Percutaneous Heart Valves: The Emergence of a Disruptive Technology

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Introduction
Prof. Clayton Christensen, an expert in innovation management, describes the difference between a sustaining technology and a disruptive technology. A technology that improves upon existing, established technologies can be referred to as a sustaining technology. Its counterpart, the disruptive technology, describes an entirely new invention or innovation, often only impacting a small segment of the market. A disruptive technology is initially inferior in performance to a sustaining technology, however, over time the disruptive technology opens up new markets because it is cheaper, simpler, and more convenient to use. Eventually, with sufficient research and development, some disruptive technologies can overtake the sustainable technologies in performance and become dominant.

This paper will review the development of the percutaneous heart valve (PHV), a new invention that can be described as a disruptive technology to the traditional sustainable technology of surgically implanted heart valves. The PHV remains in the early stages of development, but is quickly gaining acceptance as more of these devices are successfully implanted in patients. The PHV is second line to surgery, but often exists as the only option to those that have been contra-indicated for surgery. Finally, the PHV is deployed by cardiologists in a cardiac catheterization laboratory quickly and with a shorter recovery time for the patients. In this light, the PHV is not a competitor to traditional surgery, but may eventually provide a life-saving or quality of life-enhancing option for many patients.

Traditional Heart Valve Replacement
In 1954, Charles Hufnagel and colleagues described the first effective surgical treatment of end-stage aortic insufficiency. During this landmark procedure, Hufnagel implanted a prosthetic ball valve into the aortic position without the use of circulatory support machinery. Later, with the development of circulatory support heart bypass machinery, the techniques for surgery on the arrested heart with full exposure of the valvular anatomy were developed for their repair and replacement. These advances in technology allowed the field of surgical prosthetic valve replacement to flourish. Although significant progress in replacement valve performance has been achieved through various innovative designs and the use of high tech materials, the valves themselves are still divided into two categories - mechanical or biological. The mechanical valves are longer lasting but require life-long anticoagulant treatment. The biological valves, further subdivided into bovine, porcine and human pericardial, have a shorter lifespan, but are less thrombogenic than the mechanical valves. The traditional surgically implanted heart valve is a high performance, reliable device with minimal risk in operation. The surgery itself is highly invasive and requires several days for patient recovery. In practice, however, this combination has provided surgical valve therapy with an enviable track record. In the UK Heart Valve Registry, the mortality rate for aortic valve replacement in octogenarians was only 6.6% at one month and 1% at one year. Postoperative morbidity is less well understood. As they have and continue to extend the lives of millions of people, surgically implantable heart valves remain an example of a sustainable technology.

There are, however, at least two contraindications for surgery with respect to this procedure. The first contraindication is concerning elderly people with multiple pathologies, most of whom require replacement of the aortic valve due to calcification or degeneration. Some of these patients are too ill or weak to withstand the stress of open heart surgery. The second contraindication is being young (a child or young adult), since many of these patients require heart valve replacement due to congenital heart disease. Some of these children are not treated until they are older because it is difficult to find a heart valve small enough for them, or because multiple highly invasive surgeries will be required to replace the valve as they grow. Additionally, replacement of the pulmonary valve has not been seen as necessary enough to justify the risk of surgery. The PHV seeks to provide an option for these patient classes.

Percutaneous Heart Valve Design & Delivery
The strength of the percutaneous heart valve in its ability to be delivered into position through the vascular system. In addition, unlike in traditional open heart surgery, the heart does not need to be arrested during the deployment of the PHV. The procedure is conducted entirely without the use of a bypass pump. Access to the heart is achieved using traditional cardiac catheterization techniques. A small incision is made and the valve is delivered to the heart in an anterograde fashion via the femoral vein or retrograde via the femoral artery. The PHV crimped inside a catheter is threaded along a guidewire under fluoroscopic guidance into the correct intracardiac position. Finally, the PHV is expanded from the collapsed state to its final diameter.
The first successful implant of a PHV in the aortic position was described by Dr. Cribier in 2002. Dr. Cribier was treating a patient with aortic stenosis due to calcification. The valve deployed by Dr. Cribier was comprised of equine pericardium leaflets, mounted on a 14 mm x 23 mm steel stent. This valve was also crimped onto a balloon and delivered through a 24F sheath.

More recently, Drs. Grube and Laborde implanted a valve designed by CoreValve to replace the aortic valve in patients with severe aortic stenosis. This valve also uses a bovine pericardial valve sutured into the stent. However, the uniqueness of this valve is the use of Nitinol for the stent material. Nitinol allows for a self-expanding valve, removing the need for balloon expansion, and ensuring that the valve is deployed in a more controlled fashion. In addition, the 5 cm long stent is shaped with a non-uniform diameter which provides better anchoring.

Bonhoeffer is leading the field with respect to the number of human patients that have received the new device. Over the last five years, Bonhoeffer has implanted 81 valves in 75 patients with a 98% success rate. The implantation of this valve has resulted in a decrease in the transvalvular gradient from 39 mmHg to 21 mmHg. In addition, the valve helped greatly reduce pulmonary insufficiency, which resulted in a decrease in the right ventricular end-diastolic volume, and an increase in the left ventricular end-diastolic volume. Practically, metabolic exercise testing results were greatly improved for these patients. Cribier attempted implantation in six patients, but succeeded in only five. The pros-thetic valve immediately increased the aortic valve area from 0.5 to 1.70 cm², and reduced the transvalvular gradient from 38 mmHg to 5.6 mmHg. CoreValve has recently received approval for a European clinical trial involving 20 patients.

Feasibility

The future of percutaneous valve repair and replacement depends on the development of collapsible and compressible valves and stents for delivery and deployment, advances in biomaterials, anti-calcification treatment, and innovative valve to stent bonding technologies. An ideal valve for percutaneous placement should be available in a variety of sizes, biocompatible with excellent intrin-
tic properties and a low profile. Finally, the valve should maintain its properties even after being attached into an expandable stent.

Currently there remain several barriers to widespread use of percutaneous heart valve replacement. First, the unanswered question of durability and longevity of the valves remains. Second, the fundamental aspect of this technology - that it be inserted in a peripheral vein or artery - places certain limitations on the application of this technique in young and small patients as well as patients with either too small or too large outflow tracts. For example, based on the current device designs, the selection of patients for percutaneous pulmonic valve replacement is limited to patients older than five years with a weight greater than 20 kg. Currently, percutaneously inserted aortic valves are inserted within the centre of a pre-dilated resident stenotic valve. In order to perform a true replacement, however, the diseased valve must be aminated and removed.

There is also much uncertainty as to the timing of pulmonary valve replacement in pulmonary valve (PV) regurgitation. It is possible that if the PV is replaced early enough, the right ventricular (RV) dilation and dysfunction may be reversible. Data to support decision making in this clinical situation, however, is not yet available and will be required to progress in this area. Currently, percutaneously inserted aortic valves are inserted within the centre of a pre-dilated resident stenotic valve. In order to perform a true replacement, however, the diseased valve must be aminated and removed.

Finally, the area that has the potential for the greatest advances in percutaneous valve technology is medical imaging. The surgeons’ ability to view the surgical site directly with their own eyes remains their greatest advantage. In contrast, percutaneous implantation must use medical imaging technology to substitute for direct observation. Currently, percutaneous implantation relies on fluoroscopic visualization of the calcified valve plane as a reference mark for deployment. Other non-calcific valve lesions may well require more than radiographic imaging. Kehne et al. reported successful deployment guidance of stents in valve positions by live magnetic resonance imaging techniques, and others have experimented with intracardiac echocardiography. It is clear that in order to make these procedures safe and effective, cardiologists, surgeons, and interventional radiologists must partner with the leaders in the imaging industry to develop better and more realistic imaging modalities.

With technology rapidly advancing, interest in percutaneous valves has sparked several companies to design and develop percutaneous aortic and pulmonic valves. Table 1 outlines the companies currently working in this area and briefly describes their technology.

**Conclusions**

Although surgical treatment of the diseased heart valve has proven to be the ultimate curative approach for these patients, the extraordinary advancements in the era of interventional cardiology have given clinicians the chance to pursue treatment options for certain diseases that previously had only surgical solutions. In the case of percutaneous heart valve replacement, the emergence of a disruptive technology has already begun to make an impact in patients that are contraindicated for surgery. With quickly advancing developments in valve materials, delivery systems, image guidance and further animal experimentation, the use of percutaneous heart valves promises to make the transition from a disruptive technology to one that is sustainable.

**Table 1**

<table>
<thead>
<tr>
<th>Company</th>
<th>Technology</th>
<th>Valve Position</th>
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<tbody>
<tr>
<td>Edwards Lifesciences</td>
<td>Balloon-expandable valve stent made of equine pericardium and stainless steel</td>
<td>Aortic</td>
</tr>
<tr>
<td>Medtronic Corporation/ NuMed Inc.</td>
<td>Balloon expandable valve stent composed of bovine jugular vein and platinum/iridium</td>
<td>Pulmonic</td>
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<tr>
<td>CoreValve</td>
<td>Self-expandable valve made of tissue and nitinol</td>
<td>Aortic</td>
</tr>
<tr>
<td>Shelhigh Inc.</td>
<td>Self-expandable valve made of porcine valve and nitinol</td>
<td>Pulmonic</td>
</tr>
<tr>
<td>Cook Inc.</td>
<td>Self-expandable valve made of small intestinal submucosa of pigs and nitinol</td>
<td>Pulmonic</td>
</tr>
<tr>
<td>Palmaz/Bailey’s</td>
<td>Self-expandable valve made of nitinol membrane and nitinol stent</td>
<td>Aortic</td>
</tr>
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References