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On the way to the optimal design of an aortic heart valve -or- discovering the obvious?

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The irst task of tissue engineer trying to make a scaffold of a heart valve is to adopt some model of a heart valve to establish target geometries and properties that should be recreated in the artificial scaffold. The natural way to do so is to conduct literature research and find the current scientific consensus on the topic. Here the problems start, each researcher seems to have an individual opinion about the optimal geometry of valve. What makes the situation more complicated is that each researcher has carefully chosen arguments to explain why that particular design is better than others. Hence, the consensus is not there yet; we decided to contribute to this discussion. The analysis of available reports enables to "cook out" 2 distinguishable and to some extent contrary hypothesis.

1st the optimal architecture of artificial valve is an architecture of native one (Professor Sir Magdi Yacoub).

2nd there is not such a thing as optimal architecture of a heart valve, and never will be.

The first option is very tempting due to its simplicity. Of course, in most of the human beings, the valves work fine for entire life so let's make the same structure for the sick patient. But which one? – Mine or yours? Maybe we should make an average from 1000 or million healthily examples? Hypothetically, if you would need a new face, would you like to have the "median" appearance or you rather would go for the most beautiful one? Let's take it further: what is an optimal design of human face? Perhaps one would wish to get the most beautiful face possible while others would opt for a younger variant of their old one. When it comes to faces, it is easy to distinguish beautiful from average and ugly. Using our internal standards, we are doing this every day hundreds of times. But valves are usually not visible, so do we need to work out the standard of "beauty" for HV. Frequently, clinicians and researchers seem to use the same face-related-internal standards to propose geometries of the scaffold: "I like this more than that because it follows better my internal and visual standards of HV beauty". But this is not the way to go. We need hard core evidence to distinguish structure that is better than the other.
The second option is more radical than the first one. Each patient needs individually chosen the design of the heart valve that will reflect its particular needs and conditions. It is certainly very elegant but horribly expensive solution since an individualized scaffold not only needs to be designed but also produced only in few copies.

The consensus of both strategies is in our opinion the establishing the most "beautiful HV" but according to objective physical parameters. What additionally supports this logic is that the scaffold, under physiological condition, will adjust to the patient by changing the geometries.
To confirm our observation and conclusion we contacted prominent clinicians and tissue engineers with question:

What is an optimal design of aortic heart valve?

In this report we are presenting their responses and comments.

The responses are presented in order in which they were received.

Dr. Piotr Wilczek, Zbigniew Religa Foundation of the Cardiac Surgery Development in Zabrze, Poland
The change of valve's shape is a result of changes in heart geometry due to its illness. Therefore, it is not enough to bring back the native shape of the valve, because the changes in geometry and tension occur in whole heart muscle. The optimal shape should guarantee possibly widest aortic valve area; it should not generate additional tensions, energy dissipation, etc. To obtain the optimal shape of the heart valve, we close into personalized medicine. Due to the production of small series of valves it is a costly approach, but like in all technologies - there is always a compromise between costs and an optimal product. It rarely goes together. However considering the 3D printing method development, in several years, creating a customized valve may not be a problem. Of course, there is a known method of creating pericardial heart valves, which is a simplified, but cost efficient way of prostheses' personalization (…). (Due to poster size limitations the answer was shortened, the full answer is available online in supporting materials)

Dr. Zbigniew Nawrat Director of the Institute of Heart Prosthesis FRK, adjunct in the Department of Cardiac Surgery, Medical University of Silesia
natural aortal valve has a spherical shape (e.g., Chong model) and is working properly due to unique construction properties of the leaflets (collagen and elastin). It is malpractice to use a similar shape and different material, e.g. polyurethane. It was proved by Prof. Helmut Reul from Aachen roughly 30 years ago.

Prof. Ziyad M Hijazi, MD, Professor of Pediatrics, Weill Cornell Medicine Chair, Department of Pediatrics, Director, Sidra Cardiovascular Center of Excellence, Editor-in-Chief, Journal of Structural Heart Disease, Sidra Medical and Research Center
The optimal shape is similar to their own native valve. Of course, their own valve now is diseased and not a good example. However, most cardiac patients when they start complaining of symptoms may have had an echo or other imaging modalities. We should try to mimic that valve. Of course, if no data is available for this individual patient, then we should use population median valve shape as you mentioned. This can be done by evaluating thousands of patients and basically choose the average shape and take it from there.

Prof. Jarosław D. Kasprzak, MD, FESC, FACC , Professor of Medicine, Head, Chair and Department of Cardiology, Medical University of Lodz, Poland
Optimal shape is just one of the parameters of an ideal valve we should think about. As such, I would envision a valve which has a conveniently shaped ring, perhaps with adjustable shape, for easy suturing then a short height of the valve frames is important because it reduces the risk of structural interaction with cardiac structures.
Finally, the shape of the valve must allow for the lowest possible profile of opened valve leaflets (and thus maximized anatomical flow orifice) during the flow phase to reduce energy loss and turbulence generation. Streamline optimization and vortex reduction may contribute to reduced risk of thrombosis.

Assc. Prof. Henrik Bjursten M.D. Ph.D., Dept of Cardiothoracic Surgery, Anesthesia and Intensive Care, Lund University/Skane University Hospital
The optimal heart valve scaffold is the one that nature/evolution has created, as the tricuspid valve with thin leaflets ant thicker free edge works well in almost animals and humans and have done so for millions of years.

Assc. Prof. Jonathan T. Butcher, Ph.D., Associate Chair, Director of Undergraduate Studies, Nancy E. and Peter C. Meinig School of Biomedical Engineering, Cornell University
(…) Our suggestion is to conduct a comparative 3D analysis of the pulmonic and aortic roots of healthy patients so that one could extrapolate the necessary geometry for replacing the diseased aortic valve using the patients healthy pulmonic valve anatomy as a guide. One final comment is that one must consider the fact that an engineered living valve may exhibit the capacity for emergent morphological remodeling such that it arrives at the appropriate dimensions with proper hemodynamic and biochemical signaling over time. Therefore, we must balance our desire for perfect dimensions with other manufacturing limitations, or else the patient may not benefit for a long time.
(Due to poster size limitations the answer was shortened, the full answer is available online in supporting materials)

Tal Golesworthy, C Eng MEI MRSC, www.exstent.com
Assuming that no serious study has gone into a re-design of an aortic valve from basic principles (St Jude? Terumo Vascutek?), it would seem sensible to mimic the biological structure and shape of the existing aortic valve sinuses, commissures, and leaflets. This can be done relatively easily(?) from MRI/CT image conversion into CAD models and from CAD into physical models using Rapid Prototyping. If not a truly optimal design, it would at least partly preserve the hemodynamic transfer function between the LVOT and the ascending aorta. Once this process is complete, and the macro shape of the valve sinuses and leaflets is fixed, one needs to address the micro structure of the scaffold, how it will propagate and internally transfer seed cells and how it will interact with the "fully populated" cellular matrix of the various different structures within the finished valve, ie will the scaffold remain in place (as a structural component) or will it be metabolised by the living structure as a bio-re-sorbable material, and if so, how will an intracellular matrix be established to replace the mechanical structure of the scaffold.
Rapid prototyping using appropriate, bio-compatible materials would need investigating, as would scaffold structure, pore size, pore structure, pore surface bio-activation, etc.

Dr. Helmut Goldmann, Director Production Facility Melsungen Aesculap AG
In principle, I agree to the first option with some amendments. The optimal architecture of aortic heart valve scaffold is an architecture which mimics the native one in its best way. This means that the artificial valve mimics the essential, objective physical and physiological characteristics of the native one. This is not a question of beauty but of function.

Prof. Robert T. Tranquillo, Distinguished McKnight University Professor, Department of Biomedical Engineering, University of Minnesota
The optimal shape of aortic heart valve scaffold depends on the mechanical properties of the scaffold. The closer they are to native values, the closer the shape should be to the native valve. If one uses a tubular heart valve approach, then the question is moot.

Prof. Philippe Pibarot, Laval University, Québec
Well, I think the optimal valve is trileaflet with leaflet having a semi-lunar configuration just as the normal native aortic valve.
This is from a biomechanical stand-point the most robust configuration while still optimizing hemodynamic results.
Also, the valve leaflet ideally needs to be 100% biocompatible, does not require anticoagulation and highly durable.

Cemil Izgi MD, Royal Brompton and Harefield NHS Foundation Trust, Harefield, United Kingdom
In my opinion, optimal design of a scaffold for the aortic valve and/or root should follow copying the original shape as much as possible; this can be achieved with 3D modeling. Obviously, I would recommend d this only in cases in whom the aorta/valve has normal/near normal shape that I want to preserve after valve/root replacement.

Prof. Maisano Francesco, Chair of Cardiovascular Surgery, Professor of Cardiac Surgery. University Hospital Zurich
It is summarize in few words. However, it should be tridimensional, flexible and adaptable to the different interplay between aorta, mitral and LVOT.

Assc. Prof. Richard W. Bianco, Associate Professor of Surgery, Director of Experimental Surgery University of Minnesota
The most important aspect of natural aortic architecture, in my opinion, is to understand that the geometry is not circular. The shape is elliptical or oval. Designs of devices to repair or replace should consider this architecture.

Dr. Michael Scharfschwerdt, Klinik für Herz- und thorakale Gefäßchirurgie, Universitätsklinikum Schleswig-Holstein, Campus Lübeck
(…) First of all, we totally agree with your first statement. As we do some heart valve development ourselves, we have spent a lot of time to optimize cusp geometry of an aortic bioprosthesis in order to provide the best opening characteristics to reduce energy loss across the valve and achieve the best result on the base of the native aortic valve shape (...).
On the other hand, as you also stated in your abstract, what is the geometry of the native aortic valve? It is not easy to answer because the true shape of the native aortic valve is a complex one. (…). We ourselves are working on the determination of the real 3D shape from patient's echocardiographic, CT and MRI data, and it is challenging, firstly to fetch good geometrical formulas from these data and then there are a lot of individual variations. (…) Actually, we use a machine learning approach to deal with the variations and also working on alternative approaches to get the aortic valve geometry in our experimental setups especially for reconstruction in context with valve-sparing aortic procedures. Our goal is a sophisticate model for aortic valve reconstruction.
(Due to poster size limitations the answer was shortened, the full answer is available online in supporting materials)

Supporting materials avaliable at: http://albert-liberski.eu/cardiovascular-science/on-the-way-to-the-optimal-design-of-an-aortic-heart-valve-or-discovering-the-obvious/