

[72] Inventors **Brian J. Bellhouse**
The Ridings, Islip, near Oxford;
Francis H. Bellhouse, 34 Hill Rise, Old
Woodstock, both of England

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[56]

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Primary Examiner—Robert M. Walker

Attorney—Shapiro and Shapiro

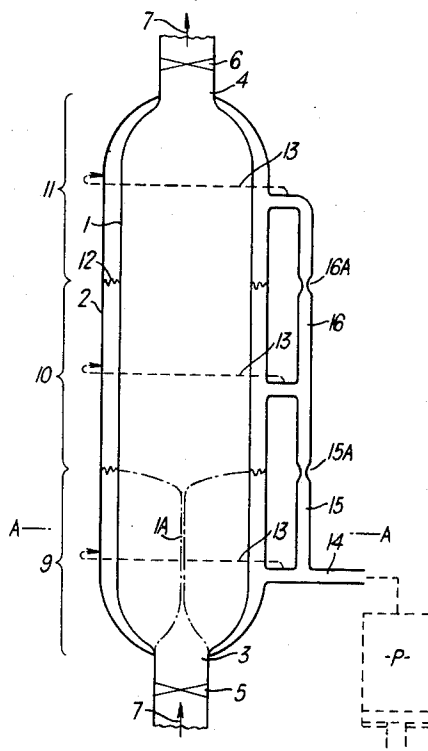
[54] **FLUID PUMP AND ACTUATION THEREOF**
16 Claims, 5 Drawing Figs.

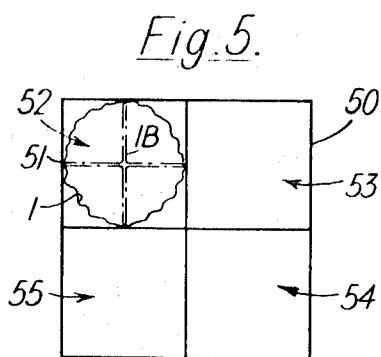
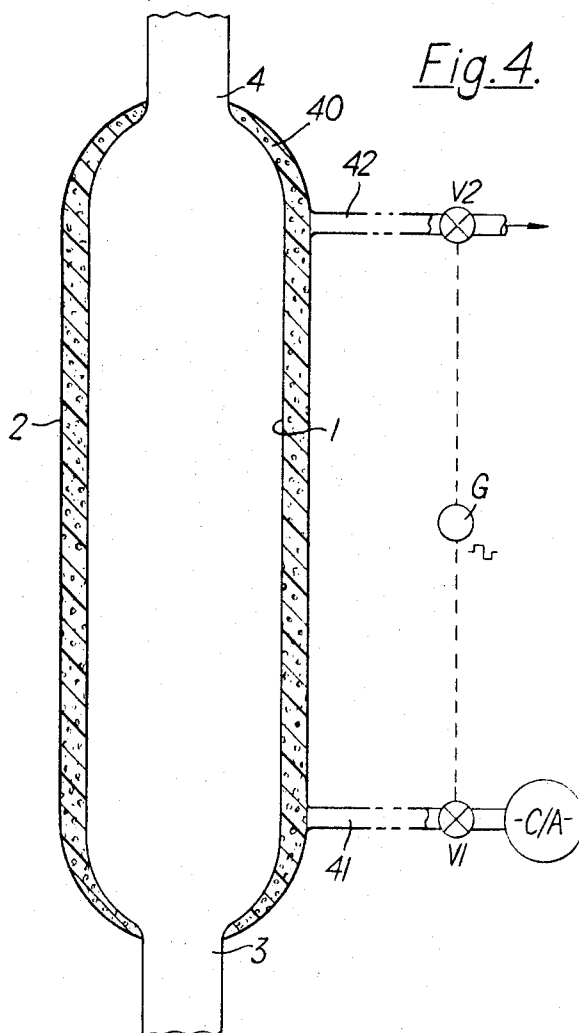
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ABSTRACT: The invention disclosed resides in a pump operating on what are generally thought of as "peristaltic" lines, and in which a flexible-walled duct is the pumping chamber and is surrounded by a cell structure into and out of which a flow of an actuating pressure-fluid is pulsatingly caused by some external means. The duct may have check valves in its entry and exit, or it may be self-valving by closing up completely when contracted, such closing being progressive from the upstream to the downstream end.





FLUID PUMP AND ACTUATION THEREOF

The invention relates to a pump primarily for liquids, of which the actuation is by means of the pulsating or alternating flow of a separated actuating fluid. The purpose for which the pump is first intended is use as a left ventricle bypass pump in connection with human cardiac treatment. In this context it may be used externally for example during open-heart surgery, or it may when purpose designed be used as an implantation. However, the pump is such that it may have other applications, especially where an intermittent or rhythmic pumping action is required with minimalization of turbulence or of violent treatment of the fluid to be pumped.

A pump operating according to the invention is somewhat analogous in its action to so-called peristaltic pumps in which a flexible tube is squeezed (for example) between a surface and a roller, the nip of the tube displacing any fluid ahead of it. Indeed the invention may be used in a number of circumstances in which a mechanically actuated peristaltic pump might be used.

A pump according to the invention is of very simple construction, without independent mechanically moving parts, is if required progressive (in the sense of a peristaltic pump) in its action, and is particularly well adapted to be included in series in a duct with the minimum of complication either as to the installation or as to the disturbances it may impose on the pumped fluid. Because of its action, the pump is well adapted to pump a fluid in which solids or near-solids are included, such as sludge, flowable food products, suspensions of particulate solids in liquid, and so on.

According to one aspect of the invention a pump comprises a flexible-walled duct of which the wall is the inner wall of a cellular structure adapted to receive and contain actuating pressure fluid said wall being such as to collapse inwardly by reason of the pressure of fluid in said structure, and means pulsatingly to supply into and relieve from said structure the pressure fluid whereby fluid to be pumped is alternately discharged from and recharged into said duct convergently flowing therethrough.

The structure of the pump in one example, designed as a left ventricle bypass pump in one example, designed as a left ventricle bypass pump for use in cardiac surgery, has a series of three external cells each itself divided in trefoil manner as seen in section into three cell compartments (i.e. nine cells in all). Actuating pressure fluid, which is preferably pulsatingly compressed air, is introduced into all three cellular chambers of a first group and its supply is connected through a flow restrictor to the second group of cells so that inflation of the second group is delayed and lags in phase behind that of the first; the third group of cells is likewise restrictedly connected to the supply of the second group and is thus phase lagged behind the second. The chamber wall is of flexible fabric or sheet material and is, when relaxed, of approximately cylindrical form.

The flow-restricting connections may be external and adjustable. Or, each may comprise a preset restriction orifice provided in a diaphragm of flexible material which separates each cell from its neighbor. The compartments may be formed by attaching the cylindrical wall of the duct along three parallel axially divided lines to the inside of the outer wall of the pump which is itself of cylindrical form and (usually) of rigid structure, or of relatively rigid structure as compared to the very flexible duct wall. The duct wall may be of slightly greater circumference than the outer wall; this enables each compartment when squeezed inwards by the actuating pressure to close up with practically total displacement. In such a case the pump requires no valves (though in practice valves are intended to be provided) because the first cell in collapsing virtually closes the duct against backflow from the next cell, and so on. When the pump is for use in blood, complete closure of the duct could cause cell damage, so the inner duct wall will be restrained along the axial-dividing lines in such a way as to prevent complete closure.

The flexible duct wall may be elastomeric, so as to be self-returning to its "rest" position against the external wall, or if

merely flexible the duct is reexpanded after a pumping stroke merely by the inlet pressure within it, of the fluid.

In an alternative form of the pump, instead of the actuating fluid working in separated cells, the volume between the duct and its surrounding external wall may be cellular in the porous manner of a porous synthetic sponge, the restricted communication between its pores having a similar peristaltic effect because, the actuating fluid being supplied at one end, its pressure takes time, by reason of the restricted leakage through the spongelike structure, to be effective throughout, so that the entry end of the duct is fully constricted before the outlet end.

The pump is of course made of materials compatible with its duty. For example, if it is to be a prosthetic left ventricle substitute intended for implantation, it will be of plastics material which is physiologically compatible, and may have external provision for suturing.

The invention includes a particular system of actuation of such a pump especially when used for implantation. In such a case the actuating fluid may be a liquid and it is contained in a completely sealed self-contained loop circuit branched to the pump cells. Also connected in this loop circuit is an impulse pump of any suitable type which is energized by solenoid means (for example a thin diaphragm or capsule of magnetic metal) which is so formed as to lie near the patient's skin and in an anatomically suitable location for it to be moved rhythmically by an electromagnetic field external to the skin. By such system the cardiac prosthetic pump may be operated with no foreign intrusion of the body, but the actuating fluid may, in other application of the invention, be supplied percutaneously.

In another operational system, the actuating fluid may itself be impulsively pumped by a source of pressure energy which is charged by pulmonary reaction. That is to say, the act of breathing at its own frequency (say, a respiratory rate of 20 c.p.m.) is used to charge a pressure accumulator, which is drawn upon at the normal pulse rate of (say) 72 c.p.m. or roughly in a frequency ratio of 1:4, to actuate the heart pump. In such a system no external source of energy will be required, though it may be that the pulse rate may have to be controlled in some known neuroelectrical manner. To integrate the pulmonary action with the circulatory action fully, it may be necessary to allow for the physiological phenomena which are known to occur. For example, an incident creating a demand for supranormal blood circulation indicated by increase of respiratory rate automatically speeds up the "heart" rate. This indicates that the pulmonary activity—the breathing—should not only charge an accumulation of pressure energy, but should result in a pulse rate related to the breathing rate. In general, it might be assumed that the 1:4 frequency ratio above mentioned should be a substantially constant ratio. There are valve systems which by acting on what may be called a half-wave principle, will double a frequency; obviously two such systems in cascade will quadruple the basic frequency. Therefore the invention comprises a system which involves

- a. a first fluid pump mechanically energized by the act of breathing using a share of the muscular power involved in breathing;
- b. a second fluid pump supplying the rhythmic impulses required to operate the cardiac prosthetic pump previously outlined;
- c. a pressure accumulator charged by the first fluid pump and discharging to energize the second pump; and
- d. a valve arrangement which controls the rhythm of the second pump by reference to the respiratory rate.

The pump first above described is well suited to the described system whether it be an electromagnetic system or entirely intramuscular. Although we have enlarged upon the cardiac application of the invention, it is to be remembered that the pump, as such, is well adapted to a variety of other uses.

The invention is illustrated by the accompanying diagrammatic drawings. In these:

FIG. 1 is a sectional elevation illustrating the basic construction of a nine-cell pump;

FIG. 2 is a section approximately on line A — A of FIG. 1;

FIG. 3 is a partial vertical section, to illustrate a closed-up phase of two adjacent cells;

FIG. 4 is an illustrative section, corresponding to that of FIG. 1, of a sponge cell variant;

FIG. 5 is a cross-sectional view, illustrating a rectangular arrangement intended to be used as an external heart substitutional machine.

The illustration shows a pump duct 1 which is approximately cylindrical in a state of rest (as in full line), and is made of flexible sheet reinforced plastics; for example it is woven and sealed Terylene coated with a "silastic" dispersion, viz a silicon rubber. It may, however, (and chiefly for nonmedical applications) be of wholly elastomeric sheet. This duct 1 is housed in a cylindrical substantially rigid, and substantially nondistortable, external casing or outer wall 2, which at each end is sealed to the duct 1, as at 3 and 4 (inlet and outlet ends respectively). Upstream from the end 3 of the duct 1 is preferably provided a nonreturn valve 5. At the outlet end at 6 is a similar nonreturn valve in the outlet of the duct 1. The arrows 7 in the illustration indicate the sense of direction of flow of the pumped flow.

The pump duct 1 is so dimensioned that if fully distended it would conform to the interior of the casing or outer wall 2 and, in some cases, have slightly excessive peripheral dimensions so judged; an attempt is made in FIG. 2 to illustrate such excess by the wavy showing of the wall at 1. It (the duct 1) is sealedly secured to the outer wall 2, along three lines (indicated at 8 in FIGS. 2 and 3) circumferentially spaced at 120° to the longitudinal duct axis and parallel with that axis. It follows that, at least through most of the length thereof, sections of the duct 1 can be contracted or collapsed inwardly, at first to the position indicated in dotted line at 1A in FIG. 2 and, partly, in FIG. 1, and finally as indicated at 1B in FIG. 3. In this collapsed condition, and if there is excessive peripheral length, the three compartments of a cell will meet and be contiguous as shown in the dotted lines 1B of FIG. 3 and this represents an almost total volumetric displacement in the cell region of these compartments, (i.e. as indicated by the bracket 9 of FIG. 1) and also represents a flow cutoff in that region so that the contracted and contiguous walls of the duct 1, in this region, act not only to displace volume but as a nonreturn valve.

In FIG. 1 it is seen that there are three groups of cells disposed in longitudinal series. Upstream is the cell group indicated by bracket 9; in the middle is the cell group bracketted at 10, and downstream, the cell group bracketted at 11. Each of these three cell groups, which are conveniently referred to as 9, 10 and 11, is separated from its neighbor by a flexible annular diaphragm attachment formed a wall 12, which is sealedly attached to the casing or outer wall 2 and to the duct 1: such wall is seen fully extended in FIG. 3.

Each cell (9,10,11) is circumferentially divided into three compartments along the lines of attachment indicated at 8, so that each cell group comprises three cell compartments. The three compartments of each cell group are interconnected for fluid flow by external pipes indicated as dotted lines 13. The upstream cell group 9 is supplied from a source in a pulsating manner, with actuating fluid entering by pipe 14. The compartments of this cell group are thus expanded, and the wall 1, within the said length of the upstream cell group 9, consequently squeezed and collapsed inwards, to take up the dotted-line position, at first as indicated by 1A in FIGS. 1 and 2, and finally as in FIG. 3. The source of pipe 14 is, however, connected also by pipe 15 to cell 10, through a constriction indicated at 15A (which may be adjustable). The connection to cell group 10 is (like cell group 9) three branched by dotted connections 13, but the supply of actuating fluid is delayed by the constriction at 15A. The cell group 11 is again connected, by pipe 16 through constriction 16A, from the source 14 so that its behavior though like that of the cell groups 9 and 10, lags behind them.

A single impulse of pressure fluid through 14 therefore first squeezes the wall 1 in cell group 9; this causes valve 5 to close and forces fluid in the duct 1 downstream (upwards in FIG. 1 as drawn). Overlapping and following this action, the actuating fluid passed through 15 and retarded by 15A, squeezes section (cell group) 10 of the duct 1 (section 9 remaining and maybe continuing to be squeezed) and thereafter the like happens in the section of cell group 11. The fluid in the duct 1 is consequently impelled along the duct, in the arrow 7 sense. If nonreturn valves as at 5,6, are provided it is unimportant whether or not the contractions of the duct 1 are so complete as to cause contiguity of the duct wall (as in FIGS. 2 and 3) or only partial; in either case the pumping operation occurs.

In FIG. 1 there is diagrammatically represented at P a conventional reciprocating liquid pump connected to the pipe 14. This is preferably a solenoid-operated pump arranged to have a square wave output, and it is intended to be controlled by any suitable "pacemaker"-type system. The pump P when discharging, activates the cellular device positively, and when returning, sucks the actuating liquid back out of the cell structure, thus causing distension of the wall 1 and recharging of the duct through valve 5.

The structure both of the duct 1 and wall 2, may be of frustoconical form instead of cylindrical; especially if convergent in the sense of direction of flow (7) the acceleration of the pumped fluid will then be less likely to be turbulent. This comment also applies to the construction of FIG. 4, described below.

After FIG. 4 has been understood, it will be appreciated that instead of having the annular attachments 12 and the pipe connections 15, 16, and their restrictions, there may be a variant in which the volume between the duct 1 and wall 2 is occupied by a porous sponge of restrictively interconnected pores, supplied with pulsating actuating fluid at one end (as by 14) and relieved back through the same end. Then the so-called peristaltic action will be even more smooth and progressive.

In the variant of FIG. 4, the duct 1 is again seen, and is now one flexible-walled duct which is uninterrupted in its length, and which is sealedly connected at 3 and 4 to the outer nondistensible wall 2. Between walls 1 and 2 is provided a mass of porous (i.e. interconnected) cells, shown at 40 in a contracted condition. The mass of porous, interconnected cells form a cell structure, and each of the individual cells of this structure are interconnected due to the porous nature of the sponge by pores which permit restricted flow therebetween being thus analogous to the restricted flow means 15A and 16A of FIG. 1. Into the cellular space between 1 and 2 is connected at 41 an actuating pressure fluid supply, at the upstream end of wall 2. Likewise, from the downstream end of wall 2, is a connection 42. Connection 41 is supplied by a C/A of compressed air or other actuator fluid, either gas or liquid, through a solenoid-operated pulsator valve V1. The valve V1 is operated by a square wave generator G. The generator G may be replaced by an electrical source and a time switch of the kind used in heart regulator devices. The connection 42 exhausts actuating fluid when a valve V2 is operated, also by the generator G. Alternatively a pump such as P of FIG. 1 may be employed first to generate positive pressure released—as we prefer according to a square wave form—by the valve V1 into the cellular structure 40 at the upstream end of the pump; and second, actually to suck actuating fluid from the cells through the valve V2, so distending the duct 1. The proportions of FIG. 4 are to be disregarded since it is not practicable to represent cellular sponge structure by drawing. Suffice it to say that the Figure shows the cells fully contracted (and duct 1 fully distended) whereas at the end of a pressure pumping phase the structure 40 would be fully distended and the duct 1 fully contracted. By reason of the restricted flow between the cells of the spongy cellular structure, the duct 1 is first contracted by expansion of the cellular structure at its upstream end as pressurized fluid is introduced at that end through pipe 41, and progressive contraction follows along the duct in what is, by analogy, to be described as peristaltic

manner as the pressurized fluid flows through the pores and causes expansion of the cells in a downstream direction. No valves equivalent to 5 and 6 of FIG. 1 are shown though they may be provided. The duct wall 1 may be self-valving in "peristaltic" manner, merely by the wall becoming contiguous progressively from the upstream to the downstream end in the pumping phase, and conversely in the recharging phase.

A pump such as described is, clearly, capable of passing a liquid with solid particles in suspension and may therefore be used for a variety of sludge or sewerage purposes, or in liquid-suspended solid flotation or like conveying. However, its first purpose is the pumping of human blood, as clearly indicated above.

Such a pump to be effectively used in the bloodstream, is to be controlled as to cycle, as before mentioned. This may, according to the invention, involve a system which is compatible with the physiological and anatomical requirements if the pump 0 is to be implanted. Percutaneous leads are relatively safe for short-term use, but not for permanent implantation; it follows that the pressure source to pipe 14 may perhaps not be permanently connected to a live body in which the pump is implanted. To overcome this the invention provides possible provisions. For example, the pipe 14 or the pipes 41 and 42 may be branched off a closed circuit of actuating fluid in which there is included in series a second (implanted) pump energized electromagnetically by a field outside the body, such as a diaphragm or continuous-output pump of which the diaphragm, or a valve, is, or is armed with, a solenoid magnet. This is so positioned that it is oscillated by an electrical field outside the body. Therefore the pump of the invention may be operated entirely by an external energy source, the timing of which will of course be under control.

In FIG. 5 is illustrated, again diagrammatically by way of example, a feature of arrangement which lends itself to being a pump in an external heart bypass machine. Such machines are, for mechanical reasons, conveniently cuboid in their general form. The invention may be adapted to such use, as illustrated. That is to say, there may be (say) four lengths of duct 1, each housed in a rectangular outer wall 50 and each attached longitudinally to such wall 50 by four attachments, at 51. The circumferential length of each quarter-periphery of the duct 1 is such that the four quarters can become contiguous as shown at 1B in the Figure, so that a group of four cells in one rectangular section can close up and, in effect, close the duct. Four such rectangular-sectioned pump units are shown in FIG. 5, which as a block, form a cuboid-shaped pump. Units 52, 53, 54 and 55 are then arranged in series both as to the flow of pumped fluid through their ducts 1, and the flow of actuating fluid in their respective cell groups.

We claim:

1. A pump comprising a flexible-walled duct of which the wall constitutes the inner wall of a cell structure having a plurality of cells surrounding the duct, and means pulsatingly to introduce into and relieve from the cell structure an actuating pressure fluid, the combination of duct and cell structure being such that distension of the latter causes collapse of the former, said cells of the cell structure being interconnected through flow restriction means in a sequential manner from a pressure fluid input connection so that the duct is collapsed in a correspondingly sequential manner from its upstream to its downstream end.

2. Pump according to claim 1, in which the duct wall is so dimensioned perimetrically that when fully collapsed it constitutes a closure of the duct.

3. Pump according to claim 1, in which the duct is provided with a first check valve upstream and a second check valve downstream of the location of the cell structure the valves being in series so as to prevent flow in one sense of direction through the duct.

4. Pump according to claim 1, in which cells are interconnected by duct means within which is provided a flow restriction between one cell and the next in sequence.

5. Pump according to claim 1, in which the cells are those of porous spongy material contained between the said duct wall and a substantially nondistendable outer wall.

6. Pump according to claim 1, further including a substantially nondistendable outer wall surrounding said duct wall and sealed thereto at upstream and downstream ends thereof and at least two connections spaced symmetrically about the duct axis being provided between said duct wall and the outer wall along lines directed in the direction of flow in the duct.

7. Pump according to claim 1, further including a substantially nondistendable outer wall surrounding said duct wall and sealed thereto at upstream and downstream ends thereof and at least one flexible impervious diaphragm sealed peripherally to the interior of the outer wall and to the exterior of the duct wall and defining one cell or cell group from its sequential neighbor.

8. Pump according to claim 7, in which said diaphragm has a sufficient radial dimension when extended, to enable the duct wall to collapse so completely that the interior duct wall surfaces become contiguous.

9. A pump according to claim 1, of which the duct is convergent in cross section in the sense of direction of flow therethrough.

10. A pump according to claim 1, of which the external cross-sectional shape is rectangular.

11. A pump according to claim 10, comprising a plurality of units assembled with external rectangular shape.

12. A pump comprising a substantially nondistendable outer wall of substantially cylindrical form, a flexible-walled duct extending through the length and from the ends of the outer wall and enclosed thereby, fluidtight attachments between the ends of the outer wall and the duct wall, at least two attachments between said two walls along symmetrically spaced longitudinal lines from end to end of said outer wall,

the circumferential length of the inner wall being greater than the perimetric length of the outer wall at a corresponding cross section,

at least one annular impervious flexible connection extending between the outer and inner walls to form a common end wall of two adjacent cell groups defined by the walls, and

means for admitting a pulsating supply of actuating pressure fluid into the cell structure between the walls.

13. A pump as claimed in claim 12, in which cell groups arranged sequentially along the duct wall are supplied with pulsating pressure fluid from the upstream end of the pump through flow restriction such as to delay flow into each sequential cell group from the most upstream to the most downstream group.

14. A pump according to claim 12, having three longitudinal lines of attachment and two flexible connections thus defining three groups of three cells.

15. A pump comprising a flexible-walled duct of which the wall constitutes the inner wall of a cell structure surrounding the duct, and means pulsatingly to introduce into and relieve from the cell structure an actuating pressure fluid, the combination of duct and cell structure being such that distention of the latter causes collapse of the former, said cell structure having an inlet pipe connection at its upstream end and an outlet pipe connection at its downstream end, in combination with a continuous external source of actuating pressure fluid and two valves arranged and operated to open and close alternatively to admit pressure fluid to the cell structure at the upstream end thereof and release it from the downstream end, said valves being solenoid operated in accordance with a square-wave form of electrical input.

16. A pump comprising a flexible-walled duct forming the inner wall of a cell structure, an outer wall surrounding said duct and sealed thereto at each end of the cell structure said walls defining space with a volume varied by distension and

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contraction of said inner wall, means for admitting and emitting to and from said space a pulsating flow of actuating fluid, an inlet for pumped fluid into one end of the duct and an outlet for such fluid from the other end of the duct, means to prevent reverse flow of the pumped fluid from the duct, and means to restrict flow of the actuating fluid between the ends

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of the cell structure so that the said inner wall is collapsed by distension of the said space by the pressure of the actuating fluid, which distension is progressive from said one end to the other end.

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