the complete removal of all diseased valve tissue in patients will lead to better results than leaving it behind. It has been reported that it is difficult to fix valved stents to the aortic valve annulus in healthy animals. In healthy pigs, it has

been reported that only 67% of valved stents introduced through the left ventricular apex were deployed successfully, whereas 78% of deployed valved stents showed some degree of paravalvular leakage.<sup>5</sup> In one third of the cases the valved stents migrated back into the left ventricle or distally into the ascending aorta.<sup>5</sup> In healthy sheep, Eltchaninoff and colleagues<sup>6</sup> decided to deploy valved stents in the descending aorta because the lack of calcium and elasticity in the sheep's aortic root can easily lead to valve migration or death. One can argue that we still used some sutures during implantation. However, these sutures were not essential for VAR-valve attachment. The circular annular suture was used to compensate for prosthetic–annular mismatch, because the diameter of the annulus varied and the annulus was flexible in the young pigs, and only 1 size VAR-valve prototype was available. The 3 guiding sutures were only used to guide the device to its desired destination and were not essential for fixation of the device. The ascending aorta of a pig is so small that after introduction of the device and applicator, direct view of the annulus is hindered. In surgically used valved stents in humans, such as the Enable valve (3F, ATS Medical Inc, Minneapolis, Minn), similar guiding sutures are used.<sup>7</sup> Further studies in the chronic animal model, and eventually in the clinical human setting, are necessary to demonstrate the feasibility and safety of the VAR devices and method in patients.

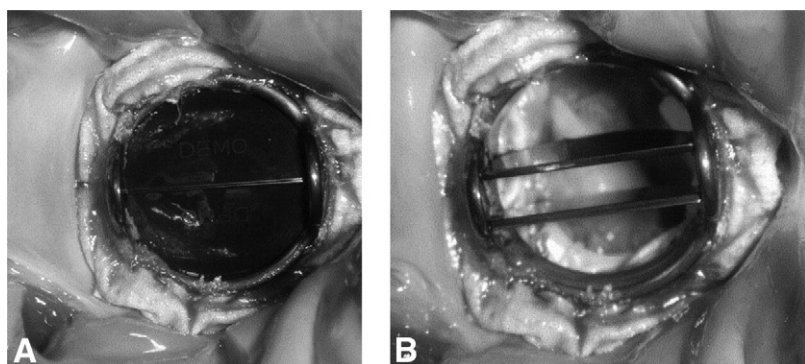
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**Figure 5.** Echogram device in situ during diastole. Closed valve blade (arrow).



**Figure 7. A, Postmortem device in situ from above, valve blades closed. Probes in coronary arteries. B, Postmortem device in situ from above, valve blades opened with probe.**



**Figure 8. A, Postmortem device in situ from below, valve blades closed. B, Postmortem device in situ from below, valve blades opened.**

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