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Mini-Review

Mechanical Factors Necessitating Pacemaker Implantation after Transcatheter Aortic Valve Replacement

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ABSTRACT

Complications of Transcatheter Aortic Valve Replacement (TAVR) often result in a need for subsequent permanent pacemaker implantation. However, the risk factors for delayed pacemaker implantation remain unclear. Characteristics of TAVR prostheses and aortic root anatomy determine their mechanical relationships, which might damage the conduction bundle. At present, it is believed that the continuous compression of surrounding tissues by Self-Expandable Valves (SEV) after implantation is one of the main mechanisms of delayed pacemaker implantation. Exploring the mechanical sequelae of implantation might provide a basis for future predictions. This article summarizes and discusses current literature regarding the mechanical sequelae of TAVR.

Keywords: Transcatheter aortic valve replacement; Self-expandable valve; Pacemaker implantation; Mechanical stress

INTRODUCTION

Permanent Pacemaker Implantation (PPMI) is often required after Transcatheter Aortic Valve Replacement (TAVR) due to complications [1,2]. Permanent left bundle branch block developed in approximately 22.7% of patients undergoing TAVR and 5.9%-32.0% of them require PPMI [3]. Pacemaker implantation not only increases the economic burden of patients and the length of hospital stays but might also increase mortality rates [4].

The need for delayed PPMI after TAVR has recently increased, which might be attributed to early discharge and post-discharge surveillance [5]. The complications of TAVR can result in syncope and occur outside the hospital, which could be fatal for elderly patients. However, predicting the need for delayed PPMI is challenging, and associated risk factors are unknown. Current literature suggests that persistent compression of surrounding tissues by Self-Expandable Valves (SEVs) might be a key factor driving the need for PPMI.

LITERATURE REVIEW

The main mechanism of conduction bundle injury after TAVR may be related to the anatomical proximity of the atrioventricular conduction system to the structures under the aortic valve. Pressure damage to the conduction system after valve implantation can cause tissue inflammation, edema, or ischemia [6]. It is a key complication of TAVR that requires management with PPMI. Therefore, investigating the mechanisms associated with mechanical pressure is crucial.

Direct measurement of stress around valve implants is challenging. Research has chiefly focused on the anatomical evaluation of the aortic root through imaging, physical characteristics of the valve stent, and preoperative prediction of the pressure exerted by the stent on the aortic root and left ventricular outflow tract through Finite Element Analysis (FEA). FEA is a modern mathematical and computer modeling method widely used in the development of medical devices. It enables an in-depth analysis of the interaction forces between tissues and implants [7,8]. Two TAVR modeling methods are currently based on FEA. One is universal and based on the average aortic root geometry of numerous patients or on simplified aortic root geometry with a complex structure [9,10]. The second involves three-dimensional reconstruction of an aortic root model of a single patient using Computed Tomography (CT) or Magnetic Resonance Imaging (MRI). In this method, the anatomical model, obtained using MRI or CT, combined with the characteristics of the memory-metal used in the prosthesis, can simulate and predict the TAVR procedure through computer simulation [11].

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Finite element analysis has revealed uneven distribution of forces on tissues surrounding implanted valves and that this depends on the anatomical characteristics of the aortic root and size and shape of the SEVs [12]. Analysis of the forces exerted by the valve frame in 12 patients showed that the median combined force of the valve frame under squeezing flow was 74.9 N. Furthermore, the force (average, 9.9 N) was usually the greatest on the lowest part of the valve frame [13]. That study also showed that the pressure distribution and shape of the valve holder after implantation of bicuspid aortic valves were different from those after implantation of tricuspid aortic valves, with the site of the maximum force being higher. This could explain why the probability of undergoing PPMI after TAVR is lower among patients implanted with bicuspid valves than those with tricuspid valves [14].

Prostheses are often larger than the aortic annulus of patients to ensure prosthetic valves are riveted and the occurrence of perivalvular leakage is reduced in clinical practice. Therefore, the valve frame often does not expand to its original size after TAVR [15]. A study *in vitro* has confirmed that the radial expansion of prosthetic valves is approximately related linearly to the amount of compression [16].

The distribution of forces on surrounding tissues after SEV implantation is uneven [12]. Compression of the interventricular septum between the right coronary sinus and the non-coronary sinus, where the left bundle branch or His bundle is located, is most likely to cause conduction bundle damage [17]. The interventricular septum is often considered a vulnerable area, and FEA findings have shown that increased pressure on this vulnerable area significantly increases the probability that a patient will require future pacemaker implantation [18,19].

DISCUSSION

The complications of TAVR that drive the need for PPMI chiefly involve pressure-related damage to the conduction bundle. Furthermore, continuous compression of the surrounding tissues by SEVs were thought to be one of the reasons for delayed PPMI. Studying the magnitude and distribution of these forces can provide a deeper understanding of the causes of tissue damage and help to develop suitable countermeasures, including valve design and implantation strategies.

The main modality of research in this field is FEA simulation. It is non-invasive and can preoperatively predict complications of TAVR. However, the simulation parameters of FEA include only the anatomical morphology of the aortic root, calcification, and memory-metal properties, and it cannot effectively evaluate valve thickening, adhesion, and fusion. The actual depth of valve implantation during TAVR and the degree and effect of balloon dilation before and after valve implantation are also difficult to predict. Therefore, the accuracy of FEA in predicting the shape of the valve frame is limited, which further affects its accuracy in predicting force distribution. The prediction of delayed PPMI through FEA may requires a more accurate mechanical analysis, which may partially explain the paucity of reports regarding this aspect. The limited use of FEA might be attributed to the need for technical expertise, which is associated with increased labor, time, and economic costs.

We had previously found that the ratio of the postprocedural aortic valve area to preprocedural area (AVA ratio) and ratio of the postprocedural Aortic Valve Area to Prosthetic Nominal Area (AVA-PNA ratio) are related to the risk of pacemaker implantation and potentially to its timing [20]. The post- to preprocedural AVA ratio reflects the extent to which tissues are squeezed between the prosthetic valve holder and the aortic wall after prosthesis is implanted. A higher ratio indicates that the prosthetic valve holder squeezes more and increases pressure on the aortic wall and left ventricular outflow tract. The AVA-PNA ratio is an estimate of the relative expansion of the prosthetic valve holder, with a smaller AVA-PNA ratio indicating greater compression of the surrounding tissues by the prosthesis.

We previously used both AVA and AVA-PNA ratios to evaluate mechanical stress induced by prostheses. The AVA ratio estimates the expansion of aortic valve tissue due to the prosthesis, whereas the AVA-PNA ratio reflects deformation of the prosthesis under compression. These parameters enable simple and cost-effective evaluation of forces, but cannot accurately evaluate force magnitude or distribution.

We subsequently used postoperative fluoroscopic SEV images to measure and calculate compression ratios at different sites of the valve frame (unpublished findings). We compared the SEV compression ratios at the same location relative to the annulus. The results revealed significant differences in sites near the annular plane and supravalvular structures between patients requiring PPMI or not, and that higher rates of compression were associated with PPMI. The compression ratio is also associated with the timing of PPMI. This method can more appropriately quantify compression ratios at different sites corresponding to the force magnitude. It can also indicate force distribution more accurately when combined with images from different projection angles and thus has potential clinical value.

Information provided by fluoroscopic images of the valve frame is not limited to the compression ratio. The overall shape of the valve frame and diamond lattice, as well as subtle deformations of the metal wire reflect force magnitude and direction. This information is not easy to acquire solely by manual means. The application of artificial intelligence to the medical field has rapidly developed, mostly due to its ability to recognize and analyze images. Artificial intelligence might help to analyze the shape of an implanted valve frame, provide complete information regarding its forces, and enable quantitative analyses of its association with conduction bundle damage and subsequent PPMI.

CONCLUSION

An accurate analysis of forces induced by a prosthesis and patient susceptibility factors, such as right bundle branch block, might help in more precise prediction of the likelihood of delayed PPMI. Mechanical damage is the main complication of TAVR that leads to a need for PPMI. Measuring and analyzing the mechanical sequelae of TAVR can enhance understanding of the relationships between prosthetic implants and human tissues, help predict the occurrence of associated complications, and provide a basis for future problem-solving.

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