1. Introduction

Nowadays valvular repair is currently performed for mitral regurgitation, whereas aortic valve repair remains still a surgical challenge. In another hand, aortic valve replacement leads to complications and constraints. The mechanisms that produce malcoaptation of the leaflets and cardiac valve insufficiency are mainly due to prolapsus or retraction of the leaflets. We elaborated a new strategy to correct valvular insufficiency, using the magnetic force.

2. Materials and methods

Low size permanent magnets

Given the physiological and anatomical difference between the aortic and mitral valves, construction of magnets was elaborated first for the aortic valve, in collaboration between the department of cardiovascular surgery at La Pitié-Salpêtrière Hospital in Paris (France) and the Research Group in electrodynamic – GREM3, Laplace Laboratory, in Toulouse (France) [1].

Figure 1: Drawing of the proposed concept using three magnets on the aortic valve

The magnets were fabricated by taking account on the following factors: low size permanent magnets, biocompatibility, conservation of magnetization in blood medium, mechanical flexibility of the implanted elements and possibility of sterilization. One of the main concerns was to elaborate the adapted intensity of the magnetic force, strong enough to close the valve in diastole but weak enough to allow its opening during systole in aortic valve (Figure 1). The permanent magnets used are injection molded magnets which are a composite of various types of resins and magnetic powders, making parts of complex shapes. The physical and magnetic properties of the product depend on the raw materials, but are generally lower in magnetic strength and resemble plastics in their physical properties. The composite used is the plastic composite neodyme, the physical and magnetic properties are shown on Table I [2].

Several magnetic architectures were studied and compared. Finally for the aortic valve, the magnets used in our researches are parallelepiped with dimensions of 2x1x1 mm. They were polarized in thickness according to a bipolar configuration. A central hole bored in their center allowed their suture on the raw materials, but are generally lower in magnetic strength and resemble plastics in their physical properties. The composite used is the plastic composite neodyme, the physical and magnetic properties are shown on Table I [2].

Several magnetic architectures were studied and compared. Finally for the aortic valve, the magnets used in our researches are parallelepiped with dimensions of 2x1x1 mm. They were polarized in thickness according to a bipolar configuration. A central hole bored in their center allowed their suture on the raw materials, but are generally lower in magnetic strength and resemble plastics in their physical properties. The composite used is the plastic composite neodyme, the physical and magnetic properties are shown on Table I [2].

Surgical protocol

Seven adult Alpine sheep underwent the implantation of three low size permanent magnets on the free edge of their aortic valve. A left jugular catheter was placed, and the animal was premedicated with intravenous (IV) administration of ketamine 1.0 mg/kg, atropine 0.03 mg/kg, and propofol...
4.0 mg/kg. The animal was intubated, and ventilation was maintained with a volume respirator supplemented with oxygen at 4 L/min. Anesthesia was maintained with intermittent propofol and continuous isoflurane (1.5% to 2.5%). The heart was exposed with a standard left thoracotomy through the fourth intercostal space. The pericardium was incised, and the heart was suspended in a pericardial cradle. Epicardial two-dimensional color Doppler echocardiography was used to assess the good function of the aortic native valve (no regurgitation) before the surgical procedure. In preparation for cardiopulmonary bypass (CPB), a 300 U/kg bolus of IV heparin was injected, with a target activated clotting time of 480 seconds or more. The aortic arch was cannulated with #16 Fr arterial cannulae. The right atrium was cannulated with a #32 Fr venous cannula. CPB was instituted, the ascending aorta was cross-clamped, and warm blood cardioplegia was infused into the aortic root. The ascending aorta was then opened with a transverse aortotomy above the sinotubular junction. The native tricuspid aortic valve was carefully inspected in all cases. The position of the magnets was in all case the Arrantius nodule, so what all valves were implanted with 3 magnets (one for each cusp) as shown on Figure 4. A 5/0 polypropylene suture was used to attach the magnets to the free edge of the cusps. Median time for attachment of the three magnets was less than 10 minutes in all cases. Relationship between the valve and the coronary ostia were checked. Air was purged from the ascending aorta, and the aortic cross-clamp was removed. CPB flow was decreased and then stopped if possible. Epicardial, two-dimensional color Doppler echocardiography was used to assess acute function of the aortic valve with the magnets in the beating heart (Figure 5). Aortic valve regurgitation (central or paravalvular), early device migration, and leaflet movements were observed.

The protocol for the use of the animals for this project was reviewed and approved by the board of the School of Surgery of Paris, all animals were cared for in accordance with the Principles of Laboratory Animal Care.

### Results

Seven Alpine sheep (average weight 60 kg) underwent implantation of low size permanent magnets on their aortic valve. Two sheep were unable to be weaned from CPB because of irreversible ventricular fibrillation which occurred immediately after unclamping the aorta despite multiple electric shocks and drug administration. In both cases the animal was euthanized with a ventricular injection of potassium chloride, and the heart was removed (including the ascending aorta). Transverse ventriculotomy and aortotomy were performed to expose the entire length of the outflow tract and aortic root. The three magnets were found to be in place without any injury of the aortic cusps.

In five sheep the CPB was weaned easily with a satisfactory haemodynamic. Epicardial two-dimensional color Doppler echocardiography performed before closing the chest showed in three cases traces of aortic regurgitation and in one case no regurgitation at all. One sheep died suddenly the third postoperative day of unknown cause and its necropsy revealed that one magnet was missing, the two others magnets were still sutured on their Arrantius nodule. The missing magnet was not found in the coronary arteries of the harvested heart. Four sheep survived the acute phase and were sacrified at 3 months. In these sheep, a transthoracic Doppler echocardiography was performed at the end of the second month and just before sacrifice at the end of the third month.

### Table 1: Magnetic properties of the permanent magnets

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jr</td>
<td>0.4 – 0.6 T</td>
</tr>
<tr>
<td>Intrinsic coercive field</td>
<td>600 – 660 KA.m$^{-1}$</td>
</tr>
<tr>
<td>Relative permeability</td>
<td>1.44</td>
</tr>
<tr>
<td>(BH)$_{\text{max}}$</td>
<td>32 – 48 KJ.m$^{-1}$</td>
</tr>
<tr>
<td>Coercive field</td>
<td>300 – 350 KA.m$^{-1}$</td>
</tr>
<tr>
<td>Maximum temperature of use</td>
<td>120 °C</td>
</tr>
<tr>
<td>Density</td>
<td>5400 Kg.m$^{-1}$</td>
</tr>
</tbody>
</table>

### Figure 3: View of the three permanent magnets before implantation

3. Results

Seven Alpine sheep (average weight 60 kg) underwent implantation of low size permanent magnets on their aortic valve. Two sheep were unable to be weaned from CPB because of irreversible ventricular fibrillation which occurred immediately after unclamping the aorta despite multiple electric shocks and drug administration. In both cases the animal was euthanized with a ventricular injection of potassium chloride, and the heart was removed (including the ascending aorta). Transverse ventriculotomy and aortotomy were performed to expose the entire length of the outflow tract and aortic root. The three magnets were found to be in place without any injury of the aortic cusps.

In five sheep the CPB was weaned easily with a satisfactory haemodynamic. Epicardial two-dimensional color Doppler echocardiography performed before closing the chest showed in three cases traces of aortic regurgitation and in one case no regurgitation at all. One sheep died suddenly the third postoperative day of unknown cause and its necropsy revealed that one magnet was missing, the two others magnets were still sutured on their Arrantius nodule. The missing magnet was not found in the coronary arteries of the harvested heart. Four sheep survived the acute phase and were sacrified at 3 months. In these sheep, a transthoracic Doppler echocardiography was performed at the end of the second month and just before sacrifice at the end of the third month.

### Figure 4: Surgical view of the aortic valve through the aortotomy with the three magnets (black arrows) implanted on the free edge of the cusps.
M. Laali et Coll.

Recherche

14 month. Grade 1 aortic regurgitation was found in two cases and no regurgitation at all in one case. Blood samples were also analyzed at one week, one month and three month, in order to detect blood haemolysis, which never occurred in this experimental study.

At sacrifice at three months, no sign of heart failure was detected on the four remaining sheep. In two sheep one magnet was missing on the aortic valve (Figure 6). No injury was macroscopically observed on the aortic cusps of all harvested heart. Microscopic histological exam of the aortic valve showed no lesion either, the magnets were found to be fully recovered of normal endothelium.

4. Discussion

As far as we know, this study reports the first use of low size permanent magnets on a cardiac valve. Indeed, the use of magnetic force in cardiac surgery is well known for long term mechanical assist devices (Left ventricular Assist Devices such as axial or centrifugal pumps) and was also explored in coronary artery surgery [3, 4] and percutaneous annuloplasty [5]; however, the use of magnets to increase leaflets coaptation of a cardiac valve is a totally new concept. This strategy was devised to correct valvular insufficiency, using magnetic force and this report documents the first animal studies. For these experiments small sized permanent magnets were implanted on the free edge of the aortic cusps in seven sheep under cardiopulmonary bypass. No aortic insufficiency was created in this first set of experiments.

The use of magnets in valve repair is of interest because it is different from other micromechanical methods and has several advantages: Magnets are simple and easy to use, offer the benefit of a quick and repeatable repair, and may facilitate less invasive procedures.

Given the physiological and anatomical difference between the aortic and mitral valves, we experimentally studied first the possibility of implantation the magnets on the normal aortic valve (which is less complicated compared to the mitral valve), without creating aortic insufficiency, to establish:

- Methods of fixing the magnets on the free edges of aortic cusps in order to avoid any risk of systemic embolization.
- The safeguarding of the shape of the aortic cusps in spite of the weight of the magnets sutured on their free border, studied with echocardiography (absence of aortic cusp prolapse)
- The biotolerance with the implanted magnets (absence of hemolytic reaction) without any postoperative anticoagulation treatment, tested with laboratory markers.
- The presence or absence of fibrous and/or cicatricial and/or inflammatory reactions on the aortic cusps in necropsy.

This innovating approach was found to be possible with many positive points such as: simple surgical procedure, rapidly performed (short cross clamping time), easily reproducible, well tolerated in this first short term study. However many points need also to be improved such as the attachment of the magnets to avoid systemic embolization as we reported. Currently, only one size magnet is available but a second generation of downsized magnets is currently being evaluated. Further studies should prove the viability of this concept in animals, especially with chronic implantation in long term survivors.

Limitations of the Study

The small sample size of our experiment represents an obvious limitation. The use of CPB and cardioplegia in sheep might have increased the mortality of our study but are necessary for the implantation of the magnets. The sheep model is probably not the perfect model for that kind of experiment because of the shortness and narrow diameter of the ascending aorta. However, this was primarily a feasibility study attempting to determine the advantages and disadvantages of this project.

The use of magnetic force to correct valvular insufficiency has never been reported and is an interesting field of investigation. These experiments are still at an early stage of development yet but may allow similar procedures to...
be performed percutaneously for valve insufficiency in the future. Changes in magnets design and surgical approach are indicated.  

Conflict of Interest Disclosures: none.

5. References

1. Nicolas Martinez, PhD, Pascal Leprince, MD, PhD, Bertrand Nogarede, PhD. A novel Concept of Pulsatile Magnetoactive Pump for Medical circulatory support. International Conference on Electrical Machine ICEM’08, Villamoura, Portugal, 6-9 September 2008.

which occurred