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Original Article

Innovation in Interventional Cardiology

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THE FIELD OF PAEDIATRIC PERCUTANEOUS CARDIAC interventions owes its beginning to the innovations introduced by the pioneering work of many individuals, from many countries, who recognized that the heart and vessels were not above instrumentation using catheters and devices for imaging. As the supporting technology and clinical understanding of the basic physiology and disease processes has evolved, paediatric interventionalists are increasingly able to make accurate diagnosis with subsequent intervention that effects the desired hemodynamic and anatomical change.

The history of cardiac catheterization began in Germany in 1929, where Forsmann placed a catheter in his own antecubital vein with the intent of safely injecting drugs into the heart.[1,2] Subsequently, in Cuba, in 1937, Castellanos and colleagues, who were interested in congenital lesions, were able to visualize cardiac structures using radiographic contrast injected through a peripheral vein.[3] In the 1940s Cournand and Richards, in the United States of America, pursued investigations on congenital cardiac disease, cardiac and pulmonary disorders, as well as basic cardiac physiology. They were also responsible for the increasing clinical use of cardiac catheterization. For this work Cournand, Richards and Forssmann were awarded the Nobel Prize for Physiology or Medicine in 1956 and Castellanos was nominated twice for the same honour in 1959 and 1960 (Fig. 1).[4]

Many other contributors helped to cement the role of diagnostic cardiac catheterization and angiography in the clinical study of congenital and acquired cardiac disease. It should be remembered that in these early days, the distinction between specialties such as 'cardiology' or 'radiology' or 'paediatric' or 'adult' were blurred. However, by the 1960s, the differentiation between specialties began to evolve based on the advances in surgery and imaging that differentiated between congenital cardiac disease and the effects of disease of the coronary arteries on cardiac performance. The dawn of non-surgical cardiac interventions and the differentiation between interventional cardiology for adults and paediatric interventional cardiology had arrived.

Although there were earlier, isolated, attempts to treat forms of congenital cardiac disease with percutaneous techniques, it was not until 1966 when the balloon atrial septostomy, described by Rashkind and Miller, marked "the true beginning of pediatric and adult interventional cardiology".[5] Another crucial innovation occurred when Mason Sones, then director of Pediatric Cardiology at the Cleveland Clinic, serendipitously discovered that direct injections into the coronary arteries were clinically tolerated,[6,7] Subsequently, in part from the impetus derived from the experience with the balloon septostomy and building on the experience of Mason Sones[6,7] adult cardiology, in the sense of coronary arterial disease, was revolutionized. Based on the work of Dotter and Judkins, Grüntzig and

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'Muralismo' is a Mexican art movement of the XX century that reflected the historical, social and political climate prevalent in Mexico in the decades following the Mexican Revolution. Medicine was an important subject of artistic exploration because it encapsulated the political and social views of some of the muralists who shared the conviction that health was "a fundamental right of man". One of the most famous muralists was Diego Rivera who in 1944, painted a large fresco, for the Instituto Nacional de Cardiología in Mexico City. The large mural portrays the history of cardiology in two panels. The first depicts those that helped define the shape and function of the heart and circulatory system. The second was dedicated to those that expanded the practice of cardiology by the introduction of new techniques for diagnosis and treatment. At the feet of both murals, there are depictions of traditional healing methods including images of African and Pre-Columbian Mexican healers practicing their craft. As a reflection of their important contributions to the development of cardiology, Rivera portrayed Maude Abbott and Agustín Castellanos in the second mural. Abbott was the only woman so honored and Castellanos the only Latin American. Ultimately, the choice and placement of these images emphasized Rivera's ideology as to the "essential role of the indigenous races as the founders of the modern world" and the rejection of an exclusively masculine and Western viewpoint.

(Reference: Una mirada a la historia de la cardiología: Los frescos de Diego Rivera en el Instituto Nacional de Cardiología. Enrique Soto Pérez de Celis. Elementos 65, 2007, pp. 13-20)

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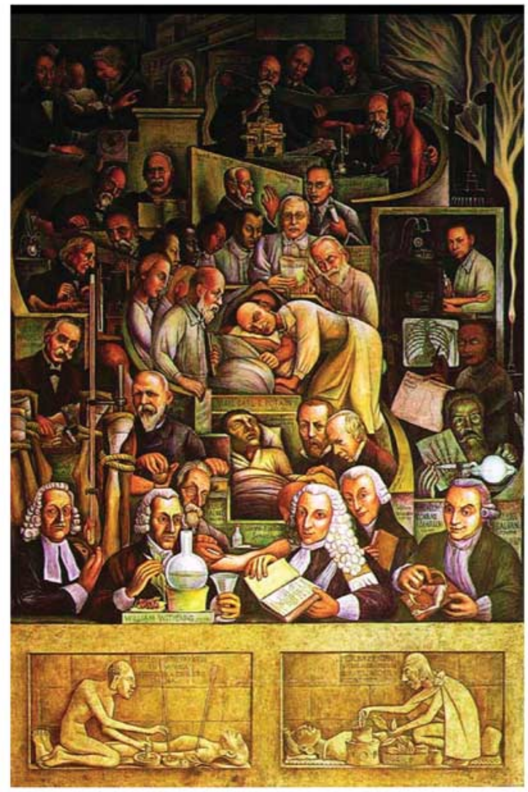

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Figure 1.
Muralismo and its Connection to the History of Cardiology.

Hopff used balloons to dilate peripheral vessels, and in September 1977, Grüntzig used the procedure to dilate coronary arteries as well.[6,8,9] This experience stimulated the now 'paediatric cardiologists' to apply this technique to stenotic vessels associated with congenital cardiac disease.[7] On the other hand, the treatment of stenotic cardiac valves remained exclusively in the domain of the cardiac surgeon. However, in 1982, Kan and colleagues further advanced the use of technology with balloons by reporting the successful dilation of the pulmonary valve with a balloon.[10] In a sense, dilation with balloons of both cardiac valves and vessels began the current era of 'paediatric interventional cardiology'. In a brief period of time dilation with balloons became the procedure of choice for paediatric cardiologists in the treatment of several congenital cardiac malformations that include stenosis of the pulmonary and aortic valves, stenosis of the branches of the pulmonary arteries, native and recurrent coarctation of the aorta, and other miscellaneous lesions.[11–15]

In parallel with the evolution of technology with balloons with the intent to 'repair' congenital cardiac defects, innovative pioneers developed techniques to intervene on some of the more common cardiac defects. In 1967, Porstmann and colleagues described a technique, using an "Ivalon plug" to close patent arterial ducts. Unfortunately, this technique required a large system of delivery, making its use in children cumbersome.[16] In a similar vein, Rashkind and colleagues developed an 'umbrella' device to close patent arterial ducts.[17] Like the plug developed by Porstmann, the original iteration of the device developed by Rashkind and colleagues had mechanical disadvantages that prevented this device from achieving widespread use. With further modifications, the 'Rashkind "PDA" device' became commonly used throughout the world for closure of the patent arterial duct, but not in the United States of America, where it never received approval for marketing and utilization.[7] As with many other contributions for use in the treatment of congenital cardiac disease, Gianturco and Wallace, interventional radiologists, reported in 1975 on the use of small, stainless steel coils, initially made with strands of wool, that could be delivered through catheters and used to occlude vessels in the body.[18] Subsequently, in 1988, Perry and colleagues reported on their use for occlusion of a variety of vascular anomalies including aorto-pulmonary collaterals and Blalock-Taussig shunts.[19] Subsequently, in the early 1990s, Cambier and colleagues reported on the use of Gianturco coils in the closure of the patent arterial duct, and with the advent of the 'Amplatzer Duct Occluder' percutaneous therapy has become "standard therapy" for the treatment of the patent arterial duct.[20,21]

In 1974, King and Mills described their technique using a 'double disk' device for successful percutaneous closure of atrial septal defects.[22] Like the plug developed by Porstmann, this device, never became popular or widely used. Rashkind and colleagues further developed the concept of a double disk or 'umbrella' for percutaneous closure of atrial septal defects, but due to constraints of design, Lock and colleagues further modified the 'Rashkind "ASD" device', which was renamed the 'Clamshell "ASD" Occlusion device'. This device was used in an investigational fashion and was successful in closing a variety of smaller and moderate sized atrial septal defects.[23] Unfortunately, due to fractures in the device, it was removed from the market and further development was stopped. A variety of other devices, all based on the concept of two opposing discs, or occluder and counter-occluder, were used in a variety of investigational trials. Currently, the 'Amplatzer Septal Occluder' and the 'Gore-Helex Septal Occluder' have international approval for marketing and are routinely used for percutaneous closure of secundum atrial septal defects.[24] Of interest is that both the Amplatzer and Helex devices utilize 'Nitinol' in their framework. 'Nitinol' is a shape memory alloy that can be deformed and returns to its original shape when unconstrained. This allows the delivery of the device through smaller sheaths. The name 'Nitinol' is derived from 'Nickel Titanium Naval Ordnance Laboratory' where the metal alloy was developed.[25] The same approach and family of devices have been used for the percutaneous closure of ventricular septal defects. At this time, CardioSEAL, which is a further modification of the 'Lock Clamshell' device, and the 'Amplatzer Muscular "VSD" Occluder', have international approval for use in the closure of muscular defects in the ventricular septum, which otherwise are difficult to approach from a surgical perspective. Outside of the United States of America, the 'Amplatzer Membranous "VSD" Occluder' has been used for percutaneous closure of perimembranous ventricular septal defects as well. However, there is reason for concern in the use for this specific indication because of the seemingly increased rate of developing complete atrioventricular block after closure of perimembranous ventricular septal defects in the cardiac catheterization laboratory.[26]

There is one final bit of 'history' to review. Once again it illustrates the convergence of multiple disciplines and serendipity to solve vexing problems involving the vascular system. With the advent of dilation of vessels with balloons, it quickly became obvious that some lesions were not amenable to intervention due to the 'rebound' effect with re-stenosis. In 1978, at a meeting in New Orleans, Grüntzig described the limitations of angioplasty with balloons. In the audience, an interventional radiologist by the name of Julio Palmaz was inspired and ultimately developed the solution: a stent, or internal scaffolding, delivered by a catheter and typically made from metal in a 'slotted tube' and designed to maintain patency. According to Palmaz, the inspiration came from the metal lathe used by masons to hold plaster on the walls of a home.[27] Subsequently, Mullins and colleagues, familiar with this work, were among the first to recognize that the "Palmaz" stent could be safely applied to children with vascular stenotic lesions that were not satisfactorily treated by either surgery, or intervention with a balloon only. In 1993, O'Laughlin and colleagues from Houston and Boston reported their medium term experience with the implantation of endovascular stents in a total of eighty-five patients, predominantly in the pulmonary arterial branches. They concluded that treatment with stents of vascular stenoses in congenital cardiac disease remained effective and offered a "much improved outlook" over previous techniques.[28] Subsequent experience has confirmed the value of implantation of stents to treat a variety of cardiovascular diseases including stenting of the arterial duct in lesions with ductal dependency, stenting of obstructions of systemic veins, as well as the more 'traditional' stenting of stenoses of pulmonary and systemic arteries.[29,30]

The future brings new and exciting areas of innovation, which includes the implantation of pulmonary percutaneous valves. Two of the investigational devices currently under evaluation are the "Melody" (Medtronic, United States of America) and the "Sapien THV" (Edwards Lifesciences, United States of America) valved stents. Both are bioprostheses with the valve mounted inside of a stent and delivered over a combined balloon and sheath. The "Melody" valve prosthesis has the most extensive investigational experience in children. It was developed by Philipp Bonhoeffer and it includes a bovine jugular vein as the valvar element of the prosthesis. It is most commonly used in patients with surgically repaired Tetralogy of Fallot, and typically with a conduit from the right ventricle to the pulmonary artery. The "Sapien THV", made from bovine pericardium, has been adapted from the

Table 1.

Interventional Therapy as Procedure of Choice
1. Dynamic and static balloon atrial septostomy, in all age groups.
2. Stenosis of the pulmonary valve, in all age groups.
3. Stenosis of the aortic valve, particularly in neonates and children without significant aortic regurgitation.
4. Recurrent coarctation of the aorta. In the older age groups, this technique may include implantation of a stent as well.
5. Stenosis of the peripheral or branch pulmonary arteries. This technique may include the use of cutting balloons and/or stents.
6. Closure of the patent arterial duct, in older infants and children.
7. Closure of coronary arterial fistulas, in selected patients.
8. Closure of important aorto-pulmonary collaterals, in selected patients.
9. Closure of decompressing venous collaterals in patients after a superior cavopulmonary anastomosis or "Glenn procedure".
10. Closure of secundum atrial septal defects.
11. Closure of muscular ventricular septal defects, in a patient considered to be high risk for surgery.
12. Closure of a patent oval foramen, in a patient with documented paradoxical embolization.

experience in adults with disease of the aortic valve, and has recently started clinical trials for implantation in the congenital cardiac patients, with similar indications as the "Melody" prosthesis. The most common indication for placement of a percutaneous valvar prosthesis is stenosis of a conduit from the right ventricle to the pulmonary artery in a patient with one of the following problems:

- Isolated right ventricular hypertension,
- Isolated significant pulmonary regurgitation,
- Combined right ventricular hypertension and significant pulmonary regurgitation.

There are limitations associated with use of these devices in children, which at the moment are in a state of evolution as clinical trials continue. Probably the most important issue is that of the longevity of the valve. All bioprostheses degrade over time, and the currently available devices are made from biological tissue. Unfortunately this question remains unanswered, since long term follow up is not yet available. Another concern includes the size and age of the patient, since the combined valved stent and balloon require a large system of delivery. Fractures of the stents have been noted, as well as compression of a coronary artery by the increased diameter of the conduit after implantation. The clinical trials to date suggest that with increased experience and careful selection of patients, procedural complications will decrease.[31,32]

In conclusion, treatment of cardiac disorders found in children is no longer the exclusive domain of the cardiac surgeons. Innovation in therapy utilizing catheters has broadened the available therapeutic options to the point that many lesions are now treated in the cardiac catheterization laboratory (Tables 1 and 2). As technology and understanding advances, it may become possible, in the interventional cardiac catheterization suite, to palliate, or even 'repair', many more cardiac lesions that affect children.

Table 2.

Interventional Therapy as an Alternative to Surgery
1. Treatment of 'native' coarctation of the aorta with either dilatation with a balloon and/or implantation of a stent.
2. Closure of perimembranous ventricular septal defect.
3. Stent implantation in the arterial duct as an alternative to surgical creation of a systemic-to-pulmonary artery shunt.
4. Stent implantation in the atrial septum to maintain an interatrial communication, in selected patients.

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