Re-creation of a sinuslike graft expansion in Bentall procedure reduces stress at the coronary button anastomoses: A finite element study

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Objective: The Bentall procedure is routinely performed using a straight Dacron graft coupled with a mechanical or a biologic valve. Creation of coronary ostia buttons significantly reduces tension on the coronary anastomoses and consequently the incidence of pseudoaneurysm formation. We sought to evaluate if the use of a specifically designed graft with a sinuslike root portion that bulges out upon pressurization can reduce stress on coronary anastomoses. A finite element computer-assisted stress analysis was used to simulate these 2 different anatomic conditions and to analyze tension in computed tomographic scans obtained from patients operated on with either a straight or a "sinus" graft.

Methods: Theoretical models of the procedures with finite element computer-aided design technique were created and tested with the Abaqus Standard Suite, verifying the pattern of stress and strain when a uniform pressure of 200 mm Hg was applied to the model. Next, using SimpleWare SCanIP technology, computed tomographic scans of patients having both procedures were used to obtain finite element mesh models. A uniform pressure of 200 mm Hg was then applied, and the distribution of stress and strain was analyzed.

Results: Von Mises Charts are color-coded, computational, 3-dimensional stress-pattern graphics that show that stress around the coronary ostia in a standard straight graft model is nearly double compared with the model with sinuses (peak stress of 0.4 Mpa for the sinus model and 0.7 Mpa for the traditional straight model). In computed tomographic scan reconstructions, the stress contour is uniformly distributed in the graft with sinuses, and it is highly concentrated around the ostia in the straight graft. Accordingly, higher-peak stress values are registered in the straight configuration (1.8 MPa for the sinus graft and 2.5 MPa for standard graft).

Conclusion: Even though finite elements technique is necessarily a simplification of a real biologic environment, all tests seem to indicate that a standard tubular graft gives a higher stress to coronary sutures. Relieving the stress on the coronary anastomoses by using a graft with preformed sinuses of Valsalva may decrease the incidence of postoperative complications such as bleeding and late pseudoaneurysm formation.

The Bentall procedure is the standard surgical approach in case of aneurysmal dilatation of the ascending aorta of any cause, associated with a diseased aortic valve. Since the original surgical description by Bentall and De Bono in 1968,¹ it has undergone a series of technical and technological modification that have greatly improved the results in terms of operative mortality and long-term survival. In fact, creation of valved conduits has simplified and expedited the procedure²; introduction of protein-coated Dacron graft have eliminated need for preclotting and reduced bleeding³; and finally, wider use of the coronary button⁴ over the inclusion technique has reduced not only operative blood loss but also the incidence of late pseudoaneurysm formation.⁵ Mobilization of coronary ostia is in fact of paramount importance in

reducing the risk of torsion or tension at the level of the coronary–Dacron graft anastomoses.

The Valsalva graft (Vascutek Terumo, Renfrewshire, UK) was recently introduced into the clinical arena with the objective to obtain a better anatomic, and possibly functional, reconstruction of the aortic root.⁶ It is a standard Dacron conduit that incorporates a short segment of the same material with corrugations oriented at 90° angle to the corrugations of the rest of the graft. This segment, called the "skirt," has a length equal to the graft diameter and has a compliance of about 30% with respect to the rest of the graft (its diameter increases by 30% once pressurized). The suture joining these 2 sections of Dacron acts as a new sinotubular junction. A small collar at the bottom of the skirt sustains a prosthetic aortic valve (Figure 1).

Besides being currently used in valve-sparing aortic procedure, where it helps the anatomic reconstruction of the shape and function of the sinuses of Valsalva,⁷ its use is increasing in the Bentall procedure. In association with either biologic or mechanical valves, its peculiar design improves the graft's adaptability at the coronary button anastomoses. In fact, bulging of the skirt of the graft, either during suturing

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Abbreviations and Acronyms

CAD	=	computer-aided design
CT	=	computed tomographic
FE	=	finite element

or at the time of graft pressurization, reduces the distance with the coronary buttons and appears to contribute to a further decrease of tension at this level.⁸

By using finite element (FE) study, we attempted to evaluate the amount of stress at the level of the coronary anastomoses with or without neosinuses of Valsalva. This information should help to better define the optimal amount of graft bulging and the best positioning of the coronary ostia with respect to the graft curvature. It might also indicate that a standard straight graft might not be the best choice for Bentall procedure.

MATERIAL AND METHODS

FE analysis is a mathematical method that evolved in the late 1950s for structural analysis in the aerospace industry. Researchers have since adopted the FE method as a standard numerical technique for analyzing complex structures and solving problems in solid and fluid mechanics. In an FE analysis, the object under study is divided into small finite segments known as elements, which are interconnected by common points, known as nodes. This enables the use of algebraic equations to describe the individual structural state at each node. The solution of the system of equations yields the displacement, stress, and strain at any point in the entire object.

FE analysis has been widely used to mimic particular anatomic conditions especially related to aortic root or mitral valve surgery.⁹⁻¹¹

To model a given structure using FE analysis, 3 key inputs must be specified: the model geometry, the material properties, and the boundary conditions that describe how the model is attached and interacts with its surroundings.

First, the geometry of theoretical simplified aortic root–coronary artery assemblies were defined with Autocad 2005 then imported in Simpleware ScanCad-ScanFE (Simpleware, Exeter, UK) suite to obtain meshed shell models. We started from a 30-mm-diameter cylindrical model mimicking the aorta, with a 90° connection to a smaller cylindrical structure mimicking the coronary artery. Subsequently, we simulated a progressive increase in diameter of the lower third of the cylinder mimicking the sinuses of Valsalva, in sequential steps of 4-mm increments while keeping constant the base of the cylinder representing the aortic annulus and the upper portion of the cylinder realizing the sinotubular junction. We therefore obtained 6 different models, which we used to test the behavior of the junction between coronary artery ostia and the respective sinus of Valsalva.

Second, the geometry of the natural aortic root–coronary artery of healthy living patients as well as those of patients having Bentall procedure either with a standard straight or a Valsalva graft were obtained with high-definition electrocardiogram-triggered computed tomographic (CT) spiral scan, then converted via Simpleware ScanIP-ScanFE into meshed shell models. Because assemblies of triangular shell elements are well suited to reproduce curved geometries, we selected the 6-node triangular shell element to take advantage of its capacity for better describing triaxial stress and strain variation. CT and magnetic resonance imaging (MRI) derived models offer great accuracy. In previous benchmark models using the same elements at similar density as in the present root model, stresses, strains, and displacements had a numerical accuracy within less than 0.5%, which is very good approximation to the real world.^{11,12} Our theoretical models of sinus and standard

FIGURE 1. The Valsalva graft consists of a standard Dacron tube attached to a lower section (*skirt*) of a Dacron tube that expands circumferentially. The collar offers a tubular portion for proper suturing of the valve prosthesis and the patient's annulus (courtesy of Vascutek Terumo, Renfrewshire, UK).

straight root replacements used 2500 and 2000 elements, respectively. However, actual CT scan–derived human models of sinus and standard grafts used 4500 and 4000 elements, respectively.

Third, the material properties were derived from biomechanical studies as largely utilized by other authors on similar studies: the material properties of human tissues were calculated from published stress-strain data,¹³⁻¹⁵ and the surgical graft (polyethylene terephthalate) was assumed to be isotropic with a Poisson ratio of 0.3, elastic modulus of 7800 kPa (based on the range of stiffness reported in the literature), with fabric thickness of 0.305 mm and a crimp angle of 40°.¹⁶⁻¹⁸

Fourth, we imposed only 1 boundary condition, at the level of the aortic valve annulus, to which we gave proprieties of “encastre,” which allows no displacement of the chosen portion on any axis ($X = Y = Z = 0$); this simulates the rigid, noncompliant artificial valve ring. This was a simplification of the real condition where each segment of the aorta has relations with other structures. However, as shown by several FE model of traumatic aortic rupture, the main boundaries are the aortic annulus, the epiaortic arteries, and the isthmus.¹⁹ The second and third boundaries (neck arteries and isthmus) were excluded from the model being very far in relative terms from the coronary–aortic sinus junction and thus were likely to be uninfluential.

FIGURE 2. Von Mises charts of computer-aided design generated 3-dimensional meshed models of aortic root–coronary artery assemblies, showing changes in stress pattern when the model configuration was progressively changed from a standard straight conduit (*top, left*) to conduits with a progressively increased sinus portion (*bottom, right*). Pressure was maintained constant at 200 mm Hg.

Our FE model was developed with the use of ABAQUS software (version 6.5; Simulia, Providence, RI). The pressure-loading pattern was simplified to linearly increasing pressurization until systolic aortic pressure level. The graft were considered to be filled by saline solution delivering uniform pressure on tubular structures, which is a simplification of the real world where blood, with its peculiar content in proteins and figured elements, actually circulates. We focused the observation on the effects of pressure on the wall of vessels. The models were solved by iteratively dividing the pressure-loading phases into a number of equal steps (100 in total). We obtained a dynamic time-related sequence of stress patterns, one for each step. All data refer to the last step, corresponding to the highest pressure value. We sequentially applied 100, 150, and 200 mm Hg of pressure. Because the stress pattern remained the same in all environments, we will refer to the 200 mm Hg data only. The output fields were analyzed through ABAQUS embedded viewer. Von Mises charts are commonly used to synoptically and clearly show the results; they show a color-code pattern of stress where the increasing stress is indicated by a progressive change from the spectrum of blue to the spectrum of red.

Model validation still lacks experimental evidence as no actual technique routinely used in clinical practice allows measurements of tensions at the coronary button suture line.

RESULTS

The Von Mises charts of the theoretical model experiments are sequentially shown in Figure 2. In a straight cylindrical, 30-mm graft, there was definitely high tension on the coronary–aortic junction, as the orange-yellow zone clearly indicates. This equaled 0.6 to 0.7 MPa. An evident tension line was also present from that point along the longitudinal axis of the graft. When the model was modified to create a sinus portion with a maximum horizontal diameter of 34 mm (about 13% increase in diameter), there was a significant re-

duction in the extension of the stress. The zone of higher stress was smaller and the peak of stress did not exceed 0.6 MPa. A tension line was still visible along the graft long axis. When the sinus portion was increased to a maximum diameter of 38 mm (26% increase in diameter), the peak tension fell to 0.5 MPa and was quite equally distributed in a circular area around the coronary–aortic junction suture. With a further 4-mm increase in diameter (corresponding to a 40% increase in diameter), the peak tension remained around 0.4 to 0.5 MPa and was similarly distributed in a circular area. Any further increase in sinus portion (maximum diameter of 46 mm and 50 mm, corresponding to a 53% and 67% increase in diameter, respectively) modified the direction of the tension line, which became horizontal following the prevalent dimension of the aortic root with peak stress progressively increasing from 0.4 to 0.6 MPa (Table 1).

TABLE 1. Peak stress around coronary ostia in computer-aided design–derived models

Skirt diameter (mm)	% Increment in root diameter from baseline	Peak stress around coronary ostia (MPa)
30	0 (straight conduit)	0.70
34	13	0.61
38	26	0.50
42	40	0.45
46	53	0.53
50	67	0.61

FIGURE 3. Von Mises charts of computed tomographic scan–derived actual aortic root–coronary artery assemblies, showing stress pattern in normal individuals (*left*) and in patients having a Bentall procedure with a standards straight conduit (*center*) or a Valsalva conduit (*right*). Both frontal and lateral views of the coronary–root junction are shown.

Collaterally, we observed that as the dimension of the sinus portion increased, the sinotubular junction became a major node of stress, exceeding the value of 3 MPa in the last model. This, however, raised no concern as in the surgical situation the above-mentioned portion was an all-Dacron component further reinforced by machine suturing at the moment of manufacturing, thus able to sustain far greater stress than the delicate hand-sewn coronary anastomoses.

CT scan reconstructions from normal individuals and from patients having Bentall procedure with a standard or a Valsalva graft are shown in Figure 3. In the normal, healthy individual (Figure 3, *left*), lateral and frontal views showed a smooth progression from the sinus portion into the coronary arteries with a computed peak stress of 1.7 MPa. On the other hand, patients having Bentall procedure with a straight graft (Figure 3, *center*) showed a nearly 90° angle between the Dacron graft and the coronary artery (clearly visible in the lateral view). Although the angle looks smoother than in the computer-aided design (CAD) model, as the coronary ostia themselves generate some grade of gradual transition, the amount of stress was highly concentrated around the ostia, and as predicted by the CAD model was also spread along the longitudinal axis of the conduit with a peak stress of 2.5 MPa. Finally, patients having Bentall procedure with a Valsalva conduit (Figure 3, *right*) showed a stress pattern more similar to normal individuals. In fact, with a sinus portion of the graft expanding between 25% and 30% of its original diameter, the lateral view of the

graft showed a smooth transition from the sinus portion into the main body of the coronary arteries. Frontal view of the coronary anastomoses showed a circular stress equally distributed around the whole anastomoses with a peak stress never exceeding 1.8 MPa (Table 2).

A simple direct comparison among the 2 configurations indicates that coronary ostia sutured to a straight Dacron graft had to sustain a 40% higher stress compared with coronary ostia sutured to a Valsalva graft.

Note that all computed peak stress levels were far higher (between 1.7 and 2.5 MPa) in the CT scan reconstruction than in CAD models (between 0.4 and 0.8 MPa). This was probably due to the completely smooth interface between the pipes in the CAD models; in real-world CT-scan models, the geometry of the connection is far more complex. Anyhow, the stress patterns remained the same, and comparison in absolute values of MPa should only be done within the same set of experiments, either CAD- or CT-derived models.

TABLE 2. Peak stress around coronary ostia in computed tomographic scan-derived models

Computed tomographic model	Peak stress around coronary ostia (MPa)	Stress increment over native aorta (%)
Native aorta	1.68	—
Bentall with straight graft	2.5	+49
Bentall with Valsalva graft	1.80	+7

DISCUSSION

Intraoperative bleeding has been a major problem in the first years after the Bentall procedure was introduced into surgical practice. Various technical surgical details as well as modification of the original technique were proposed to deal with such potential problems.⁴ Complete mobilization of the coronary ostia as well as the availability of coated graft greatly contributed to facilitate and expedite surgery drastically improving overall results. Nevertheless, the problem of tension at the level of coronary anastomoses has still been reported on several occasions. Neveux and colleagues²⁰ have proposed a special Dacron tongue extension in case of low-lying coronary ostia, although others advocate a peculiar technique for widely separated coronary arteries.²¹ Westaby and colleagues²² have proposed a pericardial patch extension to avoid tension on the right coronary button; Svensson and colleagues²³ in a review on composite valve long-term results have concluded that the Cabrol technique was a good choice for reoperation on the aortic root. In fact, the Cabrol technique, which was the first technique specifically described to deal with problem related to coronary ostia anastomoses, is still considered an optimal option whenever there are difficulties in mobilizing the coronary ostia. Besides a large amount of literature testifying that the problem of tension at the level of coronary anastomoses is still the cause of a certain morbidity, it is obvious that the problem is more evident every time we face rigid and calcific coronary ostia or when they are difficult to mobilize because of strong adhesion or diffuse tissue fibrosis. In all these cases, the chance of having a certain degree of tension around the coronary ostia anastomoses are higher and so are the risk of bleeding in the perioperative period or the incidence of late pseudoaneurysm formation.²⁴ For all these reasons, it is evident that a Dacron graft that would somehow reduce the distance between the coronary button and the corresponding holes in the Dacron graft would decrease the tension and therefore the overall morbidity. In this study, we demonstrated that the presence of a spherical root section is important not only to facilitate and expedite coronary ostia anastomoses but also to reduce or abolish any condition of undue tension at this level. Furthermore, FE studies have helped to establish the amount of root sinus curvature that optimizes the degree of tension. In fact, a 26% to 40% increase in diameter at the level of the root with respect to the standard diameter of the graft was found to be the optimal amount of curvature in guaranteeing tension-free coronary anastomoses.

Another important aspect is that as the radius of curvature of the sinus portion increases, so does the stress at the level of the new ST junction (ie, where the sinus bulge ends and the cylindrical portion of the Dacron graft begins). It can be hypothesized that the stress is progressively transferred from the coronary ostia sutures to the ST junction. Because

the new ST junction is a synthetic structure made of 2 portions of Dacron strongly sutured together (Figure 1), the stress has obviously no effect on the patient's tissues.

It must also be said that this neo-ST junction seems to represent an new hinge point where all the dynamic stress of the movement of the graft is concentrated. In fact, when the heart resumes its beating at the end of a Bentall procedure with the "Valsalva" graft, it can be clearly seen that the new aortic root follows the heart movement by bending at the level of the neo-Dacron ST junction, preventing any friction or pull and release effect at the level of coronary ostia anastomoses. On the other hand, with a standard, simple, straight valved conduit, all the movement of the heart that is transferred to the aorta can have its hinge points in the coronary ostia with an increased risk for a dynamic stress. In summary, it is possible that the coronary ostia sutured to a straight graft have to withstand not only increased static stress, as shown by the present study, but also increased dynamic stress through the cardiac cycle. This phenomenon is also highly dependent on the shape and lengths of the ascending aorta and of the graft, so making the graft too long can have a major impact. Anyhow, the fibrous tissue growing quickly into the interstices of the Dacron graft in time will firmly hold the graft, making the phenomenon less evident.

This experimental study indicates that composite grafts with a root sinus portion might be beneficial in reducing the risk of tension at the level of coronary anastomoses in the Bentall procedure. By filling the space previously occupied by the aortic root aneurysm and at the same time by optimizing the angle of coronary buttons–Dacron anastomoses, this sinus portion effectively prevents undue stress at this critical surgical site. For the same reasons, a standard straight Dacron composite conduit might not represent the optimal choice for Bentall procedure.

This study demonstrates that it is possible to effectively decrease the tension at the level of coronary anastomoses by modifying the Dacron graft design. How this will reflect in a diminution of bleeding problems or in a reduced incidence of pseudoaneurysm formation warrants further clinical data.

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