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ANTI-SUCTION BLOOD PUMP INLET

Abstract

A heart pump assembly includes an impeller blade coupled to a rotor or a drive shaft, a cannula, a distal projection coupled to a distal end of the cannula and a blood inlet having a plurality of apertures. The plurality of apertures is radially oriented and disposed about a circumference of the cannula. The plurality of apertures includes at least a first ring of apertures which are proximal to the distal projection and a second ring of apertures which are proximal of the first ring of apertures. The plurality of apertures can allow the heart pump assembly to continue to function if anatomical structures or tissue become suctioned to a portion of the heart pump.

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS [0001] The present application is a continuation of U.S. patent application Ser. No. 18/433,742, filed Feb. 6, 2024, which is a divisional of U.S. patent application Ser. No. 17/410,168, filed Aug. 24, 2021, now U.S. Pat. No. 11,938,311, which is a continuation of U.S. patent application Ser. No. 15/694,134, filed Sep. 1, 2017, now U.S. Pat. No. 11,123,541, which claims the benefit of U.S. Provisional Patent Application No. 62/382,471, filed Sep. 1, 2016, the disclosures of all of which are incorporated herein by reference in their entirety.

BACKGROUND

[0002] A heart pump, such as a percutaneous intracardiac heart pump assembly, can be introduced in the heart to deliver blood from the heart into an artery. When deployed in the heart, a heart pump assembly pulls blood from the left ventricle of the heart and expels blood into the aorta, or pulls blood from the right ventricle and expels blood into the pulmonary artery. Some heart pump assemblies pull blood through inflow apertures into a cannula and expel the blood from the cannula into the aorta through outflow apertures. Sometimes the inflow apertures suck against the interior of the ventricle in which they are located or against other structures such as the mitral valve and/or chordae. When this suction occurs, the flow of blood into the pump and/or through the cannula is blocked or impeded, lessening the assistance provided to the heart.

SUMMARY

[0003] Systems, devices, and methods described herein provide heart pump assemblies with improved inflow apertures. The inflow apertures are designed to prevent or reduce the tendency of the inflow aperture to suck against the interior of the heart or vascular system of a patient. In particular, the inflow apertures can prevent the pump inlet from sucking a valve leaflet (e.g., a leaflet of the mitral valve) into the inlet. This can reduce the risk of occlusion of the apertures to allow the pump to provide more blood pumping assistance to the heart. The improved apertures may also decrease the risk of damage to structures of the heart which may be suctioned to the pump.

[0004] The heart pump includes a plurality of inflow apertures. The inflow apertures can be disposed at a distal end portion of a cannula of the heart pump (e.g., in the case of pumps designed to assist the left ventricle). The inflow apertures can be arranged in two or more rings or rows that are offset from one another along a longitudinal axis of the pump. The use of multiple rings or rows of apertures, rather than a single ring of apertures, can allow each aperture to be smaller, which may reduce the risk that heart structures (e.g., valves) will enter the inlet through the apertures. Furthermore, the additional inflow apertures provide redundancy so that if one subset of the apertures is blocked, there are additional apertures through which blood can enter the pump. The outer edges of the apertures can be defined by struts coupled to the cannula. The struts can function as a screen to prevent the suction of valve leaflets against or into the pump.

[0005] In one aspect, a heart pump assembly includes a rotor, a motor coupled to the rotor, an impeller blade coupled to the rotor such that rotation of the rotor causes the impeller blade to rotate

and pump blood, a cannula, a distal projection coupled to a distal end of the cannula, and a blood inlet including a plurality of apertures radially oriented and disposed about a circumference thereof. The plurality of apertures includes at least a first ring of apertures which are proximal to the atraumatic tip and a second ring of apertures which are proximal of the first ring of apertures.
[0006] In some implementations, a first aperture in the first ring of apertures has a greater area than an area of a second aperture in the second ring of apertures. In some implementations, the first apertures in the first ring of apertures and the second ring in the second ring of apertures are oblong. In some implementations, the heart pump assembly includes a third ring of apertures proximal of the second ring. In some implementations, the heart pump assembly includes a fourth ring of apertures proximal of the third ring.
[0007] In some implementations, the first aperture in the first ring of apertures and a third aperture in the third ring of apertures are aligned along an axis on a surface of the cannula parallel to a longitudinal axis of the cannula. In some implementations, the second aperture in the second ring of apertures is aligned with a fourth aperture in the fourth ring of apertures along the axis on the surface of the cannula parallel to the longitudinal axis of the cannula.
[0008] In some implementations, the first aperture in the first ring of apertures has a height measured parallel to the longitudinal axis of the cannula that is greater than a height of any of the second aperture, third aperture or fourth aperture. In some implementations, the height of the first apertures is less than 9 mm. In some implementations, the height of the second aperture is less than 3 mm. In some implementations, a width of the second aperture is less than 4 mm. In some implementations, an area of the first aperture is less than 20 mm.sup.2. In some implementations, an area of the second aperture is less than 12 mm.sup.2. In some implementations, the plurality of apertures is formed on an inflow cage that is coupled to the cannula. In some implementations, the inflow cage is comprised of stainless steel. In some implementations, the plurality of apertures is formed near a terminal end of the cannula.
[0009] In some implementations, some of the pluralities of apertures are oblong. In some implementations, some of the pluralities of apertures are round. In some implementations, some of the pluralities of apertures are tear-shaped with a rounded edge oriented at a distal end of the each of the apertures and a pointed edge oriented at a proximal side of each of the apertures. In some implementations, a first aperture in the first ring of apertures has a smaller area than a second aperture in the second ring of apertures. In some implementations, a first aperture in the first ring of apertures has the same area than a second aperture in the second ring of apertures. In some implementations, the distal end portion of the cannula comprises an inflow cage. In some implementations, a distal edge of the first aperture is formed by a base of the atraumatic tip.
[0010] In some implementations, each of the plurality of apertures is defined by an inner edge intersecting an interior of the cannula and an outer edge intersecting the surface of the cannula. In some implementations, the outer edge of each of the plurality of apertures is rounded. In some implementations, the outer edge of each of the plurality of apertures is chamfered. In some implementations, the heart pump assembly is sized for percutaneous insertion.
[0011] In another aspect, a heart pump assembly includes a rotor, a motor coupled to the rotor, an impeller blade coupled to the rotor such that rotation of the rotor causes the impeller blade to rotate and pump blood, a cannula, and a blood inlet including a plurality of apertures radially oriented and disposed about a circumference thereof. The plurality of apertures includes at least a first ring of apertures and a second ring of apertures, the second ring being proximal of the first ring of apertures. In the plurality of apertures, each aperture of the first ring of apertures has a greater area than an aperture of the second ring of apertures.
[0012] In some implementations, the first apertures in the first ring of apertures and the second ring in the second ring of apertures are oblong. In some implementations, the heart pump assembly includes a third ring of apertures proximal of the second ring. In some implementations, the heart pump assembly includes a fourth ring of apertures proximal of the third ring. In some

implementations, the first aperture in the first ring of apertures and a third aperture in the third ring of apertures are aligned along an axis on a surface of the cannula parallel to a longitudinal axis of the cannula. In some implementations, the second aperture in the second ring of apertures is aligned with a fourth aperture in the fourth ring of apertures along the axis on the surface of the cannula parallel to the longitudinal axis of the cannula.

[0013] In some implementations, the first aperture in the first ring of apertures has a height measured parallel to the longitudinal axis of the cannula that is greater than a height of any of the second aperture, third aperture or fourth aperture. In some implementations, the height of the first apertures is less than 9 mm. In some implementations, the height of the second aperture is less than 3 mm. In some implementations, a width of the second aperture is less than 4 mm. In some implementations, an area of the first aperture is less than 20 mm.sup.2. In some implementations, the plurality of apertures is formed on an inflow cage that is coupled to the cannula. In some implementations, the inflow cage is comprised of stainless steel. In some implementations, the plurality of apertures is formed near a terminal end of the cannula.

[0014] In some implementations, each of the plurality of apertures is defined by an inner edge intersecting an interior of the cannula and an outer edge intersecting the surface of the cannula. In some implementations, the outer edge of each of the plurality of apertures is rounded. In some implementations, the outer edge of each of the plurality of apertures is chamfered. In some implementations, the heart pump assembly is sized for percutaneous insertion.

[0015] In another aspect, a method of manufacturing a heart pump assembly includes coupling an impeller blade to a rotor, inserting the impeller blade in a housing, coupling a cannula to the housing, and coupling an inflow cage including a plurality of apertures to the cannula. The plurality of apertures is radially oriented about a circumference of the inflow cage and the plurality of apertures are arranged in at least a first ring of apertures and a second ring of apertures proximal of the first ring of apertures.

[0016] In some implementations, the inflow cage comprises a third ring of apertures proximal of the second ring of apertures. In some implementations, the inflow cage comprises a fourth ring of apertures proximal of the third ring of apertures. In some implementations, each of the plurality of apertures includes an outer edge formed by a tumbling process. In some implementations, the plurality of apertures is formed near a terminal end of the cannula. In some implementations the method also includes coupling a distal projection to the distal end of the inflow cage. The distal projection is distal to the plurality of apertures and a base of the distal projection forms a distal edge of the first ring of apertures.

[0017] In another aspect, a method of operating a heart pump assembly includes rotating an impeller about a rotation axis using a motor to draw blood into a cannula of a heart pump assembly at a plurality of blood inlet apertures, and expelling the blood from the heart pump assembly via a plurality of blood exhaust apertures disposed at a proximal end portion of the cannula proximal to the pump. The blood inlet apertures are radially oriented about a circumference of the cannula and arranged in at least two rings at a distal end of the cannula.

[0018] Variations and modifications will occur to those of skill in the art after reviewing this disclosure. The disclosed features may be implemented, in any combination and subcombination (including multiple dependent combinations and subcombinations), with one or more other features described herein. For example, although various specific arrangements of apertures are described herein, a heart pump assembly may be configured to have any number of apertures arranged in any suitable number of rings. Further, the apertures may have any suitable size, shape, or position. The various features described or illustrated above, including any components thereof, may be combined or integrated in other systems. Moreover, certain features may be omitted or not implemented.

Description

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The foregoing and other objects and advantages will be apparent upon consideration of the following detailed description, taken in conjunction with the accompanying drawings, in which like reference characters refer to like parts throughout, and in which:

[0020] FIG. **1** shows an exemplary prior art heart pump assembly;

[0021] FIG. **2** shows a heart pump assembly including a plurality of apertures at a distal end portion, in accordance with example implementations;

[0022] FIG. **3** shows a heart pump assembly including a plurality of apertures arranged in rings at a distal end portion, in accordance with example implementations;

[0023] FIG. **4** shows a heart pump assembly including three rings of apertures at a distal end portion, in accordance with example implementations;

[0024] FIG. **5** shows a perspective view of a distal end portion of a heart pump assembly having four rings of apertures, in accordance with example implementations;

[0025] FIG. **6** shows a front view of a distal end portion of a heart pump assembly having four rings of apertures, in accordance with example implementations;

[0026] FIG. **7** shows a perspective view of a distal end portion of a heart pump assembly having two rotationally offset rings of apertures, in accordance with example implementations;

[0027] FIG. **8** shows a perspective view of a distal end portion of a heart pump assembly having two rotationally aligned apertures, in accordance with example implementations;

[0028] FIG. **9** shows a perspective view of a distal end portion of a heart pump assembly having a plurality of rotationally aligned apertures, in accordance with example implementations;

[0029] FIG. **10** shows a front view of a distal end portion of a heart pump assembly having a plurality of round apertures, in accordance with example implementations;

[0030] FIG. **11** shows a perspective view of a distal end portion of a heart pump assembly having an oblong distal aperture and a plurality of round apertures, in accordance with example implementations;

[0031] FIG. **12** shows a front view of a distal end portion of a heart pump assembly having a distal tear-shaped aperture and a plurality of round apertures, in accordance with example implementations;

[0032] FIG. **13** shows front view of a distal end portion of a heart pump assembly having a distal tear-shaped aperture and a plurality of tear-shaped apertures arranged in rings, in accordance with example implementations;

[0033] FIG. **14** shows a front view of a distal end portion of a heart pump assembly having an arrangement of apertures positioned in closely spaced rings, in accordance with example implementations;

[0034] FIG. **15** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in moderately spaced rings, in accordance with example implementations;

[0035] FIG. **16** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in widely spaced rings, in accordance with example implementations;

[0036] FIG. **17** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in a first ring of long apertures and a second ring of shorter apertures, in accordance with example implementations;

[0037] FIG. **18** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in a first ring of long apertures and a second ring of shorter apertures spaced apart from the first ring, in accordance with example implementations;

[0038] FIG. **19** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in four rings of similarly sized apertures, in accordance with example implementations;
[0039] FIG. **20** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures positioned in four rings of differently sized apertures, in accordance with example implementations;
[0040] FIG. **21** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures having chamfered edges, in accordance with example implementations;
[0041] FIG. **22** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures with rounded edges, in accordance with example implementations;
[0042] FIG. **23** shows a front view of a distal end portion of a heart pump assembly having an alternative arrangement of apertures, in accordance with example implementations;
[0043] FIG. **24** shows a plot displaying the predicted flow rate of a fluid through the plurality of apertures in an example arrangement, in accordance with example implementations;
[0044] FIG. **25** shows a percutaneous pump having a plurality of apertures at a distal end portion inserted into a blood vessel of a patient, in accordance with example implementations;
[0045] FIG. **26** is a flow chart of a method for manufacturing a heart pump having a plurality of apertures at a distal end portion, in accordance with example implementations; and
[0046] FIG. **27** is a flow chart of a method for use of a heart pump having a plurality of apertures at a distal end portion, in accordance with example implementations.

DETAILED DESCRIPTION

[0047] To provide an overall understanding of the systems, methods, and devices described herein, certain illustrative embodiments will be described. Although the embodiments and features described herein are described with reference to specific numbers, sizes, and shapes of apertures, it will be understood that the heart pump assembly may be configured to have any suitable number of apertures arranged in any number of rings, not limited to the arrangements described here. Additionally, the apertures may have any suitable size, shape, or position.
[0048] Systems, devices, and methods described herein provide heart pump assemblies with improved inflow apertures. The inflow apertures are designed to prevent or reduce the tendency of the inflow aperture to suck against the interior of the heart or vascular system of the patient. In particular, the inflow apertures can prevent the pump inlet from sucking a valve leaflet (e.g., a leaflet of the mitral valve) into the inlet. This can reduce the risk of occlusion of the apertures to allow the pump to provide more blood pumping assistance to the heart. The improved apertures may also decrease the risk of damage to structures of the heart which may be suctioned to the pump.
[0049] The heart pump includes a plurality of inflow apertures. The inflow apertures can be disposed at a distal end portion of a cannula of the heart pump (e.g., in the case of pumps designed to assist the left ventricle). The inflow apertures can be arranged in two or more rings or rows that are offset from one another along a longitudinal axis of the pump. The use of multiple rings or rows of apertures, rather than a single ring of apertures can allow each aperture to be smaller, which may reduce the risk that heart structures (e.g., valves) will enter the inlet through the apertures. Furthermore, the additional inflow apertures provide redundancy so that if one subset of the apertures is blocked, there are additional apertures through which blood can enter. The outer edges of the apertures can be defined by struts coupled to the cannula. The struts can function as a screen to prevent the suction of valve leaflets against or into the apertures.
[0050] FIG. **1** shows an exemplary prior art heart pump assembly **100**. The heart pump assembly **100** includes a motor housing **102**, a cannula assembly **108**, a plurality of apertures **116**, a plurality of blood exhaust outlets **124**, and a projection or atraumatic tip **112**. The cannula assembly **108** has

a proximal end **111**, a cannula body **109**, an inflow cage **113**, a distal end **110**, a distal end portion **114**, and a tear drop portion **142**. The motor housing **102** has a proximal end **107** and a distal end **106**. The plurality of apertures **116** are arranged in a single ring **118** in the inflow cage **113** at the distal end portion **114** of the cannula assembly **108**. The atraumatic tip **112** is coupled to the cannula assembly **108** at the distal end **110** of the cannula assembly **108** at the tear drop portion **142**.

[0051] The heart pump assembly **100** pulls blood through the plurality of apertures **116** and into the cannula assembly **108**. The pump expels the blood proximal of the proximal end **111** of the cannula assembly **108** through the plurality of blood exhaust apertures **124**. The heart pump assembly **100** may be percutaneously inserted into the heart through the aorta. The plurality of apertures **116** may be positioned past the aortic valve in the left ventricle, in order to pull blood from the left ventricle and expel the blood into the aorta. Although the atraumatic tip **112** spaces the heart pump assembly **100** from the heart walls, in some instances the plurality of apertures **116** may be positioned near to the walls of the heart or various heart structures, such as the leaflets of the mitral valve. The plurality of apertures **116** each have a large area which may suction structures of the heart, such as valve leaflets against the apertures **116** and even through the apertures **116** into the cannula assembly **108**. This can block some or all of the inflow of blood into the cannula assembly **108**. When the flow of blood through the cannula assembly **108** is blocked, the support that the heart pump assembly **100** can provide to the heart is lessened.

[0052] FIG. **2** shows a modified heart pump assembly **200** having a plurality of apertures arranged into rings, according to certain implementations. The heart pump assembly **200** includes a motor housing **202**, a cannula assembly **208**, a plurality of apertures **216**, a plurality of blood exhaust outlets **224**, and an atraumatic tip **212**. The cannula assembly **208** has a proximal end **206**, a cannula body **209**, an inflow cage **213**, a distal end **210**, a distal end portion **214**, and a tear drop portion **242**. The atraumatic tip **212** is coupled to the cannula assembly **208** at a distal end **210** of the cannula assembly **208** at the tear drop portion **242**. The plurality of apertures **216** are arranged in the inflow cage **213** at the distal end portion **214** of the cannula assembly **208**. The plurality of apertures **216** each have a smaller area relative to the plurality of apertures **116** shown in FIG. **1**, and are arranged into multiple rings. The distal end portion **214** of the cannula assembly **208** includes a first ring **218** of apertures, a second ring **220** of apertures, and a third ring **230** of apertures. The inflow cage **213**, including the plurality of apertures **216**, is approximately the same length as in the inflow cage **113** of the prior art pump **100**, but the plurality of apertures **216** includes more apertures which are smaller than those of the prior art pump **100**.

[0053] The plurality of smaller apertures **216** arranged in rings **218**, **220**, and **230** reduces the tendency of the plurality of apertures **216** to suck against the interior of the heart of the patient. In particular, the multiple smaller apertures **216** prevent the heart pump assembly **200** from sucking a valve leaflet into the plurality of apertures **216**. This can reduce the risk of occlusion of the apertures **216**, thereby allowing the heart pump assembly **200** to provide more assistance to the heart. The apertures **216** may also decrease the risk of damage to structures of the heart which could otherwise be suctioned by the heart pump assembly **200**. The heart pump assembly **200** can vary in any number of ways. For example, the embodiment of FIG. **2** and any of the other embodiments herein may exclude a motor housing. Instead, the motor can be configured to be positioned outside of a patient's body and can operatively couple to the rotor via a drive shaft or cable.

[0054] FIG. **3** shows an illustrative view of a heart pump assembly **300**, such as heart pump assembly **200** in FIG. **2**, including a plurality of apertures **316** at a distal end portion **314** according to some implementations. The heart pump assembly **300** includes a motor housing **302**, an impeller blade **304**, a cannula assembly **308**, a plurality of apertures **316**, and an atraumatic tip **312**. The motor housing **302** has a distal end **306** and a proximal end **307**. The impeller blade **304** is rotatable relative to the cannula assembly **308**. The cannula assembly **308** includes a proximal end **311**, a

distal end **310**, a distal end portion **314**, a tear drop portion **342** and a cannula body **309** having a circumference **322**. The cannula body **309** is coupled to the distal end **306** of the motor housing **302**. The plurality of apertures **316** are arranged into a first ring **318** and a second ring **320**. The first ring **318** is positioned at a distal end of the distal end portion **314** and the second ring **320** is positioned proximal of the first ring **318**. In some implementations, the plurality of apertures **316** are formed in the distal end portion **314** of the cannula assembly **308**. In certain implementations, the plurality of apertures **316** are formed in an inflow cage (not shown) which is distinct from, but coupled to, the distal end portion **314** of the cannula assembly **308**. The plurality of apertures is separated by a plurality of struts, for example **317***a-c*. The atraumatic tip **312** is coupled to the distal end **310** of the cannula assembly **308**.

[0055] The first ring **318** includes apertures **318***a-c*. The second ring **320** includes apertures **320***a-c*. Though the first ring **318** and the second ring **320** are shown with three apertures each (**318***a-c* and **320***a-c*), the plurality of apertures **316** in the first ring **318** and in the second ring **320** can extend around the entire circumference **322** of the cannula body **309**. The first ring **318** and the second ring **320** can each include any suitable number of apertures. In some implementations, the number of apertures in a first ring **318** or the second ring **320** is 3, 4, 5, 6, 7, 8, 9, 10 or any other suitable number of apertures. In some implementations, the number of apertures in the first ring **318** is the same as the number of apertures in the second ring **320**, though this is not required. In some implementations, there are fewer apertures in the first ring **318** than in the second ring **320**. In some implementations, there are more apertures in the first ring **318** than in the second ring **320**.

[0056] The heart pump assembly **300** pulls blood into the cannula assembly **308** by the rotation of the impeller blade **304**. The blood enters the cannula assembly **308** at the plurality of apertures **316** at the distal end portion **314** of the cannula assembly **308**. The heart pump assembly **300** may be positioned in the heart in such a way that the mitral valve leaflets are proximate to the plurality of apertures **316**, and in some instances, the mitral valve leaflets may be sucked against some of the plurality of apertures **316**, temporarily blocking blood from entering at the plurality of apertures **316**. Because the plurality of apertures **316** are small in size, the apertures **316** are less likely to allow a valve leaflet to enter the heart pump assembly **300** at an inlet. This keeps the interior of the cannula assembly **308** clear for the passage of blood. Furthermore, the struts **317***a-c* between the plurality of apertures **316** act as a screen to prevent the suctioning of valve leaflets and other tissues to the plurality of apertures **316**. A valve leaflet or other portion of the anatomy that is suctioned against some of the plurality of apertures **316**, or into the heart pump assembly **300**, decreases the area through which blood can enter the cannula assembly **308**, potentially decreasing the flow rate of the blood through the heart pump assembly **300**. The plurality of apertures **316** arranged at the distal end portion **314** of the cannula assembly **308** increases the likelihood that some of the plurality of apertures **316** will not be blocked. If a subset of the plurality of apertures **316** are blocked, blood can still enter the heart pump assembly **300** through the remainder of the plurality of apertures **316**.

[0057] The plurality of apertures **316** are shown having an oblong shape. The plurality of apertures **316** may have any suitable shape to allow blood to enter the cannula assembly. For example, the plurality of apertures **116** can be oblong, oval, square, tear-shaped, round or any other suitable shape. The shape of the apertures **318***a-c* of the first ring **318** may differ from the shape of the apertures **320***a-c* of the second ring **320**. In some implementations, edges of the plurality of apertures **316** are rounded or chamfered. Rounded apertures, or apertures with rounded edges, may decrease the risk of hemolysis or other damage to the blood as it enters the plurality of apertures **316**. As shown, the apertures **318***a-c* of the first ring **318** each have a greater area relative to each of the apertures **320***a-c* of the second ring **320**. In some implementations, the apertures **318***a-c* of the first ring **318** each have a smaller area relative to each of the apertures **320***a-c* of the second ring **320**. In certain implementations, each of the apertures **318***a-c* of the first ring **318** has the same area as each of the apertures **320***a-c* of the second ring **320**.

[0058] The atraumatic tip **312** coupled to the distal end **310** of the cannula assembly **308** spaces the plurality of apertures **316** from the inner surface of the heart. This spacing prevents the plurality of apertures **316** from suctioning to the walls of the heart, heart valves (e.g., the mitral valve), or any other anatomical structure in the heart. This can reduce the risk of blockage of the plurality of apertures **316** and may reduce or prevent damage to the heart tissues. The atraumatic tip **312** may be shaped as a flexible extension having a pigtail as shown in FIG. **3**. In some implementations, the atraumatic tip **312** is configured as a straight extension or as a ball. In some implementations, the atraumatic tip **312** includes a lumen for the passage of a guidewire through the atraumatic tip **312**.
[0059] In sum, both the atraumatic tip **312** and the arrangement of apertures **316** help prevent or reduce the risk of a pump inlet being occluded by the heart wall, valve leaflets, or other anatomical structures. The atraumatic tip **312** acts as a mechanical spacer to prevent suction of the apertures against the inner surface of the heart, while the arrangement of apertures **316** and struts **317***a-c* act as a screen to prevent entry of tissue into the apertures **316**. Thus, the atraumatic tip **312** and the arrangement of the apertures **316** together help preserve proper functioning of the heart pump assembly **300**.
[0060] FIG. **4** shows an illustrative view of a heart pump assembly **400**, such as the heart pump assembly **200** in FIG. **2**, including three rings of apertures at a distal end portion **414** of the cannula assembly **408**. The heart pump assembly **400** includes a motor housing **402**, an impeller blade **404**, a catheter **428**, a cannula assembly **408**, blood exhaust outlets **424**, a plurality of apertures **416**, and an atraumatic tip **412**. The cannula assembly **408** includes a proximal end **411**, a distal end **410**, a distal end portion **414**, a tear drop portion **442**, a longitudinal axis **444**, and a cannula body **409** having a circumference **422**. The motor housing **402** includes the impeller blade **404** which is rotatable relative to the cannula assembly **408**. Rotation of the impeller blade **404** creates suction through the cannula assembly **408**. Blood enters the cannula assembly **408** at the plurality of apertures **416** disposed in the distal end portion **414** of the cannula assembly **408**. The plurality of apertures **416** are arranged about the circumference **422** of the cannula body **409** in a first ring **418** having apertures **418***a-d*, a second ring **420** having apertures **420***a-d*, and a third ring **430** having apertures **430***a-d*. The first ring **418** is proximal to the distal end **410** of the cannula assembly **408**. The second ring **420** is proximal of the first ring **418**, and the third ring **430** is proximal of the second ring **420**. The plurality of apertures **416** are separated by a plurality of struts **217***a-c*. Attached to the cannula assembly **408** at the tear drop portion **442** at the distal end **410** is the atraumatic tip **412**.
[0061] Each of the plurality of apertures **416** has a height, a width, and an area. The plurality of apertures **416** can have a variety of sizes. The first ring **418** may have the aperture **418***d* having a larger area than the aperture **420***d* of the second ring or the aperture **430***d* of the third ring **430**. The area of the aperture **418***d* of the first ring **418** may be less than 20 mm.sup.2. In some implementations, the area of the aperture **418***d* of the first ring **218** is 0.5 mm.sup.2, 1 mm.sup.2, 5 mm.sup.2, 10 mm.sup.2, 15 mm.sup.2, 18 mm.sup.2, 20 mm.sup.2, 23 mm.sup.2, 25 mm.sup.2 or any other suitable area. The area of the aperture **420***d* of the second ring **420** may be less than 12 mm.sup.2. In some implementations, the area of the apertures **420***d* of the second ring **420** may be 0.25 mm.sup.2, 0.5 mm.sup.2, 1 mm.sup.2, 2 mm.sup.2, 5 mm.sup.2, 10 mm.sup.2, 12 mm.sup.2, or any other suitable area. The area of the aperture **430***d* of the third ring **430** may be the same as the area of aperture **420***d* of the second ring. The height of the apertures **418***b* of the first ring **418** as measured along an axis parallel to the longitudinal axis **444** of the cannula assembly **408** may be less than 9 mm. In some implementations, the height of the aperture **418***b* of the first ring **418** is 0.5 mm, 1 mm, 3 mm, 5 mm, 6 mm, 9 mm, 10 mm, 12 mm, 15 mm or any other suitable height. The height of the aperture **420***b* of the second ring **420** as measured along an axis parallel to the longitudinal axis **444** of the cannula assembly **408** may be less than 3 mm. In some implementations, the height of the aperture **420***b* of the second ring **420** is 0.25 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 5, mm, 6 mm, or any other suitable height. A

width of the aperture **420***b* of the second ring **420** measured transverse to the longitudinal axis **444** may be less than 4 mm. In some implementations, the width of the aperture **420***b* of the second ring **420** is 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 5, mm, 6 mm, 8 mm, or any other suitable width. In some implementations, a height and the width of aperture **430***b* is the same as the height and the width of aperture **420***b*.

[0062] The plurality of apertures **416** prevents the heart pump assembly **400** from failing due to the suction of a valve leaflet against a portion of the plurality of apertures **416**. The plurality of apertures **416** arranged in rings **418**, **420**, and **430**, reduces the tendency of the plurality of apertures **416** to suck heart structures against the inlets of the heart pump assembly **400**. The multiple apertures **416**, along with the struts **417***a-c*, prevent the heart pump assembly **400** from sucking a valve leaflet into the plurality of apertures **416**, thereby reducing risk of blocking the apertures **416** and allowing the heart pump assembly **400** to continue to provide assistance to the heart. Furthermore, the plurality of apertures **416** provide redundant inflow inlets for blood to enter even if one or more of the plurality of apertures **416** is blocked by a valve leaflet or other tissue.

[0063] In some implementations, a large portion of blood that enters the cannula assembly **408** enters through the most proximal of the plurality of apertures **416**, for example through the apertures **430***a-c* of the third ring **430**. When one or more of the plurality of apertures **416** in the third ring **430** is blocked, a larger amount of blood may enter at the plurality of apertures **416** in the second ring **420** or the first ring **418**. Additional apertures provide additional inlets through which blood can enter the heart pump assembly. Additionally, the struts **417***a-c* that define the plurality of apertures **416** can act as a screen to prevent the suction of tissue against, or into, the heart pump assembly **400**.

[0064] While FIG. **4** shows a heart pump assembly **400** having a plurality of apertures arranged in three rings, in some implementations there may be additional rings of apertures. For example, FIG. **5** shows a perspective view of a distal end portion **514** of a cannula assembly having four rings of apertures, and FIG. **6** shows a front view of the distal end portion **514** of the cannula assembly of FIG. **5**. The distal end portion **514** includes a distal end **510**, an atraumatic tip connector **548**, a tear drop portion **542**, a longitudinal axis **544**, and a plurality of apertures **516** arranged in a first ring **518**, a second ring **520**, a third ring **530**, and a fourth ring **540**. The plurality of apertures **516** in the first ring **518** include apertures **518***a-e* oriented radially around a circumference of the distal end portion **514**. The second ring **520** of apertures **520***a-e*, the third ring **530** of apertures **530***a-e*, and the fourth ring **540** of apertures **540***a-e* are radially oriented around a circumference of the distal end portion **514**.

[0065] The first ring **518** of apertures **518***a-e* has the largest height of the four rings of apertures. The first ring **518** of apertures **518***a-e* has a distal edge **551** of each aperture which is defined by a portion **552** of the tear drop portion **542**. The tear drop portion **542** may be manufactured separately from the rest of the cannula assembly in which the rest of the plurality of apertures **516** are disposed, and may be joined to the cannula assembly (not shown) as part of the manufacturing process. As a result, the first ring **518** of apertures **518***a-c* may be formed in the cannula assembly (or in the inflow cage, not shown) during the manufacture process as initially only having defined three sides, with a fourth, distal side left open. The fourth, distal edge **551** of each aperture **518***a-e* is then defined by a portion **552** of the tear drop portion **542** when it is joined to the cannula assembly. The proximal edge **553** of the apertures **518***a-e* is rounded, giving the apertures **518***a-e* an oblong shape.

[0066] The apertures **520***a-e* of the second ring **520** are rotationally offset from the apertures **518***a-e* of the first ring, such that a line **555** drawn through the center of aperture **518***b* parallel to the longitudinal axis **544** of the distal end portion **514** does not pass through a center of any of the apertures **520***a-e* of the second ring **520**. In some implementations, the line **555** may pass through a portion of one of the apertures **520***a-e*, but not the center of apertures **520***a-e*. The apertures **530***a-e* are rotationally aligned with the apertures **518***a-e*, such that the line **555** passes through a center of

the one of apertures **518***a-e* and a center of one of the apertures **530***a-e*. In particular, the line **555** passes through the center of aperture **518***b* and the center of aperture **530***b*. The line **555** does not pass through the center of any of the apertures **540***a-e* of the fourth ring **540**, as the apertures **540***a-e* are rotationally offset from the apertures **518***a-e* and the apertures **530***a-e*. The apertures **520***a-e* of the second ring **520** are rotationally aligned with the apertures **540***a-e* of the fourth ring **540** such that the line **557** parallel to the longitudinal axis **544** of the distal end portion **514** passes through a center of aperture **520***b* and **540***b*. In some implementations, different rings of apertures may be rotationally aligned or offset. For example, in some implementations the apertures **518***a-e* and **520***a-e* of the first ring **518** and second ring **520**, respectively, may be rotationally aligned, while the apertures **530***a-e* of the third ring **530** and apertures **540***a-e* of the fourth ring **540** are not rotationally aligned with the first ring **518** and the second ring **520**. In some implementations, the apertures **518***a-e* and the apertures **530***a-e* are aligned, and the apertures **520***a-e* and the apertures **540***a-e* are rotationally offset from the first ring **518** and the third ring **530**. In some implementations, the second ring **520** and fourth ring **540** are rotationally offset from first ring **518** by different amounts such that a line **557** drawn through an aperture **520***b* of the second ring **520** does not pass through a center of any aperture **540***a-e* of the fourth ring **540**.

[0067] Each of the apertures **518***a-e*, **520***a-e*, **530***a-e*, and **540***a-e* of the plurality of apertures **516** has an associated height measured parallel to the longitudinal axis **544**, a width measured transverse to the longitudinal axis **544**, and an area. For example, aperture **518***a* has a height **538** and a width **541**. Aperture **518***a* also has an area **532** through which blood may pass. The aperture **520***b* of the second ring **520** has a height **554**, a width **556** and an area **534**. The aperture **530***b* of the third ring **530** has a height **558**, a width **560** and an area **536**. The aperture **540***b* of the fourth ring **540** has a height **562**, a width **564** and an area **566**. In some implementations, the measurements including one or more of the height, the width and the area of the apertures in a particular ring are common to all the apertures in that ring, however this is not required. In some implementations, the measurements, including one or more of the height, width, and area, vary amongst the apertures in a particular ring. In some implementations, the apertures **520***a-e* in the second ring **520**, the apertures **530***a-e* in the third ring **530**, and the apertures **540***a-e* in the fourth ring **540**, have the same measurements including one or more of the height, width and area. In some implementations, one or more of the height, width or area of the apertures vary between the apertures **520***a-e* in the second ring **520**, the apertures **530***a-e* in the third ring **530**, and the apertures **540***a-e* in the fourth ring **540**. In some implementations, the combined areas of the apertures **518***a-e* of the first ring **518**, the apertures **520***a-e* in the second ring **520**, the apertures **530***a-e* in the third ring **530**, and the apertures **540***a-e* in the fourth ring **540** is equal to or greater than a cross-sectional area of the cannula assembly.

[0068] Despite the apertures **518***a-e* of the first ring **518** having a larger area **532** than the apertures **520***a-e* in the second ring **520**, the apertures **530***a-e* in the third ring **530**, and the apertures **540***a-e* in the fourth ring **540**, blood flows predominantly through the most proximal apertures of the plurality of apertures **516** due to the smaller pressure drop at these apertures. If all or a portion of the apertures **540***a-e* of the fourth ring **540** are blocked by a valve leaflet, the blood may still flow through the rest of the apertures. The smaller areas of the apertures **520***a-e* in the second ring **520**, the apertures **530***a-e* in the third ring **530**, and the apertures **540***a-e* in the fourth ring **540**, and the struts **517***a-c* between the inlets decreases the likelihood that the additional inlets will be blocked by a valve leaflet.

[0069] FIG. **7** shows a front view of a distal end portion **714** of a cannula assembly **708** having a plurality of apertures **716** which are arranged in two rotationally offset rings. The cannula assembly **708** includes a cannula body **709**, a distal end portion **714**, a distal end **710**, an atraumatic tip **712**, a tear drop portion **742**, a longitudinal axis **744**, a plurality of struts **717***a-c*, and a plurality of apertures **716**. The plurality of apertures **716** is arranged in a first ring **718** of apertures **718***a-b*, and a second ring **720** of apertures **720***a-b*. The plurality of apertures **716** in the cannula assembly **708**

are arranged such that the first ring **718** of apertures **718***a-b* is rotationally offset from the second ring **720** of apertures **720***a-b*. A line **755** drawn parallel to the longitudinal axis **744** of the cannula assembly **708** through a center of aperture **718***a* of the first ring **718** does not pass through a center of any of apertures **720***a-b* of the second ring **720**. The line **755** instead passes through the strut **717***b* dividing aperture **720***a* and aperture **720***b* of the second ring **720**. Rotationally offset apertures may prevent a valve leaflet from completely blocking more than one of the apertures. For example, if a valve leaflet is suctioned to the cannula assembly **708** such that it covers aperture **718***a* of the first ring **718**, the rotational offset of the second ring **720** of apertures **720***a-b* may prevent the valve leaflet from blocking all of an additional aperture **720***a* or **720***b* of the second ring **720**.

[0070] While FIGS. **5**, **6** and **7** show a distal end portion of a cannula assembly (for example, distal end portion **514** of FIG. **5** or distal end portion **714** of FIG. **7**) with a plurality of rotationally offset apertures (for example, plurality of apertures **516** of FIG. **5** or plurality of apertures **716** of FIG. **7**), FIG. **8** shows a perspective view of a distal end portion **814** of a cannula assembly **808** in which the plurality of apertures **816** are rotationally aligned with one another. FIG. **9** shows an alternative perspective view of the distal end portion **914** with a plurality of rotationally aligned apertures **916**. The cannula assembly **908** includes a cannula body **909**, a distal end portion **914**, a distal end **910**, an atraumatic tip **912**, a tear drop portion **942**, an atraumatic tip connector **948**, a longitudinal axis **944**, and a plurality of apertures **916**. The plurality of apertures **916** are arranged in a first ring **918** of apertures **918***a-d*, and a second ring **920** of apertures **920***a-d*. The plurality of apertures **916** in cannula assembly **908** are arranged such that the first ring **918** of apertures **918***a-d* is rotationally aligned with the second ring **920** of apertures **920***a-d*. A line **955** drawn parallel to the longitudinal axis **944** of the cannula assembly **908** through a center of aperture **918***b* of the first ring **918** also passes through a center of apertures **920***b* of the second ring **920**. Apertures **918***a-d* and apertures **920***a-d* are shown with a larger height than width such that the area of each aperture **918***a-d* and **920***a-d* is defined by an oval shape through which blood may enter the cannula assembly **908**. Rotationally aligned apertures may be simpler to machine in a cannula assembly **908** than offset apertures.

[0071] FIG. **10** shows a front view of a distal end portion **1014** of a cannula assembly **1008** having a plurality of round apertures **1016**, which are rotationally offset from each other. The cannula assembly **1008** of FIG. **10** includes a distal end **1010**, distal end portion **1014**, an atraumatic tip connector **1048**, a tear drop portion **1042**, a longitudinal axis **1044**, an atraumatic tip **1012**, and a plurality of apertures **1016**. The plurality of apertures **1016** are disposed in a first ring **1018** of apertures **1018***a-c*, a second ring **1020** of apertures **1020***a-b*, a third ring **1030** of apertures **1030***a-c*, and a fourth ring **1040** of apertures **1040***a-b*. The apertures **1018***a-c* of the first ring **1018** are oblong in shape. In particular, the first ring **1018** of apertures **1018***a-c* are rounded on a proximal edge **1053** and have a distal edge **1051** defined by a portion of the tear drop portion **1042**. The apertures **1020***a-b* in the second ring **1020**, the apertures **1030***a-c* in the third ring **1030**, and the apertures **1040***a-b* in the fourth ring **1040** are circular. The apertures **1018***a-c* in the first ring **1018** and the apertures **1030***a-c* in the third ring **1030** are rotationally aligned such that the line **1055** through a center of aperture **1018***b* passes through a center of the aperture **1030***b*. The apertures **1020***a-b* in the second ring **1020** and the apertures **1040***a-b* in the fourth ring **1040** are rotationally offset from the apertures **1018***a-c* and the apertures **1030***a-c*, but are rotationally aligned with each other such that a line **1057** through a center of the aperture **1020** parallel to the longitudinal axis **1044** of the cannula **1008** passes through a center of the aperture **1040***a*. The plurality of apertures **1016** with circular shapes which are arranged in rings about the cannula assembly **1008** such that the apertures of each ring are rotationally offset from the apertures of the ring directly above or below it may decrease the likelihood that a valve leaflet will block multiple apertures.

[0072] While FIG. **10** shows a distal end portion **1014** of a cannula assembly **1008** having a first ring of apertures and three additional rings of round apertures, FIG. **11** shows a distal end portion **1114** of a cannula assembly having a first ring of apertures and only two additional rings of round

apertures. The distal end portion **1114** of FIG. **11** includes a distal end **1110**, an atraumatic tip connector **1148**, a tear drop portion **1142**, a longitudinal axis **1144**, and a plurality of apertures **1116**. The plurality of apertures **1116** are disposed in a first ring **1118** of apertures **1118***a-d*, a second ring **1120** of apertures **1120***a-c*, and a third ring **1130** of apertures **1130***a-c*. The apertures **1118***a-e* of the first ring **1118** are oblong in shape and are defined on a distal edge **1151** by a portion **1152** of the tear drop portion **1142**. A proximal edge **1153** of the apertures **1118***a-e* is rounded. The apertures **1120***a-c* in the second ring **1120** and the apertures **1130***a-c* in the third ring **1130** are circular. Like the plurality of apertures **1116** in FIG. **10**, the rings of the plurality of apertures **1116** are rotationally offset. For example, the apertures **1118***a-e* in the first ring **1118** and the apertures **1130***a-c* in the third ring **1130** are rotationally aligned such that the line **1155** through a center of the aperture **1118***b* passes through a center of the aperture **1130***a*.

[0073] While FIGS. **10** and **11** show distal end portions having a plurality of circular an oblong apertures, FIG. **12** shows a front view of a distal end portion **1214** of a cannula assembly having a plurality of apertures **1216**, with a first ring **1218** having apertures **1218***a* with a tear drop shape, while apertures in additional rings are circular. The distal end portion **1214** includes a distal end **1210**, an atraumatic tip connector **1248**, a tear drop portion **1242**, a longitudinal axis **1244**, and a plurality of apertures **1216**. The plurality of apertures **1216** are disposed in a first ring **1218** of aperture **1218***a*, a second ring **1220** of apertures **1220***a-b*, and a third ring **1230** of aperture **1230***a*. Though a single aperture **1218***a* and **1230***a* are visible in FIG. **12**, there may be multiple apertures in each ring **1218**, **1220**, and **1230** disposed radially about the circumference of the distal end **1214** of the cannula assembly. The apertures **1218***c* in the first ring **1218** are tear-shaped such that a distal edge **1251** defined by a portion **1252** of the tear drop portion **1242** of the atraumatic tip connector **1248** is rounded and a proximal edge **1253** is pointed in a direction of blood flow through the cannula. The second ring **1220** of apertures **1220***a-b*, and the third ring **1230** of aperture **1230***a* are circular. In some implementations, one or both of the second ring **1220** of apertures **1220***a-b*, and the third ring **1230** of aperture **1230***a* are rotationally aligned with the first ring **1218** of apertures **1218***a*.

[0074] While FIG. **12** shows a first ring **1218** of tear-shaped apertures with apertures of other rings being circular, in some implementations all of the apertures are tear-shaped. For example, FIG. **13** shows a front view of a distal end portion **1314** having tear-shaped apertures in the first ring **1318** and a plurality of tear-shaped apertures arranged in a second ring **1320** and third ring **1330**. The distal end portion **1314** includes a distal end **1310**, an atraumatic tip connector **1348**, a tear drop portion **1342**, a longitudinal axis **1344**, and a plurality of apertures **1316** disposed in a first ring **1318** of aperture **1318***a*, a second ring **1320** of apertures **1320***a-b*, and a third ring **1330** of aperture **1330***a*. As in FIG. **11**, though a single aperture **1218***a* and **1230***a* are visible in the first ring **1218** and the third ring **1230** in FIG. **12**, each ring may include a plurality of apertures disposed about the distal end portion **1214** of the cannula assembly. Similarly to the first ring **1218** of aperture **1218***a* of FIG. **12**, the aperture **1318***a* in the first ring is tear-shaped with a rounded distal edge **1351** defined by the tear drop portion **1342** of the atraumatic tip connector **1348** and a proximal edge **1353** that is pointed along the longitudinal axis **1344**. The apertures **1320***a-b* in the second ring **1320** and the apertures **1330***a-c* in the third ring **1330** are also tear-shaped, with each aperture having a rounded distal end and a pointed proximal end. The larger opening at a distal end tapering to the pointed opening at a proximal end may facilitate blood flow through the apertures and limit stagnation of the blood as it flows into the plurality of apertures **1316**.

[0075] Variations in the number and size of the apertures in the distal end portion can alter the flow distribution of blood into the cannula. FIGS. **14-23** show further arrangements of apertures in a distal end portion of a cannula. All arrangements in FIGS. **14-23** show the plurality of apertures disposed on a similar portion of the distal end portion of the cannula, but the apertures vary in the shape, positioning, and relative size. FIG. **14** shows a front view of a distal end portion **1414** of a heart pump assembly having a plurality of apertures **1416** arranged into three rings of apertures

according to certain implementations. The distal end portion **1414** includes a distal end **1410**, an atraumatic tip connector **1448**, a tear drop portion **1442**, a longitudinal axis **1444**, a plurality of apertures **1416**, a first circumferential strut **1463** and a second circumferential strut **1465**. The circumferential struts **1463** and **1465** run about a circumference of the distal end portion **1414** and divide the plurality of apertures **1416** into rings of apertures. The plurality of apertures **1416** are disposed in a first ring **1418** of apertures **1418***a-c*, a second ring **1420** of apertures **1420***a-c*, and a third ring **1430** of apertures **1430***a-c*. The first circumferential strut **1463** divides the first ring **1418** from the second ring **1420**. The second circumferential strut **1465** divides the second ring **1420** from the third ring **1430**. The apertures **1418***a-c* are defined on one side by the tear drop portion **1442**. The apertures **1418***a-c* of the first ring **1418** are oblong in shape, each having a height that is larger than a width. The apertures **1420***a-c* of the second ring **1420** and apertures **1430***a-c* of the third ring **1430** are oblong, each having a width that is larger than a height. Additionally, apertures **1420***a-c* of the second ring **1420** and apertures **1430***a-c* of the third ring **1430** have a proximal edge which is rounded and a distal edge which is straight.

[0076] FIG. **15** shows a front view of a distal end portion **1514** of a cannula assembly according to certain implementations. The distal end portion **1514** includes a distal end **1510**, an atraumatic tip connector **1548**, a tear drop portion **1542**, a longitudinal axis **1544**, a plurality of apertures **1516**, a first circumferential strut **1563** and a second circumferential strut **1565**. The circumferential struts **1563** and **1565** run about a circumference of the distal end portion **1514** and divide the plurality of apertures **1516** into rings of apertures. The plurality of apertures **1516** are arranged into three rings of apertures, a first ring **1518** of apertures **1518***a-c*, a second ring **1520** of apertures **1520***a-c*, and a third ring **1530** of apertures **1530***a-c*. The first circumferential strut **1563** divides the first ring **1518** from the second ring **1520**. The second circumferential strut **1565** divides the second ring **1520** from the third ring **1530**. The apertures **1518***a-c* of the first ring **1518** are defined on one side by the tear drop portion **1542** and have a lesser height along the longitudinal axis **1544** than the apertures **1418***a-c* of the first ring **1418** in FIG. **14**. The size and shape of apertures **1520***a-c* and apertures **1530***a-c* are the same as in FIG. **14**. Additionally, the first circumferential strut **1563** between the first ring **1518** and second ring **1520** has a larger height in the direction of the longitudinal axis **1544** than the first circumferential strut **1463** dividing the first ring **1418** and second ring **1420** in FIG. **14**. This may provide additional area which is non-sucking that can prevent suctioning of the valve leaflets to the cannula assembly according to certain implementations.

[0077] FIG. **16** shows a front view of a distal end portion **1614** according to certain implementations. The distal end portion **1614** includes a distal end **1610**, an atraumatic tip connector **1648**, a tear drop portion **1642**, a longitudinal axis **1644**, a plurality of apertures **1616**, and at a first circumferential strut **1663** and a second circumferential strut **1665**. The circumferential struts **1663** and **1665** run about a circumference of the distal end portion **1614** and divide the plurality of apertures **1616** into rings of apertures. The plurality of apertures **1616** are arranged into three rings of apertures, a first ring **1618** of apertures **1618***a-c*, a second ring **1620** of apertures **1620***a-c*, and a third ring **1630** of apertures **1630***a-c*. The first circumferential strut **1663** divides the first ring **1618** from the second ring **1620**. The second circumferential strut **1665** divides the second ring **1620** from the third ring **1630**. The apertures **1618***a-c* of the first ring **1618** are defined on one side by the tear drop portion **1642**. A height of the apertures **1618***a-c* of the first ring **1618** which is less than the height of the apertures **1518***a-c* of the first ring **1518** in FIG. **15**. The size and shape of apertures **1620***a-c* and apertures **1630***a-c* are the same as in FIGS. **14** and **15**, but the height of the apertures **1618***a-c* of the first ring **1618** is less than the height of the corresponding apertures in FIGS. **14** and **15**. The first circumferential strut **1663** dividing the first ring **1618** from the second ring **1620** is additionally greater in height along the longitudinal axis **1644** in the arrangement of FIG. **16** than in the corresponding circumferential struts **1463** and **1563** in FIG. **14** or **15**.

[0078] FIG. **17** shows a front view of a distal end portion **1714** of a cannula assembly having a

plurality of apertures **1716** arranged into two rings of apertures according to certain implementations. The distal end portion **1714** includes a distal end **1710**, an atraumatic tip connector **1748**, a tear drop portion **1742**, a longitudinal axis **1744**, a plurality of apertures **1716**, and a circumferential strut **1763**. The circumferential strut **1763** runs about a circumference of the distal end portion **1714** and divides the plurality of apertures **1716** into rings of apertures. The plurality of apertures **1716** are disposed in a first ring **1718** of apertures **1718***a-c*, and a second ring **1720** of apertures **1720***a-c*. The circumferential strut **1763** divides the first ring **1718** from the second ring **1720**. The shape of the apertures **1718***a-c* of the first ring **1718** may be the same oblong shape defined at a distal edge **1751** by the tear drop portion **1742** as in FIGS. **14-16**. The size and shape of the apertures **1720***a-c* of the second ring **1720** may be the same as in FIGS. **14-16**. The apertures **1718***a-c* of the first ring **1718** and the apertures **1720***a-c* of the second ring **1720** are shown offset from one another. However, in some implementations, the apertures **1718***a-c* of the first ring **1718** are rotationally aligned with the apertures **1720***a-c* of the second ring **1720**.

[0079] FIG. **18** shows a front view of a distal end portion **1814** of a cannula assembly having a plurality of apertures **1816** arranged into two rings of apertures according to certain implementations. The distal end portion **1814** of the cannula **1808** includes a distal end **1810**, an atraumatic tip connector **1848**, a tear drop portion **1842**, a plurality of apertures **1816**, and a circumferential strut **1863**. The circumferential strut **1863** runs about a circumference of the distal end portion **1814** and divides the plurality of apertures **1816** into rings of apertures. The plurality of apertures **1816** are arranged into a first ring **1818** having apertures **1818***a-c* and a second ring **1820** having apertures **1820***a-c*. The circumferential strut **1863** divides the first ring **1818** from the second ring **1820**. The apertures **1818***a-c* of the first ring **1818** are defined on one side by the tear drop portion **1842** and have a lesser height than the apertures **1718***a-c* of the distal end portion of FIG. **17**. The area through which blood may enter the cannula assembly **1808** may be decreased in FIG. **18** as compared to FIG. **17**. However, the circumferential strut **1863 1820** is greater in FIG. **18** than circumferential strut **1763** in FIG. **17**. This increases the area over which there is no suction and may decrease the likelihood of suctioning a valve leaflet or other tissue to the cannula assembly.

[0080] FIGS. **19-23** show arrangements according to various implementations in which a distal end portion includes a plurality of apertures arranged in four rings. For example, FIG. **19** shows a front view of a distal end portion **1914** of a cannula assembly. The distal end portion **1914** includes a distal end **1910**, an atraumatic tip connector **1948**, a tear drop portion **1942**, a longitudinal axis **1944**, a plurality of apertures **1916**, a first circumferential strut **1963**, a second circumferential strut **1965**, and a third circumferential strut **1967**. The circumferential struts **1963**, **1965**, and **1967** run about a circumference of the distal end portion **1914** and divide the plurality of apertures **1916** into rings of apertures. The plurality of apertures **1916** is disposed in a first ring **1918** of apertures **1918***a-c*, a second ring **1920** of apertures **1920***a-c*, a third ring **1930** of apertures **1930***a-c*, and a fourth ring **1940** of apertures **1940***a-c*. The first circumferential strut **1963** divides the first ring **1918** from the second ring **1920**. The second circumferential strut **1965** divides the second ring **1920** from the third ring **1930**. The third circumferential strut **1967** divides the third ring **1930** from the fourth ring **1940**. The apertures **1918***a-c* are defined on one side by the tear drop portion **1942**. The respective heights of the apertures **1918***a-c* of the first ring **1918**, the apertures **1920***a-c* of the second ring **1920**, the apertures **1930***a-c* of the third ring **1930**, and the apertures **1940***a-c* of the fourth ring **1940** are similar. The first circumferential strut **1963** has a similar height as the second circumferential strut **1965** which is also similar to a height of the third circumferential strut **1967**. The area of the apertures **1918***a-c* of the first ring **1918** is similar to the areas of the apertures **1920***a-c* of the second ring **1920**, the apertures **1930***a-c* of the third ring **1930**, and the apertures **1940***a-c* of the fourth ring **1940**. Though the apertures in the second ring **1920**, the third ring **1930**, and the fourth ring **1940** are shown in alignment with the apertures **1918***a-c* of the first ring, in some implementations the apertures can also be rotationally offset.

[0081] FIG. **20** shows a front view of a distal end portion **2014** of a cannula assembly **2008** having a plurality of apertures **2016** in which each ring of apertures has a different size and shape according to certain implementations. The distal end portion **2014** includes a distal end **2010**, an atraumatic tip connector **2048**, a tear drop portion **2042**, a longitudinal axis **2044**, and a plurality of apertures **2016**. The plurality of apertures **2016** are disposed in a first ring **2018** of apertures **2018***a-c*, a second ring **2020** of apertures **2020***a-b*, a third ring **2030** of apertures **2030***a-b*, and a fourth ring **2040** of apertures **2040***a-b*. The apertures **2018***a-c* are defined on one side by the tear drop portion **2042**. The apertures **2018***a-c* of the first ring **2018** have the greatest height of the plurality of apertures **2016**. The apertures **2020***a-b* of the second ring **2020** have the next greatest height. The apertures **2030***a-b* of the third ring **2030** have the next greatest height. The apertures **2040***a-b* of the fourth ring **2040** are the smallest in height of the plurality of apertures **2016**. The plurality of apertures **2016** are shown having rounded shapes; however, the plurality of apertures **2016** may have any suitable shape while maintaining the relationship between the heights. In some implementations, the height the apertures **2018***a-c* of the first ring **2018** is less than six times the height of the apertures **2020***a-b* of the second ring **2020**. In some implementations, the height of the apertures **2020***a-b* of the second ring **2020** is less than three times the height of the apertures **2030***a-b* of the third ring **2030**. In some implementations, the height of the apertures **2030***a-b* of the third ring **2030** is less than five times the height of the apertures **2040***a-b* of the fourth ring **2040**.
[0082] In each of FIGS. **21-22** the apertures of the first ring have the same oblong shape and same size, and the apertures of the second, third and fourth rings have the same size and shape. In FIG. **21**, a distal end portion **2114** includes a distal end **2110**, an atraumatic tip connector **2148**, a tear drop portion **2142**, a longitudinal axis **2144**, and a plurality of apertures **2116**. The plurality of apertures **2116** are disposed in a first ring **2118** of apertures **2118***a-c*, a second ring **2120** of apertures **2120***a-c*, a third ring **2130** of apertures **2130***a-c*, and a fourth ring **2140** of apertures **2140***a-c*. The apertures **2118***a-c* of the first ring **2118** are oblong. In particular, the first ring **2118** of apertures **2118***a-c* are rounded on a proximal edge **2153** and have a distal edge **2151** defined by a portion **2152** of tear drop portion **2142**. The apertures **2120***a-c* in the second ring **2120** are the same shape and size as the apertures **2130***a-c* in the third ring **2130** and as the apertures **2140***a-c* in the fourth ring **2140**. The plurality of apertures **2116** in the second ring **2120**, the third ring **2130**, and the fourth ring **2140** are oblong, each having a width which is greater than a height as measured along a line parallel to the longitudinal axis **2144**. The plurality of apertures **2116** in the second ring **2120**, the third ring **2130**, and the fourth ring **2140** are rounded at their proximal edges **2169***a-c* with the centers of the proximal edges **2153** and **2169***a-c* being the proximal-most point of each aperture. Each aperture has an inner edge **2171***a-d*. The inner edge **2171***a-d* of each of the plurality of apertures **2116** is chamfered. The chamfer may be at an angle of 45 degrees or less relative to a line normal to the surface of the cannula assembly **108**. In some implementations, the chamfered inner edge **2171***a-d* includes a chamfer of 10. degree., 20. degree., 30. degree., 40. degree., 50. degree., >50. degree., or any other suitable angle. The use of a chamfered inner edge **2171***a-d* can reduce hemolysis of the blood as it enters the cannula assembly **2108**. Though the chamfered inner edge **2171***a-d* is shown here in an arrangement having four rings of apertures, a chamfered inner edge may be used in any of the arrangements shown herein. In FIG. **22**, as in FIG. **21**, the distal end portion **2214** includes a distal end **2210**, an atraumatic tip connector **2248**, a tear drop portion **2242**, a longitudinal axis **2244**, and a plurality of apertures **2216** disposed in a first ring **2218** of apertures **2218***a-c*, a second ring **2220** of apertures **2220***a-c*, a third ring **2230** of apertures **2230***a-c*, and a fourth ring **2240** of apertures **2240***a-c*. Each of the plurality of apertures **2216** has an inner edge **2271***a-d*, which is rounded. In some implementations, the rounded inner edge **2271***a-d* includes a radius ranging from 40 microns to 105 microns. In some implementations, only an outward facing portion of the inner edge **2271***a-d* is rounded. In some implementations, the rounding of the inner edge **2271***a-d* is accomplished by polishing. In some implementations, the rounding of the inner edge **2271***a-d* is accomplished by a tumbling process. Rounded edges may decrease hemolysis of

the blood as it enters the cannula assembly **2208** through the plurality of apertures **2216**. Though the rounded inner edge **2271***a-d* is shown here in an arrangement having four rings of apertures, a rounded inner edge may be used in any of the arrangements shown herein.

[0083] FIG. **23** shows a front view of a distal end portion **2314** of a cannula assembly. The distal end portion **2314** includes a distal end **2310**, an atraumatic tip connector **2348**, a tear drop portion **2342**, a longitudinal axis **2344**, and a plurality of apertures **2316**. The plurality of apertures is disposed in a first ring **2318** of apertures **2318***a-c*, a second ring **2320** of apertures **2320***a-c*, a third ring **2330** of apertures **2330***a-c*, and a fourth ring **2340** of apertures **2340***a-c*. The apertures **2318***a-c* of the first ring **2318** have an oblong shape defined at a distal edge **2351** by the tear drop portion **2342**. The plurality of apertures **2320***a-c*, **2330***a-c*, and **2340***a-c* of the second ring **2320**, third ring **2330**, and fourth ring **2340**, respectively, are oval in shape such that a width is larger than a height, and all of the plurality of apertures in the second ring **2320**, third ring **2330**, and fourth ring **2340** are the same size.

[0084] FIG. **24** shows a plot **2400** displaying a predicted flow of fluid through the plurality of apertures to the arrangement of FIG. **23**. The plot **2400** includes a cut-away of a distal end portion **2414** of a cannula assembly, a second aperture **2420**, a fourth aperture **2440**, and a box **2441** indicating a region of high flow. The plot shows the predicted flow of fluid through two apertures of a heart pump as shown in cross-section. The heart pump has a first, second, third, and fourth ring of apertures, though only an aperture of the second ring **2420** and fourth ring **2440** are visible, as the first ring **2418** and third ring **2430** are rotationally offset in the depicted implementation. Areas of higher velocities in the plot are depicted with longer lines, while areas of lower flow are shown with fewer lines. The velocity magnitude of the fluid flow ranges from 1.28.Math.times.Math.e.sup.−05 m/s (about 0 m/s) to 6.08 m/s. The highest volumetric flow rate (highlighted by the box **2441**) occurs at the most proximal apertures, in this case through the aperture **2440***a* of the fourth ring **2440**. The high inflow of fluid into the cannula assembly **2408** at this point is due to the relatively higher-pressure gradient at this aperture. The blood is pulled from outside of the cannula assembly **2408**, through the apertures and into the cannula assembly **2408** where the blood flows to the downstream apertures (not shown).

[0085] FIG. **25** shows a percutaneous heart pump assembly **2500** having a plurality of apertures **2516** at a distal end portion **2514** inserted into a blood vessel **2501** of a patient. In particular, the heart pump assembly **2500** is introduced through a blood vessel **2501** of a patient and into a heart **2503**. The heart **2503** includes an aorta **2568**, aortic arch **2577**, aortic valve **2570**, left ventricle **2572**, left atrium **2576**, and mitral valve **2574**, as well as other structures. The heart pump assembly **2500** includes a catheter **2528**, a motor housing **2502**, a cannula assembly **2508**, a cannula body **2509**, a distal end portion **2514**, a proximal end **2506**, a distal end **2510**, an atraumatic tip **2512**, a plurality of apertures **2516**, and a plurality of blood exhaust outlets **2524**. The motor housing **2502** of the heart pump assembly **2500** is connected to a motor (not shown). The motor is internal to and integrated with the motor housing **2502**. In other implementations the motor is external to the body and connected to the pump via a drive shaft (not shown) within a catheter **2528** and in such an example the assembly **2508** may not include the motor housing **2502**. The cannula assembly **2508** is connected to a distal end of the motor housing **2502**. The distal end portion **2514** of the cannula assembly **2508** includes the plurality of apertures **2516** through which blood may enter the cannula assembly **2508**. The plurality of apertures **2516** are arranged into at least a first ring **2518** and a second ring **2520** of apertures which are radially oriented and disposed about a circumference of the cannula assembly **2508**. Though two rings of apertures are depicted here, any arrangement of apertures described herein may be used. In some implementations, the plurality of apertures **2516** is arranged into three, four, or more rings of apertures. The atraumatic tip **2512** is coupled to the distal end **2510** of the cannula assembly **2508**, distal of the plurality of apertures **2516**. Blood is pulled into the cannula assembly **2508** at the plurality of apertures **2516** along path **2578**. The blood passes through the cannula assembly **2508** and exits at the plurality of blood exhaust outlets **2524**

proximal to the motor housing **2502** via path **2580**.
[0086] The heart pump assembly **2500** may be introduced percutaneously during a cardiac procedure through the vascular system. Specifically, the heart pump assembly **2500** can be inserted percutaneously via a catheterization procedure through the femoral artery, into the ascending aorta **2568**, across the aortic valve **2570** and into the left ventricle **2572**. The heart pump assembly **2500** can be positioned in a heart **2503** of a patient such that the heart pump assembly is inserted over the aortic arch **2577**. The plurality of blood exhaust outlets **2524** may be positioned in the aorta **2568** above the aortic valve **2570**. The cannula assembly **2508** is positioned across the aortic valve **2570** such that the plurality of apertures **2516** through which blood enters is placed in the left ventricle **2572** of the heart **2503**. The atraumatic tip **2512** spaces the cannula assembly **2508** from the walls of the heart **2503** and prevents the plurality of apertures **2516** from suctioning to the walls of the heart **2503**.
[0087] In some instances, however, the positioning of the heart pump assembly **2500** places the plurality of apertures **2516** near the mitral valve leaflets **2574** at the entrance to the left atrium **2576**. This may be due to the individual anatomy of the particular heart **2503**. The mitral valve leaflets **2574** may be sucked by the suction of the pump towards the plurality of apertures **2516** and may become suctioned to some of the plurality of apertures **2516**, blocking the inflow of blood through the plurality of apertures **2516**. In some instances, in particular in pumps with large inlets, for example heart pump assembly **100** in FIG. **1**, the mitral valve leaflets **2574** can be sucked through one of the plurality of apertures **2516** into the cannula assembly **2508** where the mitral valve leaflet **2574** blocks blood flow through the cannula. A plurality of apertures **2516** of a smaller size prevents the suctioning of the mitral valve leaflets to the plurality of apertures **2516**. Furthermore, the plurality of apertures **2516** allows blood flow through the cannula assembly **2508** to be maintained despite suction of the mitral valve leaflet **2574** or other tissue or debris to some of the plurality of apertures **2516**. In another embodiment (not shown) the heart pump assembly may be designed to support a patient's right heart. In certain aspects, the device may be inserted percutaneously through the femoral vein, into the right atrium or inserted via other techniques. With the device so positioned, the cannula of the assembly may extend across the tricuspid and pulmonic valves, and into the pulmonary artery. In this case, the plurality of apertures can be located on the inlet of the pump which is positioned in the inferior vena cava (IVC). As will be appreciated, such a device can include any of the configurations of apertures described above. The device may or may not include an atraumatic tip or projection.
[0088] FIG. **26** is a flow chart of a method for manufacturing a heart pump (e.g., heart pump assembly **200** of FIG. **2**, heart pump assembly **400** of FIG. **4**, heart pump assembly **2500** of FIG. **25**, or any other suitable heart pump) having a plurality of apertures at a distal end portion, according to certain implementations. The method **2600** may be implemented to form a heart pump having any number of apertures at the distal end portion, disposed in any number of rings. The method **2600** may be implemented for manufacture of a heart pump assembly having apertures of any size or shape with straight, chamfered or rounded edges. In step **2602** an impeller blade is coupled to a rotor of a motor. The impeller blade may have any suitable number of blades and may be rotated by a drive shaft connected to a motor. In some implementations, the motor is configured to be external to a patient during operation of the pump. In some implementations, the motor is integrated with the motor housing. In step **2604**, the impeller blade is inserted into a motor housing. In step **2606**, a cannula is coupled to the motor housing. The cannula may be attached to a distal end of the motor housing. In some implementations, the cannula is expandable. In some implementations, the cannula is self-expandable. In some implementations, the cannula may be comprised of a mesh, such as a nitinol mesh, covered by an elastic covering. In some implementations, the cannula may be comprised of a solid wire such as nitinol wire with a polymer cover or fabric.
[0089] In step **2608**, the cannula is coupled to an inflow cage which comprises a plurality of

apertures. In some implementations, the inflow cage is comprised of stainless steel. The plurality of apertures may be of any number, shape, or size which is suitable for the passage of blood through the apertures in the inflow cage and into the cannula. The plurality of apertures is radially oriented about a circumference of the inflow cage. The plurality of apertures is arranged into at least a first ring of apertures and a second ring of apertures proximal of the first ring of apertures. The number of apertures in a ring is 3, 4, 5, 6, 7, 8, 9, 10 or any other suitable number of apertures. In some implementations, the number of apertures in the first ring is the same as the number of apertures in the second ring. The first ring of apertures extends to an end of the distal end portion of the inflow cage. In some implementations, the plurality of apertures additionally has more rings, including a third ring proximal of the second ring and a fourth ring proximal of the third ring. Each of the plurality of apertures may have an outer edge which in some implementations is formed or altered by a tumbling process.

[0090] The plurality of apertures may have a size, shape, number, or positioning which helps to prevent the suction of heart tissues including valve leaflets onto or into the plurality of apertures which blocks the inflow of blood to the pump, limiting efficiency of the heart pump. For example, in some implementations, the height of the first apertures is less than 9 mm. In some implementations, the height of the aperture of the first ring is 0.5 mm, 1 mm, 3 mm, 5 mm, 6 mm, 9 mm, 10 mm, 12 mm, 15 mm or any other suitable height. In some implementations, the height of the second aperture is less than 3 mm. In some implementations, the height of the aperture of the second ring is 0.25 mm, 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 5, mm, 6 mm, or any other suitable height. In some implementations, a width of the second aperture is less than 4 mm. In some implementations, the width of the apertures of the second ring is 0.5 mm, 1 mm, 1.5 mm, 2 mm, 2.5 mm, 3 mm, 3.5 mm, 4 mm, 5, mm, 6 mm, 8 mm, or any other suitable width. In some implementations, a height and width of an aperture in the third ring is the same as the height and width of an aperture in the second ring.

[0091] The area of each aperture may vary. In some implementations, the area of an aperture in the first ring is greater than the area of apertures in other rings. In some implementations, the area of the first aperture is less than 20 mm.sup.2. In some implementations, the area of the aperture of the first ring is 0.5 mm.sup.2, 1 mm.sup.2, 5 mm.sup.2, 10 mm.sup.2, 15 mm.sup.2, 18 mm.sup.2, 20 mm.sup.2, 23 mm.sup.2, 25 mm.sup.2 or any other suitable area. The area of aperture of the second ring may be less than 12 mm.sup.2. In some implementations, the area of the apertures of the second ring may be 0.25 mm.sup.2, 0.5 mm.sup.2, 1 mm.sup.2, 2 mm.sup.2, 5 mm.sup.2, 10 mm.sup.2, 12 mm.sup.2, or any other suitable area.

[0092] The apertures may have inner edges which are straight, rounded or chamfered. In some implementations, the apertures have at least one chamfered edge. The chamfer may be at an angle of 45 degrees or less relative to a line normal to the surface of the inflow cage. In some implementations, the chamfered inner edge includes a chamfer of 10. degree., 20. degree., 30. degree., 40. degree., 50. degree., >50. degree., or any other suitable angle. The use of a chamfered inner edge can reduce hemolysis of the blood as it enters the inflow cage. In some implementations, the apertures have at least one rounded edge. In some implementations, the rounded inner edge includes a radius ranging from 40 microns to 105 microns.

[0093] In some implementations, the plurality of apertures is formed in a distal end portion of the cannula. In some implementations, the distal end portion of the cannula is comprised of stainless steel. The plurality of apertures formed in the cannula may be of any number, shape, or size which is suitable for the passage of blood through the apertures and into the cannula. The plurality of apertures may be radially oriented about a circumference of the cannula. The plurality of apertures is arranged into at least a first ring of apertures and a second ring of apertures proximal of the first ring of apertures. The number of apertures in a ring is 3, 4, 5, 6, 7, 8, 9, 10 or any other suitable number of apertures. In some implementations, the number of apertures in the first ring is the same as the number of apertures in the second ring. The first ring of apertures extends to an end of the

distal end portion of the cannula. In some implementations, the plurality of apertures additionally has more rings, including a third ring proximal of the second ring and a fourth ring proximal of the third ring. Each of the plurality of apertures may have an outer edge which in some implementations is formed or altered by a tumbling process.

[0094] In step **2610**, a distal projection is coupled to the distal end of the inflow cage. The distal projection or atraumatic tip is distal to the plurality of apertures. A base of the distal projection may form a distal edge of the plurality of apertures in the first ring of apertures. In some implementations, this step is optional and no distal projection is attached to the heart pump. In some implementations, the distal projection is configured as a pigtail. In some implementations, the distal projection is configured as a flexible projection or extension. The distal projection is an atraumatic tip configured to space the plurality of apertures on the inflow cage away from a wall of the heart. In some implementations, the distal projection includes a lumen through which a guidewire may be inserted. The distal projection provides mechanical lengthening of the cannula in order to prevent suction at the plurality of apertures to the tissues of the heart.

[0095] FIG. **27** shows a flow chart of a method for use of a heart pump (e.g., heart pump assembly **200** of FIG. **2**, heart pump assembly **400** of FIG. **4**, heart pump assembly **2500** of FIG. **25**, or any other suitable heart pump) having a plurality of apertures at a distal end portion. The method **2700** may be implemented to form a heart pump having any number of apertures at the distal end portion, disposed in any number of rows. The method **2700** may be implemented for use of a heart pump assembly having apertures of any size or shape with straight, chamfered or rounded edges. In step **2702**, an impeller is rotated about a rotation axis using a pump motor to draw blood into a cannula of a heart pump assembly at a plurality of blood inlet apertures. The motor may be external to a patient and connected to the impeller by a drive shaft. Alternatively, the motor may be integrated into the pump and used internally. The blood inlet apertures may have any size, shape or number. The blood inlet apertures are radially oriented about a circumference of the cannula and are arranged in at least two rings at a distal end portion of the cannula. The size, shape, number, and position of the blood inlet apertures can be configured to decrease the occurrence of suctioning of heart tissues, valve leaflets and other debris to block the inlet apertures.

[0096] In step **2704**, the blood is expelled from the heart pump assembly at a plurality of blood exhaust apertures disposed at a proximal end portion of the cannula proximal to the motor housing. The blood may be sucked into the cannula at the blood inlet apertures in the left ventricle and may be expelled from the blood exhaust apertures into the aorta above the aortic valve. The plurality of small inflow apertures prevents or reduces the tendency of the aperture to suck against heart structures or valve leaflets. The small apertures prevent the pump from sucking a leaflet into the inlet, allowing the pump to provide more assistance to the heart and decreasing potential damage to heart structures which may be suctioned to the pump.

[0097] The foregoing is merely illustrative of the principles of the disclosure, and the apparatuses can be practiced by other than the described embodiments, which are presented for purposes of illustration and not of limitation. It is to be understood that the apparatuses disclosed herein, while shown for use in percutaneous heart pumps, may be applied to apparatuses in other applications requiring a clear aperture for inflow.

[0098] Variations and modifications will occur to those of skill in the art after reviewing this disclosure. The disclosed features may be implemented, in any combination and subcombination (including multiple dependent combinations and subcombinations), with one or more other features described herein. The various features described or illustrated above, including any components thereof, may be combined or integrated in other systems. Moreover, certain features may be omitted or not implemented.

[0099] Examples of changes, substitutions, and alterations are ascertainable by one skilled in the art and could be made without departing from the scope of the information disclosed herein. All

references cited herein are incorporated by reference in their entirety and made part of this application.

Claims

1.-**40**. (canceled)
41. A heart pump assembly comprising: a rotor; a motor coupled to the rotor; an impeller blade coupled to the rotor such that rotation of the rotor causes the impeller blade to rotate and pump blood; a catheter; and a cannula assembly comprising a cannula body and a blood inlet including a plurality of apertures radially oriented and disposed about a constant circumference exterior portion of the blood inlet, wherein the plurality of apertures include at least a first row of apertures spaced apart linearly about the constant circumference exterior portion of the blood inlet and a second row of apertures spaced laterally from the first row of apertures on the constant circumference exterior portion of the blood inlet, wherein the second row of apertures are proximal of the first row of apertures such that the second row of apertures are closer to the catheter than the first row of apertures, and wherein apertures in the first row of apertures are oblong in shape and are rotationally offset from apertures in the second row of apertures, which are circular in shape.
42. The heart pump assembly of claim 41, wherein a first aperture in the first row of apertures and a second aperture in the second row of apertures are not aligned along an axis on a surface of the cannula body parallel to a longitudinal axis of the cannula body.
43. The heart pump assembly of claim 41, wherein the apertures in the first row of apertures are rounded on a proximal edge and have a distal edge defined by a tear drop portion of the cannula assembly, wherein the proximal edge is closer to the catheter than the distal edge.
44. The heart pump assembly of claim 41, wherein the plurality of apertures further comprises a third row of apertures proximal of the second row of apertures.
45. The heart pump assembly of claim 44, wherein the apertures in the first row of apertures are rotationally aligned with apertures in the third row of apertures.
46. The heart pump assembly of claim 44, wherein a first aperture in the first row of apertures and a third aperture in the third row of apertures are aligned along an axis on a surface of the cannula body parallel to a longitudinal axis of the cannula body.
47. The heart pump assembly of claim 44, wherein apertures in the third row of apertures are circular in shape.
48. The heart pump assembly of claim 44, wherein the plurality of apertures further comprises a fourth row of apertures proximal of the third row of apertures.
49. The heart pump assembly of claim 48, wherein apertures in the fourth row of apertures are circular in shape.
50. The heart pump assembly of claim 48, wherein the apertures in the second row of apertures are rotationally aligned with apertures in the fourth row of apertures.
51. The heart pump assembly of claim 48, wherein a second aperture in the second row of apertures and a fourth aperture in the fourth row of apertures are aligned along an axis on a surface of the cannula body parallel to a longitudinal axis of the cannula body.
52. The heart pump assembly of claim 50, wherein the apertures in the second row of apertures and the apertures in the fourth row of apertures are rotationally offset from the apertures in the first row of apertures and the apertures in the third row of apertures.
53. The heart pump assembly of claim 41, wherein each of the plurality of apertures is defined by an inner edge intersecting an interior of the cannula body and an outer edge intersecting an outer surface of the cannula body.
54. The heart pump assembly of claim 41, wherein each of the plurality of apertures is defined by an inner edge intersecting an interior of the cannula body and an outer edge intersecting an outer surface of the cannula body, and wherein the outer edge of each of the plurality of apertures is

chamfered.

55. The heart pump assembly of claim 41, further comprising a distal projection coupled to a distal end of the cannula assembly.

56. The heart pump assembly of claim 41, wherein the heart pump assembly is sized for percutaneous insertion.