

HYBRID HEART VALVES ADAPTED FOR POST-IMPLANT EXPANSION

[0001] This application claims the benefit of U.S. Application No. 62/188,467, filed July 2, 2015, the entire disclosure of which is incorporated by reference. This application is related to a U.S. patent application filed on June 30, 2016, titled “INTEGRATED HYBRID HEART VALVES”, the entire disclosure of which is incorporated by reference.

[0002] The present disclosure relates to a hybrid heart valve for heart valve replacement, and more particularly to modifications to the construction of surgical heart valves to enable them to receive an expandable prosthetic heart valve therein.

[0003] The heart is a hollow muscular organ having four pumping chambers separated by four heart valves: aortic, mitral (or bicuspid), tricuspid, and pulmonary. Heart valves are comprised of a dense fibrous ring known as the annulus, and leaflets or cusps attached to the annulus.

[0004] Heart valve disease is a widespread condition in which one or more of the valves of the heart fails to function properly. In a traditional valve replacement operation, the damaged leaflets are typically excised and the annulus sculpted to receive a replacement prosthetic valve.

[0005] In tissue-type valves, a whole xenograft valve (*e.g.*, porcine) or a plurality of xenograft leaflets (*e.g.*, bovine pericardium) can provide fluid occluding surfaces. Synthetic leaflets have been proposed, and thus the term “flexible leaflet valve” refers to both natural and artificial “tissue-type” valves. In a typical tissue-type valve, two or more flexible leaflets are mounted within a peripheral support structure that usually includes posts or commissures extending in the outflow direction to mimic natural fibrous commissures in the native annulus. The metallic or polymeric “support frame,” sometimes called a “wireform” or “stent,” has a plurality (typically three) of large radius cusps supporting the cusp region of the flexible leaflets (*e.g.*, either a whole xenograft valve or three separate leaflets). The ends of each pair of adjacent cusps converge somewhat asymptotically to form upstanding commissures that terminate in tips, each

extending in the opposite direction as the arcuate cusps and having a relatively smaller radius. Components of the valve are usually assembled with one or more biocompatible fabric (*e.g.*, polyester, for example, Dacron® polyethylene terephthalate (PET)) coverings, and a fabric-covered sewing ring is provided on the inflow end of the peripheral support structure.

[0006] Sometimes the need for complete valve replacement may arise after a patient has already had an earlier valve replacement for the same valve. For example, a prosthetic heart valve that was successfully implanted to replace a native valve may itself suffer damage and/or wear and tear many years after initially being implanted. Implanting the prosthetic heart valve directly within a previously-implanted prosthetic heart valve may be impractical, in part because the new prosthetic heart valve (including the support structure and valve assembly) will have to reside within the annulus of the previously-implanted heart valve, and traditional prosthetic heart valves may not be configured to easily receive such a valve-within-a-valve implantation in a manner that provides secure seating for the new valve while also having a large enough annulus within the new valve to support proper blood flow therethrough.

[0007] Some attention has been paid to the problem of implanting a new valve within an old valve. In particular, the following disclose various solutions for valve-in-valve systems: U.S. Patent Application Publication No. 2010/0076548, filed September 19, 2008; U.S. Patent No. 8,613,765, filed July 7, 2011; and International Publication No. WO 2012/018779, filed August 2, 2011. The entire disclosures of these publications are expressly incorporated herein by reference.

[0008] Despite certain advances in the valve-in-valve area, there remains a need for a prosthetic heart valve that facilitates the process while maximizing the life of the first valve and simplifying manufacturing techniques.

[0009] Embodiments of the invention provide a prosthetic heart valve configured to receive a prosthetic heart valve, such as a catheter-deployed (transcatheter) prosthetic heart valve, therein. In one embodiment, the prosthetic heart valve has a support structure that is substantially resistant to radial compression (and that may be substantially resistant to radial

expansion) when deployed in the patient's native heart valve annulus to replace the native heart valve (or to replace another prosthetic heart valve), but is configured to be radially expandable, and/or to transform to a generally expanded and/or expandable configuration, in order to receive a prosthetic heart valve therein, such as a percutaneously-delivered prosthetic heart valve. The transformation from expansion-resistant to expanded/expandable can be achieved by subjecting the expansion-resistant support structure to an outward force, such as a dilation force, which may be provided by a dilation balloon used to deploy a replacement prosthetic valve.

[0010] A prosthetic heart valve according to embodiments of the invention may further be a "hybrid" heart valve with an additional support portion in the form of a stent frame positioned at the inflow end of the prosthetic heart valve configured to plastically expand into a substantially flared shape when subjected to a dilation force that is by itself insufficient to cause expansion of the main support structure. The stent frame is positioned upstream or on the inflow end of the entire valve portion.

[0011] A first exemplary hybrid prosthetic heart valve is adapted for post-implant expansion and has an inflow end and an outflow end. A valve member includes an inner structural support stent having upstanding commissure posts extending in the outflow direction alternating with arcuate inflow cusps. The inflow end of the valve member undulates up and down corresponding to the commissure posts and cusps. The support stent defines an implant circumference that is non-compressible in normal physiological use and has a first diameter, wherein the support stent permits expansion from the first diameter to a second diameter larger than the first diameter upon application of an outward dilatory force from within the support stent substantially larger than forces associated with normal physiological use. Also, a plurality of flexible leaflets attach along the commissure posts and inflow cusps of the support stent and ensure one-way blood flow therethrough. A plastically-expandable inflow stent frame secured to and projecting from an inflow end of the support stent has a strength requiring a predetermined expansion force to convert to an expanded state. An outflow end of the stent frame undulates with peaks and valleys to at least partially conform to the inflow

end of the support stent, and wherein the outflow end has limited radially compressibility to enable compression of the stent frame during delivery of the heart valve.

[0012] The first prosthetic heart valve support stent may include a radially outer band located concentrically around and attached to a radially inner band having a single one of the expandable segments formed by overlapping free ends located at one of the cusps and separated by a sliding insert, and further including a flexible sleeve surrounding the overlapping free ends of the outer band to maintain alignment of the free ends. The single expandable segment is desirably located at one of the cusps of support the stent and the inner band is configured to expand below each of the commissure posts when the outer band expands.

[0013] A second hybrid prosthetic heart valve adapted for post-implant expansion has an inflow end and an outflow end, and a valve member including an undulating wireform with alternating cusps and commissures supporting a plurality of flexible leaflets configured to ensure one-way blood flow therethrough. A plastically-expandable inflow stent frame having a radially-expandable inflow end and an outflow end is secured to and projects from an inflow end of the wireform. The outflow end of the stent frame undulates with peaks and valleys corresponding to the wireform, and further, the outflow end includes integrated commissure posts located adjacent to and radially outward from the wireform commissures to which the leaflets attach. The outflow end defines an implant circumference with a nominal diameter that enables physiological functioning of the valve member when implanted, and the stent frame outflow end permits limited expansion from the nominal diameter to a second diameter larger than the nominal diameter upon application of an outward dilatory force from within the outflow end substantially larger than forces associated with normal physiological use.

[0014] In the second prosthetic heart valve, the stent frame is preferably configured to expand below each of the commissure posts upon application of the outward dilatory force. The integrated commissure posts may separate elements secured with sutures to the stent frame outflow end, or may be integrally formed of the same homogeneous material as the rest of the stent frame. Preferably, the stent frame includes a plurality of

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circumferential row struts connected by a series of spaced axial column struts, and includes an outflow row strut that extends continuously around a periphery of the stent frame having the peaks and valleys corresponding to the wireform, wherein the outflow row strut has a series of spaced V-shaped notches that permit limited expansion and contraction.

[0015] A third exemplary hybrid prosthetic heart valve adapted for post-implant expansion also has an inflow end and an outflow end and a valve member including an undulating wireform with alternating cusps and commissures supporting a plurality of flexible leaflets configured to ensure one-way blood flow therethrough. A plastically-expandable inflow stent frame having a radially-expandable inflow end and an outflow end is secured to and projects from an inflow end of the wireform. The outflow end of the stent frame undulates with peaks and valleys corresponding to the wireform, and further, the outflow end includes three commissure posts located adjacent to and radially outward from the wireform commissures to which the leaflets attach outside of the wireform. The three commissure posts are secured directly to an upper circumferential row of struts defining a nominal diameter that enables physiological functioning of the valve member when implanted. The upper circumferential row of struts is radially compressible to a smaller contracted diameter to enable compression of the outflow end during delivery of the heart valve, and the upper circumferential row of struts also is radially expandable from the nominal diameter to a larger expanded diameter upon application of an outward dilatory force from within the stent frame substantially larger than forces associated with normal physiological use.

[0016] In the third prosthetic heart valve, the stent frame is desirably configured to expand below each of the commissure posts upon application of the outward dilatory force. The stent frame may have a series of compression sections including spaces that enable a limited compression of the circumferential structure. Preferably, the upper circumferential row of struts extends continuously around a periphery of the stent frame having the peaks and valleys corresponding to the wireform, and the upper circumferential row of struts has a series of spaced V-shaped notches that permit limited

expansion and contraction. Also, the upper circumferential row of struts preferably has limited radially compressibility of between about 7–20% of the nominal diameter to reduce the size of the outflow end during delivery of the heart valve.

[0017] A fourth hybrid prosthetic heart valve adapted for post-implant expansion and having an inflow end and an outflow end comprises a valve member including a plurality of flexible leaflets configured to ensure one-way blood flow therethrough and a leaflet support structure defining alternating cusps and commissures to which peripheral edges of the leaflets attach. A plastically-expandable inflow stent frame secured to and projecting from an inflow end of the leaflet support structure has a strength requiring a predetermined expansion force to convert to an expanded state. The stent frame comprising a plurality of expandable struts and an upper edge at an outflow end of the stent frame that undulates with peaks and valleys to at least partially conform to the undulating leaflet support structure. The upper edge defines an implant circumference with a nominal diameter that enables physiological functioning of the valve member when implanted, wherein the upper edge is configured to expand a limited amount from the nominal diameter to an enlarged diameter larger than the nominal diameter upon application of an outward dilatory force from within the outflow end substantially larger than forces associated with normal physiological use.

[0018] The prosthetic heart valves further may include a biodegradable band disposed concentrically and in close contact with the support stent, the biodegradable band being configured to provide resistance to expansion of the support stent after implantation, which resistance lessens over time as the band degrades in the body. Consequently, the biodegradable band is configured to provide resistance to expansion of the support stent when the predetermined expansion force is applied to the radially-expandable inflow stent.

[0019] In the various prosthetic heart valves a unique identifier may be provided on the support stent or stent frame visible from outside the body after implant that identifies the support stent or stent frame outflow end as being expandable.

[0020] Other features and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings that illustrate, by way of example, the principles of the invention.

[0021] Figures 1A and 1B depict top and side views, respectively, of a support frame assembly for a hybrid prosthetic heart valve of the present application;

[0022] Figure 1C is a side view of the hybrid prosthetic heart valve of Figures 1A and 1B, with a balloon catheter expanding the expandable skirt but not expanding the main support structure portion, and Figure 1D shows the prosthetic heart valve after skirt expansion;

[0023] Figures 1E and 1F depict top and side views, respectively, of the prosthetic heart valve support structure of Figures 1A and 1B after a balloon catheter has radially expanded the main support structure portion into an expanded configuration;

[0024] Figure 2 is an exploded perspective view of an exemplary prosthetic heart valve having an inner structural band combination that permits post-implant expansion, and also includes a reinforcing band that biodegrades after implant;

[0025] Figure 3A is an elevational view of the assembled prosthetic heart valve of Figure 2 during a step of balloon-expanding an anchoring skirt, and Figure 3B is a sectional view through the prosthetic heart valve during a post-implantation procedure of expanding the first valve while implanting a secondary heart valve therewithin;

[0026] Figures 4A–4D are perspective and exploded views of an exemplary prosthetic heart valve of the prior art having inner structural bands;

[0027] Figures 5A and 5B are perspective and elevational views of a first band for an exemplary combination of structural bands that can be used in various prosthetic heart valves to enable post-implantation expansion thereof;

[0028] Figures 6A–6C are perspective and enlarged views of a second band that can be coupled with the first band of Figures 5A and 5B to form a combination of structural

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bands that can be used in various prosthetic heart valve to enable post-implantation expansion thereof;

[0029] Figure 7 is a perspective views of a combination of the structural bands in Figures 5 and 6 to enable post-implantation expansion of prosthetic heart valves;

[0030] Figure 8A is a side view of a hybrid prosthetic heart valve of the present application, while Figure 8B shows an anchoring skirt therefor with a valve member in phantom, and Figure 8C is a perspective view of the prosthetic heart valve with portions cutaway to reveal internal structural leaflet supports;

[0031] Figures 9A–9C are perspective views of an exemplary anchoring skirt for use in the hybrid prosthetic heart valve of Figures 8A–8C;

[0032] Figure 10A is an exploded perspective view of components of an alternative hybrid prosthetic heart valve, while Figure 10B shows an exemplary leaflet and wireform subassembly and an anchoring skirt and commissure post subassembly for the hybrid prosthetic heart valve;

[0033] Figures 10C and 10D show details of separate commissure posts;

[0034] Figure 11 is another exploded perspective view of subassemblies of the alternative hybrid prosthetic heart valve;

[0035] Figure 12 shows the relative positions of the anchoring skirt and commissure post subassembly and wireform for the alternative hybrid prosthetic heart valve;

[0036] Figure 13 is a perspective view of the finished hybrid prosthetic heart valve;

[0037] Figures 14A–14D are perspective, elevational, and flat plan views of an exemplary integrated frame member for use in the hybrid prosthetic heart valves disclosed herein;

[0038] Figures 15A–15D are several views of an alternative integrated frame member much like that shown in Figures 14A–14D but with commissure posts that are separated from a lower expandable frame;

[0039] Figure 16 is a perspective view of an alternative integrated frame member having an expandable frame connected to a polymer band that forms commissure posts;

[0040] Figures 17A and 17B are elevational and perspective views of an exemplary expandable frame for use in the frame member of Figure 16; and

[0041] Figure 18 is an elevational view of an integrated frame member similar to that shown in Figure 16 with the polymer band overlapping an upper edge of the expandable frame.

[0042] The prosthetic heart valves disclosed herein are “hybrid” in that they include a prosthetic valve member constructed similar to conventional surgical valves, with a relatively stable diameter that is not intended to be compressed or expanded during use after implant, and a lower expandable frame structure to help in anchoring the valve in place. Most prior valves have either a wholly non-compressible/non-expandable valve member or a wholly expandable frame structure that incorporates a valve therein. One specific commercial prosthetic heart valve that is constructed in a hybrid manner is the Edwards Intuity® valve system from Edwards Lifesciences of Irvine, CA. The hybrid Edwards Intuity® valve system comprises a surgical non-compressible/non-expandable valve member (*e.g.*, similar to a Carpentier-Edwards Magna Ease® valve) having bioprosthetic (*e.g.*, bovine pericardial) leaflets coupled to a stainless steel expandable frame structure on its inflow end.

[0043] The prosthetic heart valves described herein each include an internal (meaning incorporated into the valve member itself as opposed to being a supplemental element) structural stent or frame that is generally tubular in shape and defines a flow orifice area through which blood flows from an inflow end to an outflow end. Alternatively, the shape of the internal stent can be oval, elliptical, irregular, or any other desired shape. The valves include flexible leaflets that selectively open and close to allow for one-way fluid flow therethrough.

[0044] Various internal stents disclosed herein have “expandable segments” that enable the stent to expand. This can occur from the expandable segment rupturing,

plastically stretching, or elastically elongating. Thus, an “expandable segment” means a location on the stent that enables it to enlarge in diameter, such as when a balloon is inflated within the stent. Examples include weak points that can rupture, thinned areas that rupture or stretch, accordion-like structures that elongate elastically or plastically, breaks in the stent that are held together with a breakable member such as a suture or spot weld, and various other means. The term, “expandable segment” thus encompasses each and every one of these alternatives.

[0045] Figures 1A and 1B depict an exemplary embodiment of a “hybrid” prosthetic heart valve 20, where an upper support stent 24 of a valve member 25 is joined to a lower expandable frame structure 26. The lower frame structure 26 is radially weaker than the upper support structure 24, and is configured to flare, as seen in Figure 1B, when subjected to a radially dilating pressure such as that provided by a catheter balloon 28 such as depicted in Figure 1C. In the embodiment depicted (and seen most clearly in Figures 1C–1D), the lower frame structure 26 is covered by a skirt of material 30. The prosthetic heart valve 20 includes valve leaflets (not shown for clarity) to control blood flow. The prosthetic heart valve also has a sealing or sewing ring 32 to assist in seating the prosthetic heart valve 20 in the desired location (*e.g.*, a native valve annulus in a patient). Details on the initial deployment in a patient of the prosthetic heart valve 20 (with the upper support structure 24 in the unexpanded configuration) are set forth in U.S. Patent No. 8,308,798, filed Dec. 10, 2009; U.S. Patent No. 8,348,998, filed June 23, 2010; and U.S. Patent No. 8,641,757, filed June 23, 2011; the contents of which are expressly incorporated herein by reference.

[0046] A key feature of the “hybrid” valve embodiment of Figures 1A–1F is that the lower frame structure 26 will flare when subjected to a dilation pressure that is insufficient to cause radial expansion of the upper support structure 24, during initial deployment of the prosthetic heart valve 20 in the patient. For instance, a catheter balloon 28 may be used to achieve the required flaring of the lower frame structure 26, while still preserving the non-expanded nature of the upper support structure 24 in order to maintain the patency of the valve leaflets, as depicted in Figures 1A–1B. If the

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prosthetic heart valve 20 should fail or otherwise need replacing in the future, a balloon catheter can be introduced into the patient, and a pressure (such as 3 atmospheres or more) sufficient to radially expand the upper support structure 24 (*e.g.*, by causing a failure at a designed weakened area 36), which pressure is also higher than that required to flare the lower frame structure 26, may be applied to the prosthetic heart valve 20. With the resulting expansion, depicted in Figures 1E and 1F, the entire prosthetic heart valve 20, including the upper support structure 24 and at least an inflow end of the lower frame structure 26, are radially expanded in order to enlarge the valve orifice 34 to accommodate a new catheter-delivered prosthetic heart valve therein. Note that, post-dilation, the lower frame structure 26 may have little if any flaring, and instead has a generally constant diameter along its length, as indicated in Figure 1F.

[0047] Note also that in another embodiment, the balloon 28 may be specially shaped (such as depicted in Figures 38–40 of related U.S. Patent No. 8,641,757) so it can be positioned in such a way as to apply radially expansive pressure to the lower frame structure 26 while applying little to no radially expansive pressure to the upper support structure 24. In such an embodiment, the specially shaped balloon for radially expanding just the lower frame structure (*e.g.*, during initial implantation of the prosthetic heart valve 20) could be positioned to apply pressure only to the lower support portion. The specially shaped balloon could then be expanded to a desired pressure, such as 4–5 atmospheres, with the pressure being applied to expand the lower support portion but not being applied to the upper support portion. At a later time when it is desired to radially expand the upper support structure (*e.g.*, when it is desired to deploy a new valve within the existing valve), a much longer and cylindrical balloon can be used to expand both the upper and lower structures. For example, a cylindrical balloon could be positioned within both the upper and lower structures and inflated to between 4 and 5 atmospheres, thus radially expanding both the upper and the lower structures.

[0048] The “hybrid” type of prosthetic heart valve such as shown at 20 in Figures 1A–1F is implanted by advancing it into position at the annulus, and then inflating the balloon 28 or other mechanical expander to cause outward flaring of the lower frame

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structure 26. Although the upper support stent 24 is intended to remain with a constant diameter and only expand later if needed when implanting a second valve directly within, use of a traditional cylindrical balloon can inadvertently expand or distort the upper stent and possibly cause malfunction of the valve. Therefore, the present application contemplates a temporary reinforcing band to prevent any adverse effects to the upper stent from initial balloon expansion, as will be explained.

[0049] Figure 2 is an exploded perspective view of an exemplary “hybrid” prosthetic heart valve 40 having an inner structural band combination 42 that permits post-implant expansion, and also includes a reinforcing band 44 that biodegrades after implant. The main structural components of the heart valve 40 include a plurality of flexible leaflets 50 that are connected to and supported by a continuous undulating wireframe 52, the structural band combination 42 including an inner band 54 and an outer band 56, the reinforcing band 44, and a lower frame structure 58 or anchoring skirt adapted to be expanded once implanted. Various cloth covers and interfaces are not shown for clarity, but are typically used along with sutures to hold the parts together. Again, the flexible leaflets 50 can be a combination of separate leaflets such as bovine pericardial leaflets, or a single bioprosthetic structure such as a porcine valve. The lower frame structure 58 is preferably plastically-expandable, such as being made from a suitable plastically expandable material, for example, stainless steel or cobalt-chromium alloy (*e.g.*, Elgiloy® alloy), but may also be self-expandable in certain configurations, for example, made from nitinol.

[0050] The structural band combination 42 is desirably adapted to enable post-implant expansion, much like the embodiments described in U.S. Patent Application Publication No. 2014/0188221, filed December 20, 2013, the disclosure of which is hereby expressly incorporated by reference.. Indeed, the inner band 54 and outer band 56 are illustrated the same as those shown in Figures 6A–6B of the '221 publication, though any of the expandable band combinations can be utilized.

[0051] When the components are assembled into the valve 40, it will resemble the valve 20 shown in Figures 1A–1F, and also as seen in Figure 3A that shows the valve

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during a step of balloon-expanding the anchoring skirt or lower frame structure 58. Once again, this is essentially the same as the heart valve in the Edwards Intuity® valve system. In addition to the modification that permits post-implant expansion, the new valve 40 features the biodegradable reinforcing band 44. The band 44 may be made sufficiently thin and shaped the same as the outer band 56 so as to be almost unnoticeable in the finished product. Furthermore, various biodegradable materials are known that are routinely included in surgical implants, and thus do not introduce any problematic materials. For example, biodegradable polymers accepted for use include polyglycolide (PGA), PGA/polylactide (PLA), polydioxanone (PDS), polycaprolactone (PCL), poly(dioxanone), and PGA/trimethylene carbonate (TMC). Consequently, the modified valve 40 includes relatively small form factor changes from the valve in the Edwards Intuity® valve system.

[0052] As mentioned, Figure 3A illustrates the hybrid valve 40 isolated from the anatomy but shown at the moment of implantation in the annulus, such as the aortic annulus. The valve 40 is delivered on the distal end of a tubular shaft 60, such as a cannula or catheter. Although not shown, a valve holder may be utilized to couple the valve 40 to the shaft 60. An expansion member 62 such as a balloon is used to expand the anchoring skirt or lower frame structure 58 against the surrounding anatomy. For example, the frame structure 58 may be expanded to a flared shape as shown that generally conforms to the subvalvular terrain in the left ventricle, just below the aortic annulus. Again, the frame structure 58 is desirably plastically expandable, such as being made of stainless steel or cobalt-chromium alloy, and holds its flared shape. Alternatively, the frame structure 58 may be self-expandable, such as being made of nitinol, which spreads outward upon release and may apply an outward bias against the surrounding tissue. Also, the frame structure 58 may provide the sole means of holding the valve in place, or it may be supplemented with a small number of sutures, clips, or the like evenly distributed around a sealing ring 63 of the valve 40. In any event, the time of the implant process is greatly reduced from prior surgical implants by the elimination of up to 20 knot tying steps when just sutures are used.

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[0053] The functional portion of the valve 40 defines an orifice diameter d that is relatively stable by virtue of the structural band combination 42, and the valve is intended to function for many years without problem. However, as mentioned, occasionally the valve 40 develops issues such as calcification, which reduces its effectiveness. This process may take decades, but eventually a re-operation to fix the valve may become necessary. The modified valve 40 is designed to enable direct expansion of a replacement valve within its orifice, the expansion widening the valve 40 without the need to explant it.

[0054] Figure 3B thus shows a sectional view through the prosthetic heart valve 40 during a post-implantation procedure of implanting a secondary heart valve 64 therewithin. The secondary heart valve 64 is typically delivered on the distal end of a balloon catheter 66 having a balloon 68 around which a plastically-expandable stent 70 of the secondary valve is crimped. One specific valve of this type is the Sapien® valve sold by Edwards Lifesciences. If the primary valve 40 is implanted in the aortic annulus, the delivery shown is retrograde typically using a transfemoral access procedure, though an antegrade transapical procedure is also contemplated in which case the delivery catheter 66 would be shown entering the valve 40 from the opposite end. Such valves are also known as “transcatheter” valves as they typically are introduced from the end of a catheter.

[0055] The strength of the balloon 68 expansion force is sufficient to not only expand the secondary valve 64 outward into contact with the inside of the primary valve 40, but also to outwardly expand the primary valve. As mentioned with reference to Figure 2, the reinforcing band 44 degrades over time, perhaps after 6 months to a year after implant. Consequently, the inner structural band combination 42 remains to hold the circular shape of the valve 40. Due to the expandable character of the structural band combination 42, however, the balloon 68 can cause it to outwardly expand to a larger diameter D as shown in Figure 3B. Additionally, as stated elsewhere herein, any of the structural band configurations disclosed in the '221 publication may be utilized or modified for use as the particular structural band combination 42. Preferably the

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secondary valve 64 expands to have an orifice diameter that matches the original orifice diameter d of the primary valve 40, which may mean a total outward expansion of the primary valve of about 2–4 mm, equivalent to one or two valve sizes at 2-mm increments. Preferably, the flow orifice defined by the secondary valve 64 is at least equal to the flow orifice of the primary valve 40 so as to avoid any reduction of flow capacity. The plastically-expandable stent 70 is desirably robust enough to hold the primary valve 40 open despite any recoil forces generated by the valve or the surrounding annulus.

[0056] The present application discloses specific modifications to existing surgical and hybrid valves that enable manufacturers to rapidly produce a valve that accommodates valve-in-valve (ViV) procedures. Specifically, the present application contemplates retrofitting or modifying components within existing surgical valves to enable post-implant expansion. Not only does this convert any proven surgical or hybrid valve for use in a ViV procedure, but it also reduces design and manufacturing work. It is therefore necessary to describe components of one popular surgical valve to explain certain modifications thereto.

[0057] Figures 4A–4D are perspective and exploded views of an exemplary surgical prosthetic heart valve 80 of the prior art oriented around a flow axis 82. The heart valve 80 comprises a plurality (typically three) of flexible leaflets 84 supported partly by an undulating wireform 86 as well as by a structural stent 88. The wireform 86 may be formed from a suitably elastic metal, such as a Co-Cr-Ni alloy like Elgiloy® alloy, while the structural stent 88 may be metallic, plastic, or a combination of the two. As seen in Figure 4B, outer tabs 90 of adjacent leaflets 84 wrap around a portion of the structural stent 88 at so-called commissures of the valve that project in an outflow direction along the flow axis 82. A soft sealing or sewing ring 92 circumscribes an inflow end of the prosthetic heart valve 80 and is typically used to secure the valve to a native annulus such as with sutures. The wireform 86 and structural stent 88 are visible in the figures, but are normally covered with a polyester fabric to facilitate assembly and reduce direct blood exposure after implant.

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[0058] It should be understood that a leaflet support structure defining alternating cusps and commissures is provided for many prosthetic heart valves, and that such a support structure may or may not include a wireform. That is, some valves have a cloth-covered wireform such as shown at 86 to which the leaflets attach, as well as a structural stent 88, while in other valves a structural stent alone performs the function of the wireform. As such, the term “leaflet support structure” encompasses both variations.

[0059] Figures 4C and 4D show the inner structural stent 88 in both assembled and exploded views. Although the general characteristics of the prosthetic heart valve 80 as seen in Figures 4A and 4B may be utilized in a number of different prosthetic heart valves, the illustrated structural stent 88 is that used in a particular heart valve; namely, pericardial heart valves manufactured by Edwards Lifesciences of Irvine, CA. For example, the Perimount® line of heart valves that utilize pericardial leaflets 84 features an inner stent 88 much like that shown in Figures 4C and 4D. In particular, the stent 88 comprises an assembly or composite of two concentric bands – an outer band 94 surrounding an inner band 95. The bands 94, 95 are relatively thin in a radial dimension as compared to an axial dimension, and both have coincident lower edges that undulate axially up and down around the circumference. The outer band 94 exhibits three truncated peaks between three downwardly curved valleys, while the inner band 95 has generally the same shape but also extends upward at commissure posts 96. The downwardly curved valleys are typically termed cusps 98, as seen in Figure 4C.

[0060] In the exemplary Perimount® valves, the outer band 94 is metallic and is formed from an elongated strip of metal bent to the generally circular shape and welded as at 100. In contrast, the outer band 95 is formed of a biocompatible polymer such as polyester (PET) or polyacetal (*e.g.*, Delrin® polyacetal), which may be molded, and also may be formed as a strip, bent into a circular shape and welded (not shown). Both the outer and inner bands 94, 95 feature a series of through holes that register with each other so that the assembly can be sewn together, as schematically illustrated in Figure 4C. The wireform 86 and the commissure posts 96 of the inner band 95 provide flexibility to the commissures of the valve, which helps reduce stress on the bioprosthetic

material of the leaflets 84. However, the inflow end or base of the valve 80 surrounded by the sewing ring 92 comprises the relatively rigid circular portions of the structural stent 88. The combination of the metallic outer and plastic inner bands and 94, 95 presents a relatively dimensionally stable circumferential base to the valve, which is beneficial for conventional surgical use. However, the same characteristics of the structural stent 88 that provide good stability for the surgical valve resist post-implant expansion of the valve. Consequently, the present application contemplates a variety of modifications to the structural stent 88 to facilitate expansion thereof.

[0061] The exemplary prior art surgical valve 80 described above may thus be modified for post-implant expansion. Furthermore, a similar surgical valve structure is used in the aforementioned commercial Edwards Intuity® valve system, and the same modifications can be made in the valve component of that system so that it may be easily expanded post-implant. Figures 5–7 illustrate one such particular modification.

[0062] Figures 5A and 5B are perspective and elevational views of a first band 120 for use in an exemplary combination of structural bands to replace existing bands and to enable post-implantation expansion thereof. The first band 120 again has a relatively small radial thickness relative to its axial height, and includes an undulating annular shape having downwardly curved cusps 122 intermediate upwardly projecting commissure posts 124. In a preferred embodiment, the first band 120 comprises a polymer material molded as a flat strip that is then bent into a circular shape and its two free ends welded as at 126.

[0063] The first band 120 includes weakened areas located below each of the commissure posts 124 that enable the band to rupture and easily expand along with the rest of the prosthetic heart valve. Such weakened areas were previously described in U.S. Patent Application Publication No. 2014/0188221, previously incorporated by reference. The first band 120 comprises a series of vertically-spaced through holes 130, 132 at each of the commissure posts 124. In particular, a first pair of through holes 130 is located closely adjacent to a lower edge 134 of the band. A vertical score line 136 through the thickness of band 120 extends vertically upwards from the first pair of through holes 130

to an upper through hole 132 that is located midway up the commissure post 124. Preferably, the score line 136 connects with the upper through hole 132. The through holes 130, 132 may be circular, as shown, or may be slightly elongated such as in a teardrop shape so as to focus any tensile forces generated from expansion of the band 120 to a certain point, such as vertically upward. Because of the relatively weak polymer material and the weakened areas provided by the through holes 130, 132 and score line 136, the first band 120 tends to split apart at three locations below the commissure posts 124. As explained, the flexible leaflets are often secured to the upper end of the commissure posts 124, which remains substantially unchanged above the upper through hole 132. Although the prosthetic heart valve in which the first band 120 is assembled is supplanted by a secondary valve, maintenance of the general integrity of the valve is desirable to avoid any loose components.

[0064] Figures 6A–6C are perspective and enlarged views of a second band 140 that can be coupled with the first band 120 of Figures 5A and 5B to form a composite structural bands for use in various prosthetic heart valve to enable post-implantation expansion thereof. In particular, the second band 140 is concentrically located around the first band 120 in intimate therewith, as seen in Figure 7. The second band 140 also has an undulating annular shape with lower-arcuate cusp regions 142 alternating with upwardly extending commissure regions 144. The two bands differ mainly in that the commissure regions 144 of the second band 140 are truncated so that they only extend up a portion of the commissure posts 124 of the first band 120.

[0065] The second band 140 is desirably metallic, such as a Co-Cr-Ni alloy like Elgiloy® alloy, and preferably formed initially as a flat band that is bent into an annular shape and has two free ends 146a, 146b that overlap and engage each other for expansion. One preferred example of such engagement is shown in Figures 6B and 6C. Other examples of overlapping free ends that permit post-implant expansion are shown and described in U.S. Patent Application Publication No. 2014/0188221.

[0066] In the illustrated embodiment, the two free ends 146a, 146b are each distinguished from the rest of the band at a pair of shoulders 148 that reduce the axial

height of an intermediate portion 150 having a central circumferential slot 152. Each free end 146a, 146b terminates in an axially enlarged head 154 (or oppositely-directed axial bumps) having an axially height that is approximately the same as the majority of the band 140. A sliding insert 156 or “spacer” is interposed between the two free ends 146a, 146b to reduce sliding friction between. For example, the insert 156 is formed of a lubricious material such as polyester. The insert 156 has a shape that somewhat mirrors the combination of the two free ends 146a, 146b; namely, having an axial height approximately the same as the intermediate portion 150, a central circumferential slot, and axial protrusions the same size as the enlarged heads 154. The polyester insert 156 between the two metal band ends 146a, 146b also prevents metal-on-metal fretting during normal cardiac cycling, which may cause slight relative motion.

[0067] The assembly of the two free ends 146a, 146b and insert 156 is seen in Figure 6B, and is held together by a flexible sleeve 158 that surrounds the free ends 146a, 146b and holds them radially together. The sleeve 158 desirably comprises polyester (*e.g.*, PET) shrink wrap tubing, or may be an elastomeric material, such as silicone rubber, and is shown transparent to illustrate the mating free ends 146a, 146b. The two free ends 146a, 146b may slide apart a predetermined distance while still being overlapping. The flexible sleeve 158 provides a minimum amount of friction against the axially enlarged heads 154 but generally just serves to maintain alignment of the free ends 146a, 146b. The flexible sleeve 158 nominally maintains the diameter of the band so that it is stable during manufacturing, but allows it to easily open up once a valve-in-valve procedure is performed.

[0068] Each of the free ends 146a, 146b further includes the circumferentially-oriented slot 152 that stops short of the terminal ends 154 and provides a pathway for fluid flow. Preferably, slots 152 extend farther outward from the sleeve 158 so that fluid can always enter the space within the sleeve. During storage, the slots 152 permit flow of a fluid between the overlapping free ends 146a, 146b to allow for sterilization. Moreover, the sleeve 158 may be biodegradable to maintain alignment of the two free

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ends 146a, 146b for a period after implant and then degrades to permit even easier expansion of the band 140.

[0069] The band 140 shows a still further identifying trait visible using external imaging and signifying it is expandable. In the illustrated embodiment, a pattern of three holes 160 are provided at each commissure region 144. Again, this permits a surgeon contemplating a replacement operation to quickly confirm that a valve-in-valve procedure is a possibility. The band 140 may also include a valve size indicator visible using external imaging, as illustrated below with respect to Figures 8–9, and as detailed in co-pending U.S. Application No. 14/745,287, filed June 22, 2015, the contents of which are hereby expressly incorporated by reference.

[0070] The assembly of the first band 120 in intimate contact with the second band 140, as seen in Figure 7, provides good stability for the prosthetic valve leaflets when in use, and an advantageous expandable structure if and when a valve-in-valve procedure is necessary. The preferably metal outer band 140 only expands at one location, while the preferably polymer band 120 expands at all three commissures. The outer band 140 is able to slide within the surrounding cloth coverings and relative to the other components such that the valve expands generally uniformly around its perimeter. That is, the commissure areas of a wireform to which the leaflets attach (such as at 52 in Figure 2) and commissure areas of the metal band 140 are initially aligned, or registered. As the metal band 140 expands, the registered commissure areas become misaligned since the wireform expands at all three commissures and the metal band only expands at the one cusp. However, the valve becomes obsolete, having been replaced with a transcatheter valve, and so this misalignment is of no consequence. The wireform maintains the upstanding commissure posts of the expanded valve in roughly the same location as when they were functional, which is intermediate the surrounding coronary ostia, and thus valve expansion will not end up blocking critical blood flow to the coronary arteries.

[0071] Figures 8A–8C illustrate a hybrid prosthetic heart valve 170 of the present application, which includes an upper valve member 172 coupled to a cloth-covered anchoring skirt 174. Figure 8B shows the valve member 172 in phantom to illustrate the

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contours of an expandable frame 176 of the anchoring skirt 174, and Figure 8C is a perspective view of the entire heart valve 170 with portions at one commissure post 178 cutaway to reveal internal structural leaflet supports.

[0072] The valve member 172 of the hybrid prosthetic heart valve 170 shares some structural aspects with the prior art heart valve 80 illustrated in Figures 4A–4D. In particular, an internal support frame defines three upstanding commissure posts 178 alternating with three arcuate cusps 180 curving in an inflow direction. Three flexible leaflets 182 are supported by the commissure posts 178 and cusps 180 and extend across a generally cylindrical flow orifice defined within the support frame. An undulating typically metallic wireform 184 mimics the up and down shape of the support frame and the leaflets 182 are attached to the wireform via a cloth covering. As with earlier valve constructions, an internal stent band 186 includes upstanding posts that rise up adjacent to and just outside of the commissures of the wireform 184, and outer tabs 188 of the leaflets 182 extend underneath the wireform, wrap around the stent posts, and are secured thereto with sutures.

[0073] In the illustrated embodiment, the heart valve 170 also includes a highly compliant sealing ring 190 extending outward therefrom at approximately the interface between the valve member 172 and the anchoring skirt 174. The sealing ring 190 as well as the expandable frame 176 are covered with a fabric 192 that helps prevent leakage around the outside of the valve once implanted. Furthermore, the sealing ring 190 is also suture-permeable and may be used to secure the valve in place in the native annulus.

[0074] Figures 9A–9C illustrate details of the exemplary expandable frame 176 for use in the hybrid prosthetic heart valve 170 of Figures 8A–8C.

[0075] With specific reference to Figure 16, the lower frame 176 is shown in perspective and includes a plurality of circumferential row struts connected by a series of spaced axial column struts. Specifically, an upper or outflow row strut 200 extends continuously around a periphery of the frame 176, and preferably follows a gently undulating path so as to match a similar shape of the underside of the upper valve member 172 (Figure 8B). As seen in Figure 9A, three peaks 204 along the upper row

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strut 200 correspond to the locations of the commissures 178 of the valve 170, where the lower edge of the stent band 186 rises upward as well. In general, the lower frame 176 attaches to an inflow end of the upper valve member 172, and preferably directly to or to fabric covering the internal support frame. The lower frame 176 is initially generally tubular and expands to be somewhat conical with the free end farthest from the upper valve member 172 expanding outward but the end closest remaining the same diameter.

[0076] The upper row strut 200 includes a plurality of eyeholes 202 evenly spaced apart and located just below the top edge thereof that are useful for securing the frame 176 to the fabric of the underside of the valve member 172. A series of axial column struts 206 depend downward from the upper row strut 200, and specifically from each of the eyeholes 202, and connect the upper row strut to two lower row struts 208. The lower row struts 208 circumscribe the frame 176 in zig-zag patterns, with an inverted “V” shape between each two adjacent column struts 206. The lower row struts 208 preferably traverse horizontally around the frame, and the length of the column struts 206 thus varies with the undulating upper row strut 200.

[0077] As mentioned above, the lower frame 176, in particular the inflow end thereof, may be plastically expanded, such as by balloon expansion, and may be formed of stainless steel, for example. In a conventional Edwards Intuity® valve, the upper row strut 200 is generally ring-like without capacity for compression or expansion. In the illustrated frame 176, on the other hand, a series of spaced notches 210 are provided that permit expansion and contraction. That is, circumferential segments of the strut 250 are interrupted by the V-shaped notches 210, which permit a limited amount of expansion, perhaps about 3 mm in diameter, to accommodate a supplemental expandable valve to be inserted and expanded therein. More particularly, the upper row strut 200 (outflow end) of the frame 176 defines a nominal diameter seen in Figure 9A that enables functioning of the valve member 172. The upper row strut 200 is radially compressible from the nominal diameter to a smaller contracted diameter to enable compression of the outflow end of the frame 176 during delivery of the heart valve. The upper row strut 200 is also radially expandable from the nominal diameter to a larger expanded diameter upon

application of an outward dilatory force from within the stent frame such as in a valve-in-valve procedure.

[0078] As shown in Figure 9B, the modified frame 176 can be collapsed to a pre-determined minimum diameter for delivery and expanded to a pre-determined maximum diameter during a valve-in-valve procedure. More specifically, the upper row strut 200 of the illustrated frame 176 may be collapsed by about 2 mm relative to the nominal diameter for ease of delivery by compressing the V-shaped notches 210 as indicated. Because the notches 210 can only be compressed until the two corners meet, the frame 176 can only be collapsed by a predetermined amount. The exemplary frame 176 is specifically designed to be collapsible to ease insertion through small incisions when the valve is implanted and for ease of seating in the annulus. The amount of collapse could be as large as about 40–50% by diameter, but would more preferably be about 2–3 mm, or between about 7–20% for heart valves having nominal operating diameters between about 19–29 mm. A compression of 2 mm in diameter, for example, corresponds to a change in circumference of about 6.28 mm. The stent frame is divided into 18 segments around its circumference by the axial column struts 206. Therefore, by placing an initial gap of 0.35 mm ($6.28 \text{ mm}/18$) in each segment, the frame can collapse by about 2 mm in diameter before adjacent segments make contact and hence prevent further compression.

[0079] Figure 9C discloses that the upper row strut 200 of the illustrated frame 176 may be subsequently expanded by 3 mm relative to a nominal diameter during a valve-in-valve procedure. Because of the configuration of the upper row of struts, the outflow portion of the frame cannot be expanded more than 3 mm. That is, the V-shaped notches 210 eventually straighten out, which prevent further expansion. Desirably, the frame is designed to expand about 3 mm in diameter beyond its nominal diameter. The nominal diameter is defined when the notches 210 are V-shaped, prior to either contraction or expansion. Similar to the gaps for limiting compression, the 3 mm in expansion corresponds to a 9.42 mm ($3 \text{ mm} \times \pi$) change in circumference. Therefore, each of the 18 segments must limit expansion to $9.42 \text{ mm}/18 = 0.52 \text{ mm}$. The length of the “V” shaped struts connecting each segment are thus $0.52 \text{ mm} + 0.35 \text{ mm}$ (from the compression

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gaps) = 0.87 mm. During a valve-in-valve expansion, the expansion of the stent frame would be limited by the expansion-limiting struts at the point where they became straight across the gap between adjacent frame segments.

[0080] If it was not desired to have the frame collapsible but expansion was still desired, the gaps could be reduced to about 25 μm , the practical limit of laser cutting. With 18 gaps of 25 μm , the amount of compression would only be $(18 \times 25 \mu\text{m} / \pi) = 0.143 \text{ mm}$ (about 0.006").

[0081] In contrast, earlier designs simply removed the upper row of struts that defines the outflow diameter of the frame. That frame configuration had no way to limit the maximum expansion of the valve during a valve-in-valve procedure. Additionally, there could be an advantage to having hybrid valves that are collapsible by a limited amount (*e.g.*, about 2–3 mm) for easier insertion. While a frame without an upper row of struts could be collapsed, there is no limit the amount of compression. It might be desirable to have the maximum compression amount limited as disclosed here for consistency and for preventing physicians from trying to collapse the valve more than it can safely be collapsed.

[0082] In addition, a number of valve type indicators 212 are integrated into the frame 176 at locations around its circumference, such as three valve size indicators. In the illustrated embodiment, the valve size indicators 212 comprise small plate-like tags inscribed with the numerical valve size in mm, for example 21 mm in the illustrated embodiment. The use of any alphanumeric characters or other symbols that signify size or other feature of the valve are contemplated. The stainless steel frame 176 may be laser cut from a tubular blank, with the plate-like size indicators 212 left connected to one more of the struts. As shown, the size indicators 212 are located just below the peaks 204 of the undulating upper row strut 200, connected between the corresponding eyehole 252 and the descending column strut 206. There are thus three size indicators 212 spaced 120° apart around the frame 176. This location provides additional space between the upper row strut 200 and the adjacent lower row strut 208. Further, the frame 176 typically has more real estate in which to place the size indicators 212 than the bands of

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the valve member 172. The inscribed or cutout valve size numerals are sufficiently large to be visualized with X-ray, transesophageal echocardiography (TEE), or other imaging modality. In one embodiment, the valve size numerals are from about 1.5 mm to about 2 mm in height, for example, about 1.75 mm in height.

[0083] Figure 10A is an exploded perspective view of components of an alternative hybrid prosthetic heart valve 300. The alternative heart valve 300 does away with an internal stent or support frame previously shown as the composite bands 120, 140 in Figure 7, for example. The composite band structure was the primary source of circumferential rigidity to the heart valves in which they were employed, and thus expansion structure was necessary to enable valve-in-valve procedures. The alternative hybrid heart valve 300 includes a lower compressible/expandable frame 302, as before, separate commissure posts 304 that are secured to the frame, and an undulating wireform 306 supporting flexible leaflets 308, also as before.

[0084] Figure 10B shows a subassembly 310 including the wireform 306 juxtaposed with the three leaflets 308, and an “integrated” subassembly 312 of the expandable frame 302 with the commissure posts 304 attached thereto. Each of the flexible leaflets 308 has two tabs 309, and pairs of tabs on adjacent leaflets are shown projecting through (under) the inverted V-shaped commissures of the wireform 306. These pairs of tabs 309 then wrap around one of the upstanding commissure posts 304 of the subassembly 312, which are located adjacent to and radially outward from the wireform commissures. The subassemblies 310, 312 are eventually covered with biocompatible fabric such as polyester, and the pairs of tabs 309 and commissure posts 304 are secured to each other with a cloth covering (see Figure 13).

[0085] Due to the attachment of the commissure posts 304 to the frame 302 the subassembly 312 integrates the frame and commissure posts, while as described below, an “integrated” frame may mean that the commissure posts are integrally formed of the same homogeneous material as the rest of the stent frame. Integrated in this sense meaning the two components are securely attached together prior to assembly with the wireform/leaflet subassembly 310, either by securing the two parts or forming them at

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the same time from the same material. Furthermore, a hybrid heart valve with an “integrated” frame means that the frame provides both the expandable skirt frame as well as commissure posts to which the leaflets attach, without any additional structural bands, such as the metal band 94 seen in Figure 1A. With this configuration, the number of parts in the valve is reduced, which reduces assembly time and expense.

[0086] Figures 10C and 10D illustrate a commissure post 304 from an outer and an inner perspective, respectively. A lower end of each of the commissure posts 304 includes a concave ledge 314 that matches the contour of one of the peaks 316 in the undulating upper row of struts 318 of the expandable frame. As seen in Figure 10B, an outer plate 320 below each of the concave ledges 314 of the commissure posts 304 extends downward on the outside of the expandable frame 302. Sutures 322 secure the commissure posts 304 to the frame 302 via suture holes 324 that align with eyeholes 326 at the peaks 316 of the undulating upper row strut 318. This shape matching followed by covering with fabric provides a relatively stable arrangement of the commissure posts 304 in the integrated frame subassembly 312.

[0087] Figure 11 is another exploded perspective view of subassemblies of the alternative hybrid prosthetic heart valve 300. In this view, the wireform in the subassembly 310 of the wireform and leaflets has been covered with fabric, and features an outwardly projecting flap 330. The fabric flap 330 is used to secure the wireform/leaflet subassembly 310 to the subassembly 312 of the expandable frame 302 and commissure posts 304. Furthermore, a suture-permeable sealing ring 332 may be attached such as by sewing at the juxtaposition between the two subassemblies 310, 312.

[0088] The relative positions of the wireform 306 and the frame/commissure post subassembly 312 is seen in Figure 12, and also in further detail in Figures 12A–12D, with the commissure posts 304 immediately outside of the commissures of the wireform 306. Finally, Figure 13 is a perspective view of the finished hybrid prosthetic heart valve 300 entirely covered with fabric.

[0089] The removal of the aforementioned stent bands and attachment (integration) of the commissure posts 304 directly to the frame 302 greatly simplifies construction,

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reduces labor hours, lowers the radial profile of the valve by about 1.6 mm, and allows for expansion during a valve-in-valve procedure. A preferred construction sequence involves attaching the sealing ring 332 to the expandable frame 302, along with 3 cloth-covered commissure posts 304, then attaching this assembly to the wireform/leaflet subassembly 310 during final assembly.

[0090] The commissure posts 304 disclosed have specific features that interface with the frame 304 to add stability to the posts in all directions. That is, the specific surfaces 314, 320 that mate with the corresponding peaks 316 on the frame 302 as well as the holes 324 that allow the posts to attach with sutures 322 to the frame provide excellent stability in all directions for subsequent covering with fabric. The commissure posts 304 could be molded from polyester or some other biocompatible material into the shape shown here, or even produced using 3D printing.

[0091] Figures 14–18 illustrate alternative integrated anchoring skirt and commissure post subassemblies. As described above with respect to Figures 10–13, the subassembly 312 shown in Figure 10B eliminates the need for annular structural bands, which bands provide stability and rigidity but which impede the ability of the valve to expand post-implant. Each of the alternative subassemblies shown in Figures 14–18 also eliminate the need for the structural bands, and further integrate the anchoring skirt and the commissure posts.

[0092] Figure 14A shows an assembly 400 of the structural components of a hybrid prosthetic heart valve having an integrated frame member 402 much like those described above but formed of a single piece. A schematic wireform 404 is shown situated on top of the frame member 402 in Figure 14A, with flexible leaflets and a cloth cover not shown and representing a wireform/leaflet subassembly such as shown at 310 in Figure 11. The schematic wireform 404 is shown with an outwardly extending sewing flange 406, which may be formed by joined lengths of two fabric tabs that wrap around and cover the wireform. When covered with cloth, the frame member 402 serves as the supportive component for the wireform, leaflets and sealing ring. Further, when covered

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with cloth, the frame member 402 provides an effective seal against paravalvular leaking (PVL) and circumferential stability to the valve.

[0093] The integrated frame member 402, which is also shown in Figures 14B–14D, comprises a lower expandable skirt portion 410, an upper annulus band 412, and leaflet support posts 414. The skirt portion 410 comprises a number of chevron patterned or V-shaped struts that can be easily crimped and then expanded. The annulus band 412 provides real estate for the attachment of a sealing ring (not shown), and preferably includes a series of holes around its circumference through which to pass sutures connecting the sealing ring. The integrated frame member 402 includes multiple cuts that enable post-implant expansion and may be laser-cut from a suitable metal such as cobalt-chromium alloy (*e.g.*, Elgiloy® alloy) and electropolished.

[0094] The frame member 402 is desirably formed from a tubular blank of a suitable material, and has a generally circular inflow or lower edge and an undulating outflow or upper edge. More particularly, the upper edge defines three arcuate cusp portions 416 intermediate three upstanding commissure posts 418. The undulating upper edge is shaped to closely fit underneath the wireform 406. After assembling the frame member 402 with the rest of the heart valve components, the skirt portion 410 is typically crimped in a generally conical manner such that its lower edge has a smaller diameter than its upper edge.

[0095] Compression/expansion sections 420 along the annulus band 412 are also added to enable a limited collapse of the frame member 402 during delivery. The compression/expansion sections 420 comprise slits formed in the upper edge of the frame member 402 that have spaces enabling a limited compression, and also permit expansion. In a preferred embodiment, solid segments 422 spaced around the annulus band 412 are connected by thin inverted U-shaped bridges 424.

[0096] As seen in Figure 14D, the frame member 402 further includes a number of slits in the region of the commissures 418 to facilitate expansion in general flexibility of the frame member. An elongated central slit 426 extends nearly the entire height of each of the commissures 418. Regions of expandable circumferential struts 428 are positioned

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within the skirt portion 410 axially aligned with both the compression/expansion sections 420 and the central slits 426. When an outward radial force is applied from within the heart valve having the frame member 402, the annulus band 412 permits expansion because of both the sections 420 and slits 426. Additionally, short arcuate slits 430 are formed at the base of each of the commissure posts 418, generally following a truncated undulating line joining the cusp portions 416. These slits 430 reduce the radial stiffness of the posts 418 such that most of the physiological load absorbed by the flexible leaflets is transferred to the wireform 406, rather than to the posts.

[0097] Despite the arcuate slits 430 in the frame member 402 of Figures 14A–14D, there are concerns that such an integrated frame design will stiffen the wireform commissure post area, thus altering the load carry mechanism of proven commercial valve platforms. To alleviate such concerns, the three commissure posts may be made of three separate pieces, preferably using polymeric material, such that when connected with the underlining metal frame with sutures, there will not be metal to metal contact.

[0098] For instance, Figures 15A–15D illustrate an alternative frame member 440 that is configured about the same as the frame member 402, but has separate commissure posts 442. The frame member 440 is shown situated just below a wireform assembly 441 in Figure 15A. As seen in Figures 15C–15D, the annulus band region 444 and the in-flow strut region 446 are exactly same as that of the frame member 402. The only difference is separate commissure posts 442 preferably made of plastic material that will be sewn together with the frame member 440 using sutures 448 before being covered with cloth. A pair of attachment holes 450 is desirably formed in each of the commissure posts 442 for this purpose. As before, the crimpable and expandable frame member 440 without commissure posts is laser-cut and electropolished.

[0099] Figure 14A is a fully integrated frame member 402, with concerns over stiffened commissure posts. The frame member 442 shown in Figure 15A alleviated that concern with three separate commissure posts 442, but those require sewing together with the expandable frame, which increases the time and steps when assembling the valve. In order to preserve the same load bearing characteristics of the existing

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commercial valve platforms, while still having a relative easy valve assembly procedure, the embodiments shown in Figures 16 and 18 are also contemplated.

[0100] Figure 16 shows an assembly 500, which includes an expandable frame 502 much like the frame 176 described above with respect to Figure 9A, and seen in isolation in Figures 17A and 17B. The frame 502 is secured via sutures to a stent band 504 with upstanding commissures 506 to form an integrated frame member. This stent band 504 is essentially the inner band 95 from Figure 4D, with suture holes 505 around its circumference to enable secure attachment to the top row of struts of the frame 502. An upper row of struts 508 includes regularly spaced compressible/expandable segments 510 to enable pre-implant compression, and post-implant expansion during a valve-in-valve procedure.

[0101] The assembly 500 is again crimpable and expandable. The stent band 504 is formed of a polymer (*e.g.*, polyester) material that is breakable when an expansion force is applied within the valve. This makes the whole valve expandable for valve-in-valve applications. Because of the polymer commissures 506, the valve load carrying characteristics will be exactly the same as the existing commercial valve platform, thus hydrodynamic performance and durability of the valve shall be the same as the existing commercial valve as well. The relative position of the polyester band and the expandable frame can be assembled as illustrated in Figure 16, with the stent band 504 positioned immediately above the frame member 502. Conversely, as seen in Figure 18, the stent band 504 may be located partly radially within the frame 502, in an overlapping manner. This aligns the series of through holes 505 in the stent band 504 with eyeholes 512 provided in the frame 502 that greatly facilitates assembly, thus reducing time and expense.

[0102] While the disclosure references particular embodiments, it will be understood that various changes and additional variations may be made and equivalents may be substituted for elements thereof without departing from the scope or the inventive concept thereof. In addition, many modifications may be made to adapt a particular situation or device to the teachings herein without departing from the essential scope

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thereof. Therefore, it is intended that the disclosure not be limited to the particular embodiments disclosed herein, but includes all embodiments falling within the scope of the appended claims.

WHAT IS CLAIMED IS:

1. A hybrid prosthetic heart valve adapted for post-implant expansion and having an inflow end and an outflow end, comprising:
 - a valve member including a plurality of flexible leaflets configured to ensure one-way blood flow therethrough and a leaflet support structure defining alternating cusps and commissures to which peripheral edges of the leaflets attach; and
 - a plastically-expandable inflow stent frame secured to and projecting from an inflow end of the leaflet support structure and having a strength requiring a predetermined expansion force to convert to an expanded state, the stent frame comprising a plurality of expandable struts and an upper edge at an outflow end of the stent frame that undulates with peaks and valleys to at least partially conform to the undulating leaflet support structure, and further wherein the upper edge defines an implant circumference with a nominal diameter that enables physiological functioning of the valve member when implanted, and wherein the upper edge is configured to expand a limited amount from the nominal diameter to an enlarged diameter larger than the nominal diameter upon application of an outward dilatory force from within the outflow end substantially larger than forces associated with normal physiological use; wherein the stent frame includes a plurality of circumferential row struts connected by a series of spaced axial column struts, and the upper edge comprises an outflow row strut that extends continuously around a periphery of the stent frame and has a series of spaced V-shaped notches that permit limited expansion and contraction, and the contraction of the outflow row strut is limited to a predetermined amount by two corners of each V-shaped notch meeting, the limited contraction enabling compression of the stent frame during delivery of the heart valve.
2. The prosthetic heart valve of claim 1, wherein the outflow row strut has limited radially compressibility of between about 7–20% of the nominal diameter to reduce the size of the outflow end during delivery of the heart valve.

3. The prosthetic heart valve of any preceding claim, wherein the leaflet support structure comprises an undulating wireform with alternating cusps and commissures.

4. The prosthetic heart valve of claim 3, wherein the outflow edge of the stent frame includes three integrated commissure posts located adjacent to and radially outward from the wireform commissures to which the leaflets attach outside of the wireform.

5. The prosthetic heart valve of claim 4, wherein the integrated commissure posts are separate elements secured with sutures to the stent frame outflow edge.

6. The prosthetic heart valve of claim 4, wherein the integrated commissure posts are integrally formed of the same homogeneous material as the rest of the stent frame.

7. The prosthetic heart valve of any of claims 1–2, wherein the leaflet support structure comprises a structural support stent having upstanding commissure posts extending in the outflow direction to which the leaflets attach alternating with arcuate inflow cusps, the support stent defining an implant circumference that is non-compressible in normal physiological use and has a first diameter, and wherein the support stent is configured to expand from the first diameter to a second diameter larger than the first diameter upon application of an outward dilatory force from within the support stent substantially larger than forces associated with normal physiological use.

8. The prosthetic heart valve of claim 7, wherein the support stent comprises two concentric bands, one of which is metal and the other of which is plastic.

9. The prosthetic heart valve of claim 7, wherein the support stent includes a support band having a single expandable segment formed by overlapping free ends located at one of the inflow cusps and separated by a sliding insert, and further including a flexible sleeve surrounding the overlapping free ends of the support band to maintain alignment of the free ends.

10. The prosthetic heart valve of claim 9, wherein the single expandable segment is located at one of the inflow cusps of the support stent and a second band concentrically positioned within the support band defines the commissure posts and is configured to expand below each of the commissure posts when the support band expands.

11. The prosthetic heart valve of any preceding claim, wherein the stent frame upper edge has limited radially compressibility to enable compression of the stent frame during delivery of the heart valve.

12. The prosthetic heart valve of any preceding claim, wherein the stent frame is configured to expand below each of the leaflet support structure commissures upon application of the outward dilatory force.

13. The prosthetic heart valve of any preceding claim, further including a unique identifier on the stent frame visible from outside the body after implant that identifies the stent frame as having an expandable outflow end.

14. The prosthetic heart valve of any preceding claim, further including a unique identifier on the leaflet support structure visible from outside the body after implant that identifies the support stent as being expandable.