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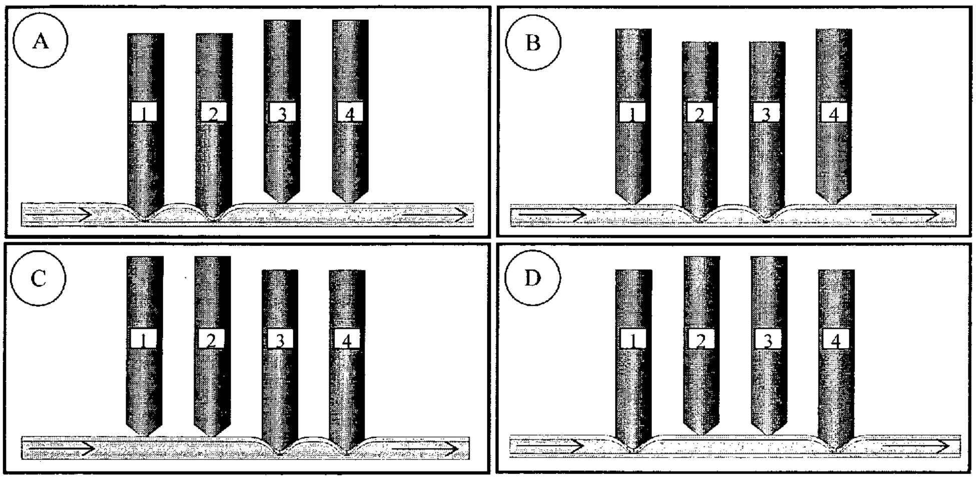
(54) **Title:** MAGNETICALLY BALANCED FINGER-TYPE PERISTALTIC PUMP




(57) **Abstract:** The present invention discloses a peristaltic pump which comprises of a plurality of effecters, actuated in a periodic manner upon by obstructive forces of a flexible infusion tube so as flow of infusion fluid is provided along said infusion tube, the magnitude of the obstructive forces being dependent upon the displacement of said moving effecters; and a plurality of balancing magnets providing balancing forces upon one or all the moving effecters, the balancing forces at each point along the path of motion of the moving effecters being of approximately equal magnitude to that of the obstructive forces at said point; such that the parasitic output due to work performed against the obstructive forces is approximately zero and yield is maximized.

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# MAGNETICALLY BALANCED FINGER-TYPE PERISTALTIC PUMP

## FIELD OF THE INVENTION

The present invention generally relates to a magnetically balanced finger-type peristaltic pump, especially a pump comprising at least one tailor made cam.

## BACKGROUND OF THE INVENTION

This invention relates to designs for cams to operate magnetically balanced fingers of a peristaltic pump. At present peristaltic pumps find use in medical settings to add nutrients to blood, to force blood through filters to clean it as in dialysis, or to move blood through the body and lungs during open heart surgery. They are advantageous in these situations since the pump elements do not contact the pumped fluid, eliminating any possibility of contamination. Additionally the pumping action may be gentle enough that blood cells are not damaged. Further uses include pumping aggressive chemicals, high solids slurries and other materials where isolation of the product from the environment, and the environment from the product, are critical. As the operation of such a pump can be critical for life support, they are generally provided with battery back up. The efficiency of the device thus becomes an important parameter since the length of time it can remain in operation while on battery power is limited by its efficiency.

A common arrangement for the operation of a peristaltic pump is shown in the prior art of Fig. 1 (**100** is a front view and **101** is a lateral view), wherein a plurality of fingers **104** press the feed tube **103** against a substrate **105** by means of a cam **102**. Neighboring fingers are operated in sequence such that a squeezing or 'peristaltic' motion operates along the length of the tube, forcing the contents of the tube in one direction. By adjusting the speed of rotation of the cams, the speed of pumping can be adjusted.

In US patent 4,725,205 a mechanically compensated cam for use in a peristaltic pump is disclosed. The system described uses specially designed cams that reduce the maximum force applied between fingers **104** and tube **103** by means of a compliant spring. In this manner problems of jamming due to poor alignment or out-of-tolerance tubes are eliminated. This system while effective and simple involves a certain amount of wasted energy as will be described below. Furthermore, being based on an eccentric circle, the fingers follow a trajectory sinusoidal in nature, which limits the volume pumped per camshaft revolution. Varying the trajectory from that of a sinusoid would offer the benefit of fixing the duration during which the tube is shut off, allowing for an increase in the volume pumped per revolution.

Thus a design and method for the cam of a peristaltic pump allowing a tailored finger trajectory that reduces the probability of jamming in out-of-tolerance tubes, as well as allowing increased volume per rotation and subsequent enhanced energy savings is a long felt need.

BRIEF DESCRIPTION OF THE DRAWINGS

In order to understand the invention and to see how it may be implemented in practice, a plurality of embodiments will now be described, by way of non-limiting example only, with reference to the accompanying drawings, in which

Fig. 1 shows in prior art a typical peristaltic pump making use of fingers **104** pressing against a uniform substrate **105**;

Fig. 2 schematically illustrating the fingers location at each of the four steps of the pumping cycle of a pumping mechanism comprising of four fingers;

Fig. 3 schematically presents the state of each finger at each of the four steps of a single pumping cycle wherein at each step, two fingers are static and two are moving;

Fig. 4 schematically presents a cross section of the pumping mechanism according to one embodiment of the invention, wherein one portion of the cams is characterized by one crescent form;

Fig. 5 schematically presents a cross section of the pumping mechanism according to one embodiment of the invention, wherein one portion of the cams is characterized by two crescent forms; and

Fig. 6 graphically presents the forces on a single finger applied along a single half pumping cycle.

## SUMMARY OF THE INVENTION

It is one object of the present invention to present a finger-type peristaltic pump (DDS) comprising a plurality of pressing-fingers, actuated in a periodic manner upon by obstructive forces of a flexible infusion tube so as peristaltic flow of infusion fluid is provided along said infusion tube, the magnitude of said obstructive forces being dependent upon the displacement of said moving finger; and a plurality of balancing magnets providing balancing forces upon said moving fingers, said balancing forces at each point along the path of motion of the moving member being of approximately equal magnitude to that of said obstructive forces at said point; such that the parasitic output due to work performed against said obstructive forces is approximately zero and yield is maximized.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above, especially adapted to be utilized as ambulatory and hospital infusion pumps.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above wherein at least a portion of said plurality of pressing-fingers is magnetically balanced and wherein each of said magnetically balanced pressing-fingers comprises one or more magnets stacked in the direction of said pressing by means of one or more metal members, said metal member is optionally selected from ferromagnetic materials, fixed magnets, static magnets that are nor actuated in respect to the pressing-fingers or any combination thereof.

It is well in the scope of the invention wherein the magnets are not located on the pressing fingers. Hence, at least a portion of the magnets are located in sides of the fingers, whereas iron or other magnetic materials are located on the fingers.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above, wherein each of said magnetically balanced pressing-fingers of linear movement is actuated periodically by a rotating cam towards a flexible infusion tube i.e., until a complete yet temporary shut off of said tube is obtained, and backwards, i.e., until said fingers are not pressing said tube; wherein said magnetic balance avoids significant pressing forces between said cam and said fingers.

It is also in the scope of the invention wherein the pressing fingers are maneuver along a non-linear movement, e.g., a curved movement etc.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above wherein said magnetic balance avoids significant pressing forces between said cam and said fingers along their entire forth and backwards linear movement. It is acknowledged in this respect that the force between the finger and the cam is negligible due to the balancing magnet force yielding almost no friction on the cam surface. As a result, no torque evolves on the cam and almost no energy is needed to rotate the pumping mechanism.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above wherein said fingers remain at maximum extension for a large angular sweep $\Delta\theta$ of the shaft, such as 87.5°, causing complete tube shutoff during said large and predetermined range.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above, comprising inter alia a plurality of N pressing fingers, N is any integer number higher 2, especially 4, wherein per any given pumping cycle, each of said fingers are in one of two alternating states of being either static or moving (or approaching to movement); in said static state said at least one finger is pressing said flexible infusion tube and at least one finger is withdrawn and not pressing said tube; in said moving state at least one finger is withdrawing from said tube and at least one finger is pressing the same.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above, wherein the static and moving states of said fingers per any given pumping cycle are as defined in figure 3.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above, wherein at least a portion of said cams are characterized by one or more crescent forms, each of which of said crescent forms is adapted to provide pressing of said finger by magnetic forces of said balancing magnets in the manner that said magnetic forces are at least slightly stronger than the oppositely directed elastic forces, provided by the squeezing of said flexible tube by said finger while shutting off said tube; by applying said magnetic force, complete tube's shut off is assured, especially in cases of worn out tubes and pumping mechanisms with noticeable tolerances.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above wherein at least a portion of said cams are characterized by a first and a second crescent forms located in opposite directions: The first crescent form is adapted to provide pressing of said finger by magnetic forces of said balancing magnets in the manner that said magnetic forces are at least slightly stronger than the oppositely directed elastic forces, provided by the squeezing of said flexible tube by said finger while shutting off said tube; by applying said magnetic force, complete tube's shut off is assured. The second crescent form is adapted to provide additional finger movement in the direction of withdrawing said tube, so as complete tube's after-press inflation is assured, especially in cases of worn out tubes, wider tubes, tubes of wider walls, and pumping mechanisms with noticeable tolerances.

Another object of the present invention to disclose a magnetically balanced finger-type peristaltic pump as defined above wherein the pressing-finger are of rounded cross sections, additionally comprising sealing means that hermetically barriers between proximal portion of the fingers, i.e., the portion constantly located inside said pump's housing, and distal portion of said fingers, i.e., the pressing tip located outside said housing; said sealing means is especially selected from O-rings, U-rings or the like.

The magnetically balanced finger-type peristaltic pump as defined above is especially useful for reduce pumping energy and provide extended working time per given set of batteries. The system reduces mechanical wear of moving members, especially of cams and fingers. Less tube degradation is provided in the system. Scaling down is facilitated by reducing sizes of both engine and gear mechanism. Tube wear out is reduced, while improved accuracy is provided due to decrease degradation. The aforesaid pumping system also provides use of pumping mechanisms of bigger tolerances in production and assembly. The system provides for improved mechanical efficiency and allows use of sealed pressing-fingers so as sealed pump is obtained, and less sensitivity is obtained to dirt and contaminated body fluids. Lastly, the patented pumping system provides for downstream pressure built up with out any requirements of applying high pumping moments.

Another object of the present invention to disclose the peristaltic pump as defined above, wherein at least a portion of said balancing magnets is located in a location selected from a group consisting of the elongated body portion of the finger-type pressing members (fingers), the fingers block or any combination thereof.

Another object of the present invention to disclose the peristaltic pump as defined above, wherein at least a portion of said balancing magnets comprises metal and other paramagnetic materials which location is one or more of a group consisting of in one or more portions of the finger-type pressing members (fingers), on one or more portions of the fingers, in the fingers block, on the fingers block or any combination thereof.

Still another object of the present invention to disclose the peristaltic pump as defined above, wherein at least a portion of said magnetically balanced pressing-fingers actuated in at least partially non-linear movement.

A last object of the present invention to disclose the peristaltic pump as defined above, wherein the magnetic force is applied in one or more specific points along the circumference of the rotating cam.

## DETAILED DESCRIPTION OF PREFERRED EMBODIMENTS

The following description is provided, alongside all chapters of the present invention, so as to enable any person skilled in the art to make use of said invention and sets forth the best modes contemplated by the inventor of carrying out this invention. Various modifications, however, will remain apparent to those skilled in the art, since the generic principles of the present invention have been defined specifically to provide a continuous billing systems and methods thereof.

The terms '**about**' or '**approximately**' apply hereinafter to any value in a range from below 30% of a specified value to above 30% of said value.

The terms '**parasitic input**' and **parasitic output** applies hereinafter in the manner that **parasitic input** refers to the energy consumed by the system to produce parasitic output. The parasitic input is greater than the parasitic output because of internal losses. For example, an elevator with a cabin of weight 10,000 N being used to raise a man of weight 700 N through 10m produces 107 kJ of output of which only 7 kJ are necessary output the remaining 100 kJ are parasitic output due to raising the cabin itself.

The term '**effecters** refers hereinafter to any portion of a device whose position changes during the working of the device, such as pressing fingers, peristaltic rollers etc..

The term '**necessary output**' applies hereinafter to the energy needed to be produced by a system in order to perform the task for which the system is designed. For example in order perform the task of raising a man of weight 700 N through 10 m the necessary output of a system such as an elevator is 7 kJ of energy.

The term '**obstructive forces**' refers hereinafter to any force which acts upon a moving member during its movement. More specifically this term is used to refer to forces dependent upon the displacement of a moving member.

The term '**output**' applies hereinafter to energy produced by a system.

The term '**actuated in a periodic manner**' applies hereinafter to any system wherein at least one component or effecter performs a series of steps repeatedly a plurality of times.

It is in the scope of the present invention to introduce the tailored cam, whose radius is not a circle rotating about an eccentric axis, but rather varies in such a manner that the fingers remain closed for a large sweep of the shaft, such as 87.5° out of the full 360° of rotation. The unique profile of the tailored cam allows complete tube shutoff during this large and predetermined range, preventing backflow through this entire range and allowing subsequent fingers a longer range of shaft angle $\theta$ in which to effect their peristaltic motion. This has an effect of decreasing the noise of the peristaltic pump, decreasing the energy consumption and effectively obtaining the conditions defined in the figures, e.g., figure 6.

It is furthermore within the scope of the present invention that a reduced-radius 'compliance zone' be included in the design of the cam, to accommodate tubes of increased diameter that would not otherwise be allowed to open completely. An out-of-compliance tube with increased diameter would remain partially closed even during the fingers' 'open' range but for the inclusion of the reduced radius 'compliance zone'. This partial closure would impede the free flow of fluid through the tube, reducing the throughput of the pump in such cases.

It is furthermore within the scope of the present invention and according to one specific embodiment of the same, wherein the aforementioned advantages are provided while still minimizing the first, second, and third derivatives of radius with shaft angle $\theta$. The first derivative directly controls the finger velocity, and thus influences the kinetic energy invested therein. The second derivative affects the force upon the tube, which it is desirable to reduce insofar as possible in order to eliminate jamming, tube rupture, or disturbance of the fragile materials such as human cells passing through the tube. The third derivate controls the 'jerk' of the finger, which it is desirable to minimize since the jerk causes undue stress and strains on the cam, introduces vorticities into the flow, and causes vibration and noise.

It is in the scope of the invention wherein the cam comprises single, double or more crescent forms. Hence for example, a crescent form located at the wide radius of the cam avoids a long pressing period where a continuous strong pressure is applied upon the tube. The magnetic forces are pressing the tube. Along this crescent form, the cam is minimally touching the pressing fingers and hence the force for rotating the cam is provided with a minimal measure. Similarly and as another example of one mode of the invention, a crescent form located at the short radius of the cam provides the cam with another possible movement, which is especially useful *(i)* in tubes with degradated walls; *(ii)* in pressing mechanism with noticeable production or assembly tolerances; *(iii)* in using tubes with relatively thin walls; *(iv)* or in cases of insufficient pressing forces. Those cases are characterized by unsealed tubes, whereat leaking is possible.

Reference is now made to figure 2, which illustrates the fingers location at each of the four steps of the pumping cycle of a pumping mechanism comprising of four fingers. Fig. 3 schematically presents the state of each finger at each of the four steps of a single pumping cycle wherein at each step, two fingers are static and two are moving. It is yet according to one embodiment of the invention wherein the rotating cams are designed in a manner that a predefined overlap (e.g., 3%) between adjacent stages is obtained. Hence, one finger is switched from *open* configuration (tube loosed) to *close* configuration (tube compressed) only after a short while where an adjacent finger is switched to its *close* configuration.

Reference is now made to figure 4 which schematically presents a cross-section of a pumping mechanism according to one embodiment of the invention. Fig. 4 specifically illustrating one portion of the cams is characterized by one crescent form, adapted to provide pressing of a finger (**41**), e.g., via a seal (**44**), by magnetic forces (**42**) of the balancing magnets in the manner that the magnetic forces are at least slightly stronger, than the oppositely directed elastic forces, provided by the squeezing of the flexible tube by the finger while shutting off the tube (**43**) against a base (**48**); by applying the magnetic force, complete tube's shut off is assured, especially in cases of worn out tubes and pumping mechanisms with noticeable tolerances; this pumping mechanism with magnetically balances pressing fingers **41** is provided with preset balancing forces at each point along the path of motion of the moving fingers being of approximately equal magnitude to that of said obstructive forces at this point; such that the parasitic output due to work performed against the obstructive forces is approximately zero and yield is maximized. The pumping mechanism further comprises a magnet (**45**), ferromagnetic metal (**46**), and a cam (**47a**). Here for example, cam **47a** is characterized by a single crescent form.

Reference is now made to Fig. 5, which schematically presents a cross-section of another pumping mechanism according to the present invention, comprises *inter alia* a magnet **45**, ferromagnetic metal **46**, and first crescent form of cam **47b** which is adapted to provide pressing of finger **41** via a seal (**44**) by magnetic forces **42** of the balancing magnets in the manner that the magnetic forces are at least slightly stronger, than the oppositely directed elastic forces, provided by the squeezing of flexible tube **43** against a base (**48**) by the finger while shutting off the tube; by applying said magnetic force, complete tube's shut off is assured; the second crescent form is adapted to provide additional finger movement in the direction of withdrawing the tube, so as to facilitate a more relaxed form of mechanical pressure on the tube walls, especially in wider tubes, tubes of wider walls, and pumping mechanisms with noticeable tolerances; the said more relaxed form of mechanical pressure on the tube enable a prolonged life of the tube and as a consequence a more accurate flow rate throughout the pumping; and,

Reference is now made to Fig. 6, which graphically presents the forces on a single finger applied along a single half pumping cycle; wherein point No. **1** symbols the upper point at with the finger tip is reaching through the pumping cycle. At this point almost no force is applied on the tube walls tube walls and the magnet was designed to apply equal small force on the finger so the total force acting between the cam and the finger is zero.

Point **2** denotes for the point in which the finger presses the tube to a flow shut off position; in this point, the magnetic force is grater than the obstructive force applied by the elastic tube so as shut off of the flow is assured at any pressure existing in the tube (up to 1 bar in this sample). At this point the magnet was designed to apply grater force then the force applied by the tube on the finger. This armament facilitates secured shut off of the tube under variant condition with very little total force acting on the finger, i.e. force acting between the cam and the finger is very small leading to decries in wear, energy consumption etc.

Point **3** represents the total force acting on the fingers witch is slightly grater do to slightly grater magnetic forces. This design ensures complete shut off (squeeze) of the tube in case where tube walls degradation is presented or in case where a tube with inadequate walls thickness is used. From this point the magnet force acting on the finger decreases to avoid puncturing of the tube.

Point **4** symbols the free movement of the finger to ensure complete shut off of the tube, especially in case of degradation of tube's walls, tolerances in pumping mechanism etc. ΣF is the total force applied on the finger in the direction of the press, i.e., the magnetic power minus obstructive forces of the elastic tube; the force applied by the cam on the pressing finger approx. equals the aforesaid force plus the forces required to overcome frictions in the pumping system. Point 4 hence describes the point whereat the magnetic forces are stronger than the elastic forces of the tube, such that the tube is effectively sealed.

CLAIMS

1. A peristaltic pump (DDS) comprising a plurality of effecters, actuated in a periodic manner upon by obstructive forces of a flexible infusion tube so as flow of infusion fluid is provided along said infusion tube, the magnitude of said obstructive forces being dependent upon the displacement of said moving effecters; and a plurality of balancing magnets providing balancing forces upon one or all said moving effecters, said balancing forces at each point along the path of motion of the moving effecters being of approximately equal magnitude to that of said obstructive forces at said point; such that the parasitic output due to work performed against said obstructive forces is approximately zero and yield is maximized.

2. A finger-type peristaltic pump (DDS) according to claim 1, comprising a plurality of pressing-fingers, actuated in a periodic manner upon by obstructive forces of a flexible infusion tube so as flow of infusion fluid is provided along said infusion tube, the magnitude of said obstructive forces being dependent upon the displacement of said moving fingers; and a plurality of balancing magnets providing balancing forces upon one or all said moving fingers, said balancing forces at each point along the path of motion of the moving finger being of approximately equal magnitude to that of said obstructive forces at said point; such that the parasitic output due to work performed against said obstructive forces is approximately zero and yield is maximized.

3. The magnetically balanced peristaltic pump according to claim 1, especially adapted to be utilized as ambulatory and hospital infusion pumps.

4. The peristaltic pump according to claim 1, wherein at least a portion of said plurality of pressing-fingers or members are magnetically balanced and wherein each of said magnetic balanced pressing-fingers comprises one or more magnets located on the moving finger and one or more metal members are located on the stationery conduit of the fingers, with is part of the static enclosure of the pumping mechanism, and with said metal members are optionally selected from ferromagnetic materials, and wherein the position of the said magnets and the said metal members is designed to produce the said balancing forces.

5. The peristaltic pump according to claim 1, wherein at least a portion of said balancing magnets is located in a location selected from a group consisting of the elongated body

portion of the finger-type pressing members (fingers), the fingers block or any combination thereof.

6. The peristaltic pump according to claim 1, wherein at least a portion of said balancing magnets comprises metal and other paramagnetic materials which location is one or more of a group consisting of in one or more portions of the finger-type pressing members (fingers), on one or more portions of the fingers, in the fingers block, on the fingers block or any combination thereof.

7. The magnetically balanced finger-type peristaltic pump according to claim 1, wherein some or all of said pressing-fingers who are magnetically balanced are combined with said metal members instead of said magnets, and were this said fingers conduct, the metal members are replaced with said magnets; and wherein some or all of the magnetically balanced fingers the metal members, either located on the fingers or on the fingers conducts, are replaced with said magnets.

8. The peristaltic pump according to claim 1, wherein each of said magnetically balanced pressing-fingers of linear movement is actuated periodically by a rotating cam towards a flexible infusion tube, i.e., until a complete yet temporary shut off of said tube is obtained, and backwards, i.e., until said fingers are not pressing said tube; wherein said magnetic balance avoids significant pressing forces between said cam, its shaft and said fingers.

9. The peristaltic pump according to claim 8, wherein at least a portion of said magnetically balanced pressing-fingers actuated in at least partially non-linear movement.

10. The peristaltic pump as defined in claim 8, wherein said magnetic balance prevent significant pressing forces build-up between said cam and said fingers along their entire forth and backwards linear movement.

11. The peristaltic pump as defined in claim 8 wherein the magnetic force is applied in one or more specific points along the circumference of the rotating cam.

12. The peristaltic pump according to claim 1, wherein said fingers remain at maximum extension for a large angular sweep $\Delta\theta$ of the shaft, such as 87.5°, causing complete tube shutoff during said large and predetermined range.

13. The peristaltic pump according to claim 1, comprising a plurality of N pressing fingers, N is any integer number higher 2, especially 4, wherein per any given pumping cycle, each of said fingers are in one of two alternating states of being either static or moving (or approaching to movement); in said static state said at least one finger is pressing said flexible infusion tube and at least one finger is withdrawn and not pressing said tube; in said moving state at least one finger is withdrawing from said tube and at least one finger is pressing the same.

14. The peristaltic pump according to claim 13, wherein the static and moving states of said fingers per any given pumping cycle are as defined in figures 2 and 3.

15. The peristaltic pump according to claim 1, wherein at least a portion of said cams are characterized by one or more crescent forms, each of which of said crescent forms is adapted to provide pressing of said finger by magnetic forces of said balancing magnets in the manner that said magnetic forces are at least slightly stronger, at the angular position per figure 4, than the oppositely directed elastic forces, provided by the squeezing of said flexible tube by said finger while shutting off said tube; by applying said magnetic force, complete tube's shut off is assured, especially in cases of worn out tubes and pumping mechanisms with noticeable tolerances.

16. The peristaltic pump according to claim 15, wherein at least a portion of said cams are characterized by a first and a second crescent forms located in opposite directions,
said first crescent form is adapted to provide pressing of said finger by magnetic forces of said balancing magnets in the manner that said magnetic forces are at least slightly stronger than the oppositely directed elastic forces, provided by the squeezing of said flexible tube by said finger while shutting off said tube; by applying said magnetic force, complete tube's shut off is assured;
said second crescent form is adapted to provide additional finger movement in the direction of withdrawing said tube, so as to facilitate a more relaxed form of mechanical pressure on the tube walls, especially in wider tubes, tubes of wider walls, and pumping mechanisms with noticeable tolerances; the said more relaxed form of mechanical pressure on the said tube enable a prolonged life of the tube and as a consequence a more accurate flow rate throughout the pumping.

17. The peristaltic pump according to claim 1, wherein the pressing-finger are of rounded cross sections, additionally comprising sealing means that hermetically barriers between

proximal portion of the fingers, i.e., the portion constantly located inside said pump's housing, including the pumping mechanism, and distal portion of said fingers, i.e., the pressing tip located outside said housing; said sealing means is especially selected from O-rings, U-rings or the like.

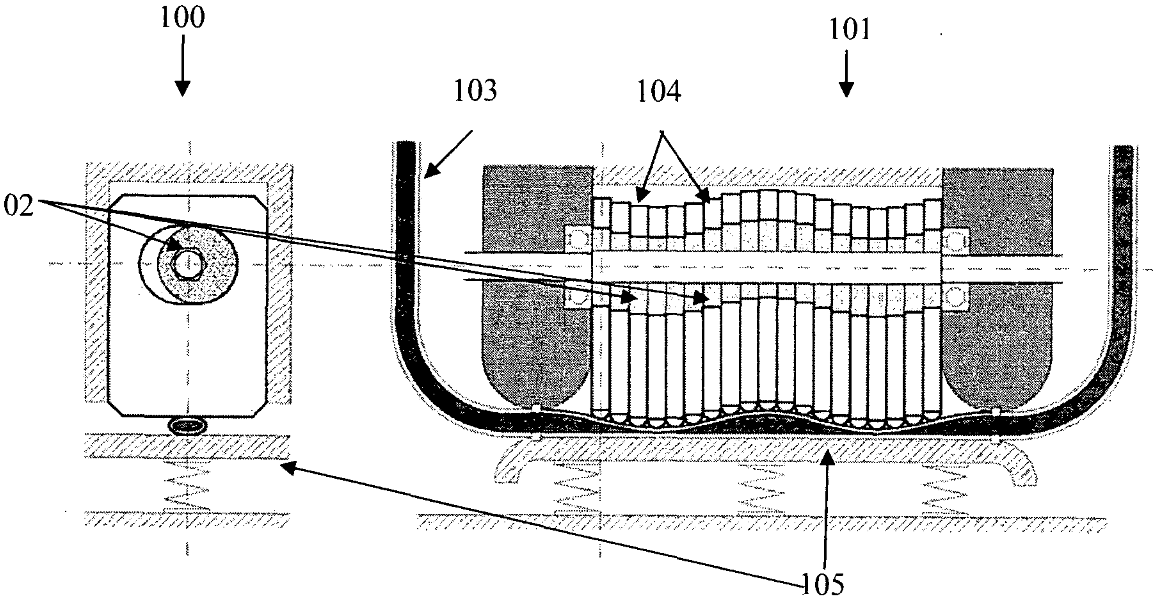



*Fig. 1*

*Prior Art*

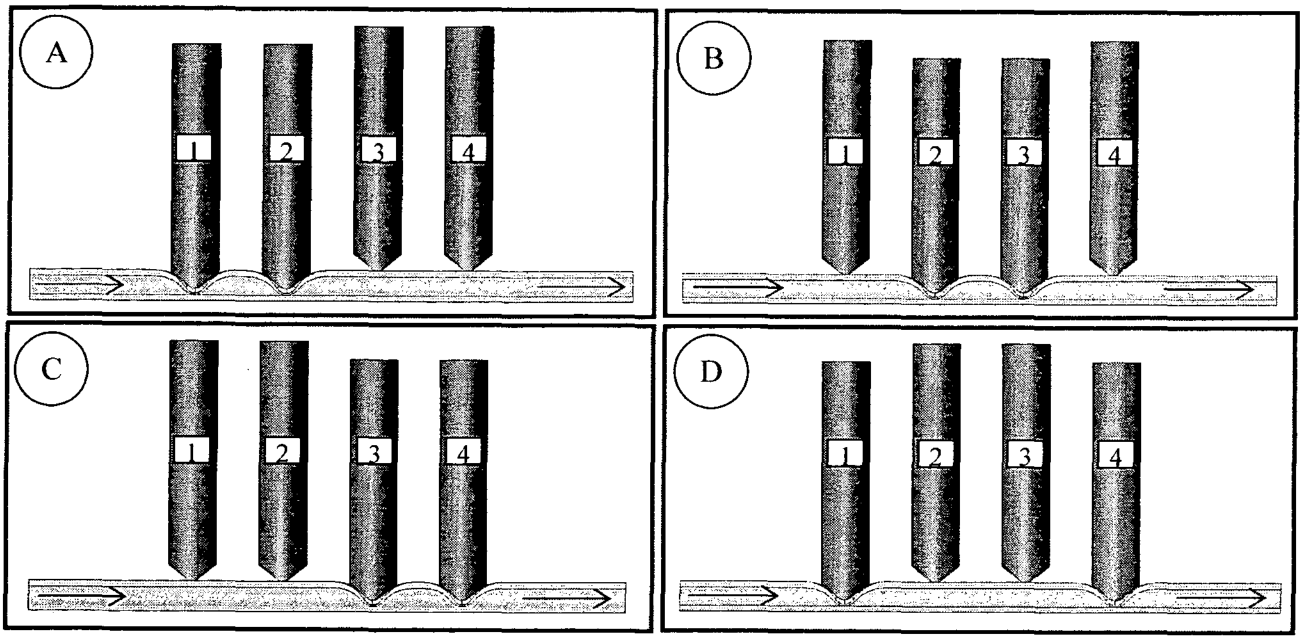



*Fig. 2*

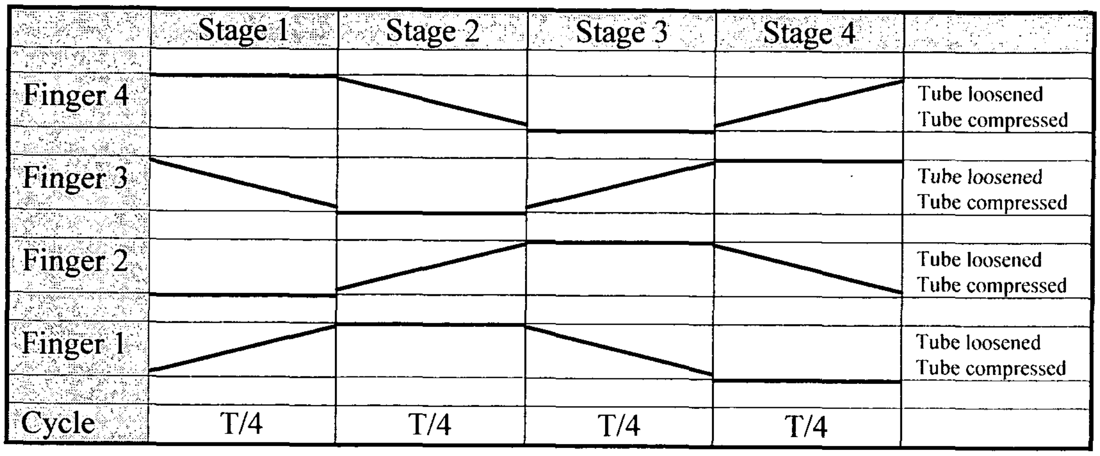

Stage 1
Stage 2
Stage 3
Stage 4
Finger 4
Tube loosened
Tube compressed
Finger 3
Tube loosened
Tube compressed
Finger 2
Tube loosened
Tube compressed
Finger 1
Tube loosened
Tube compressed
Cycle
T/4
T/4
T/4
T/4

*Fig.* 3

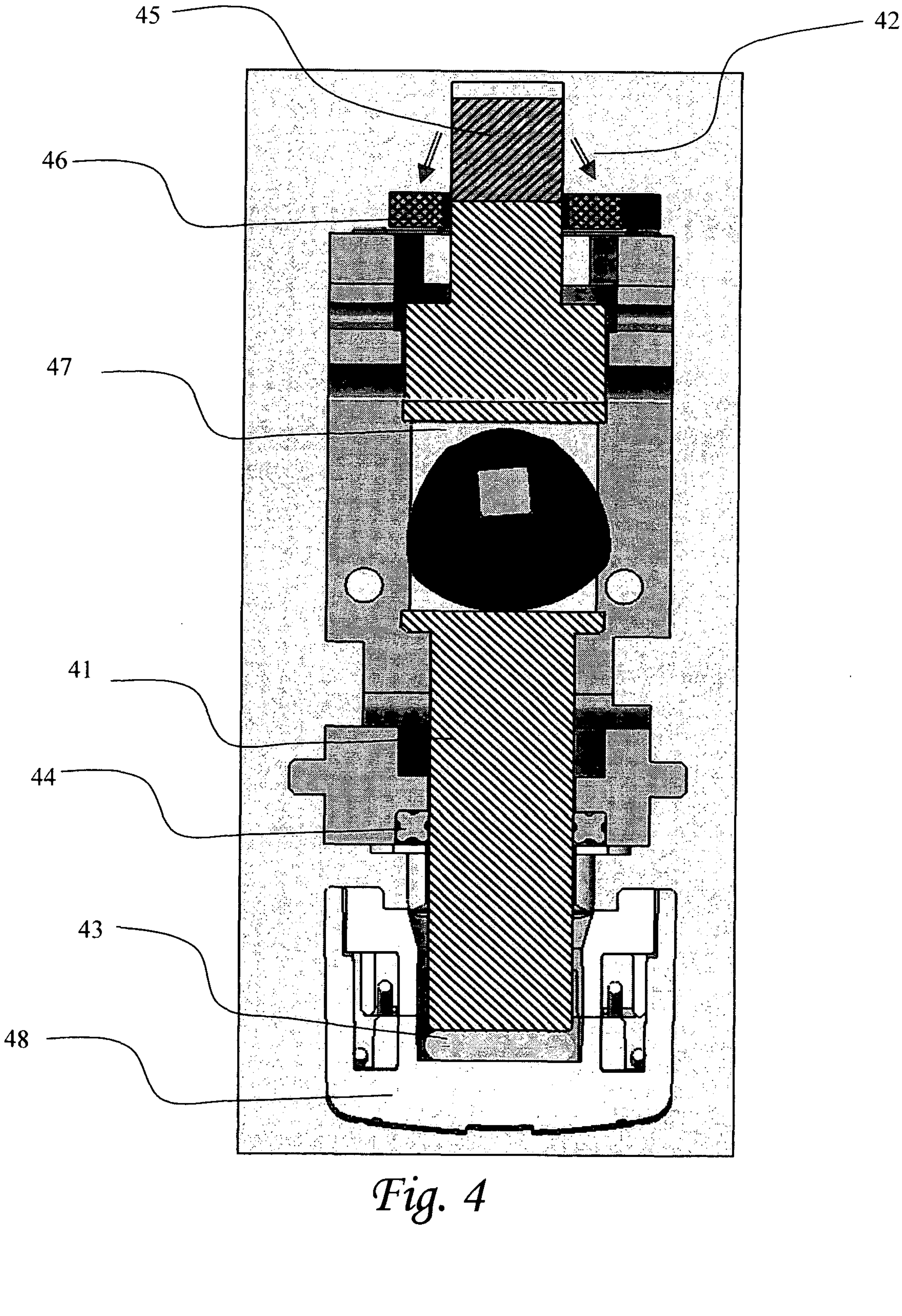



*Fig. 4*

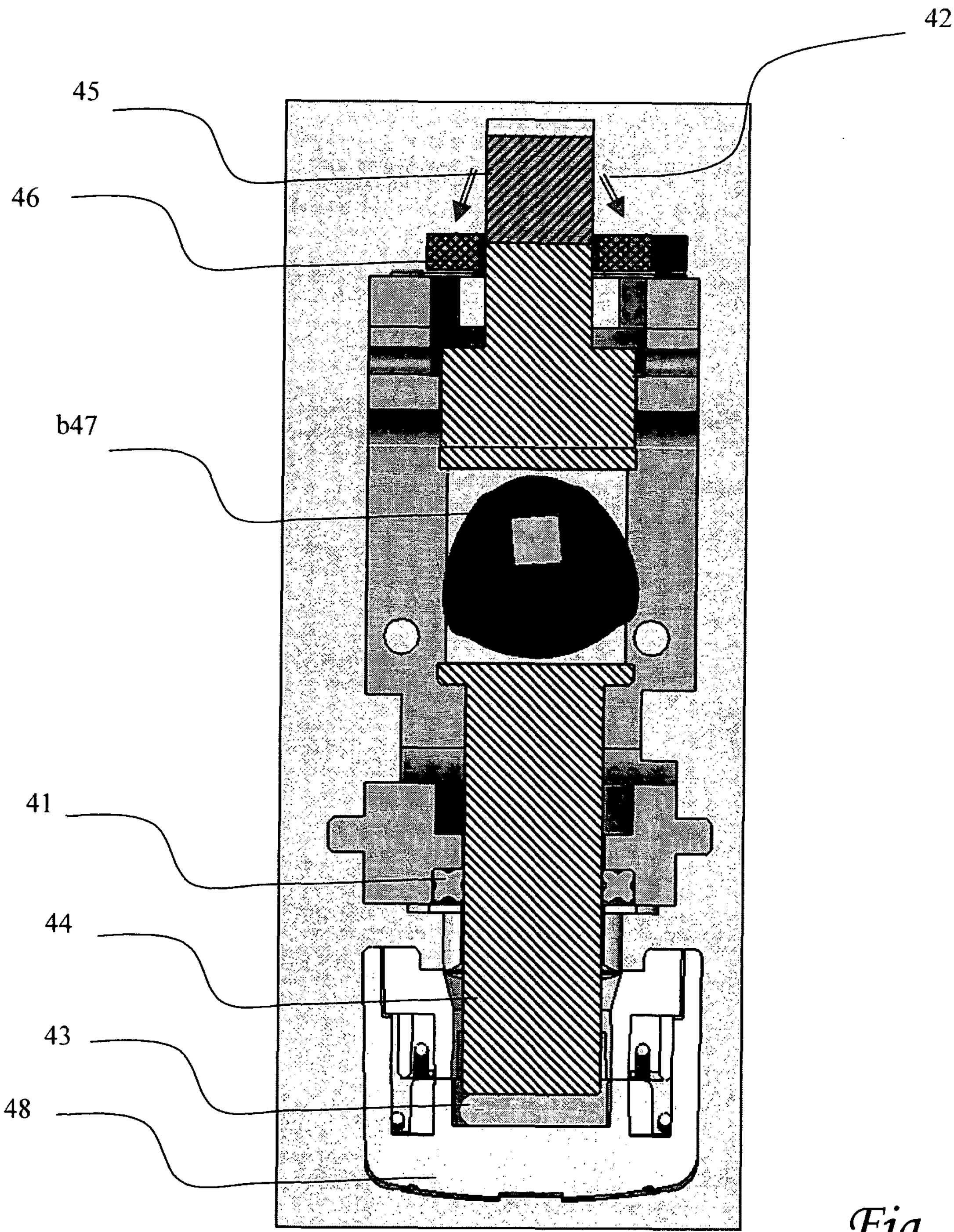
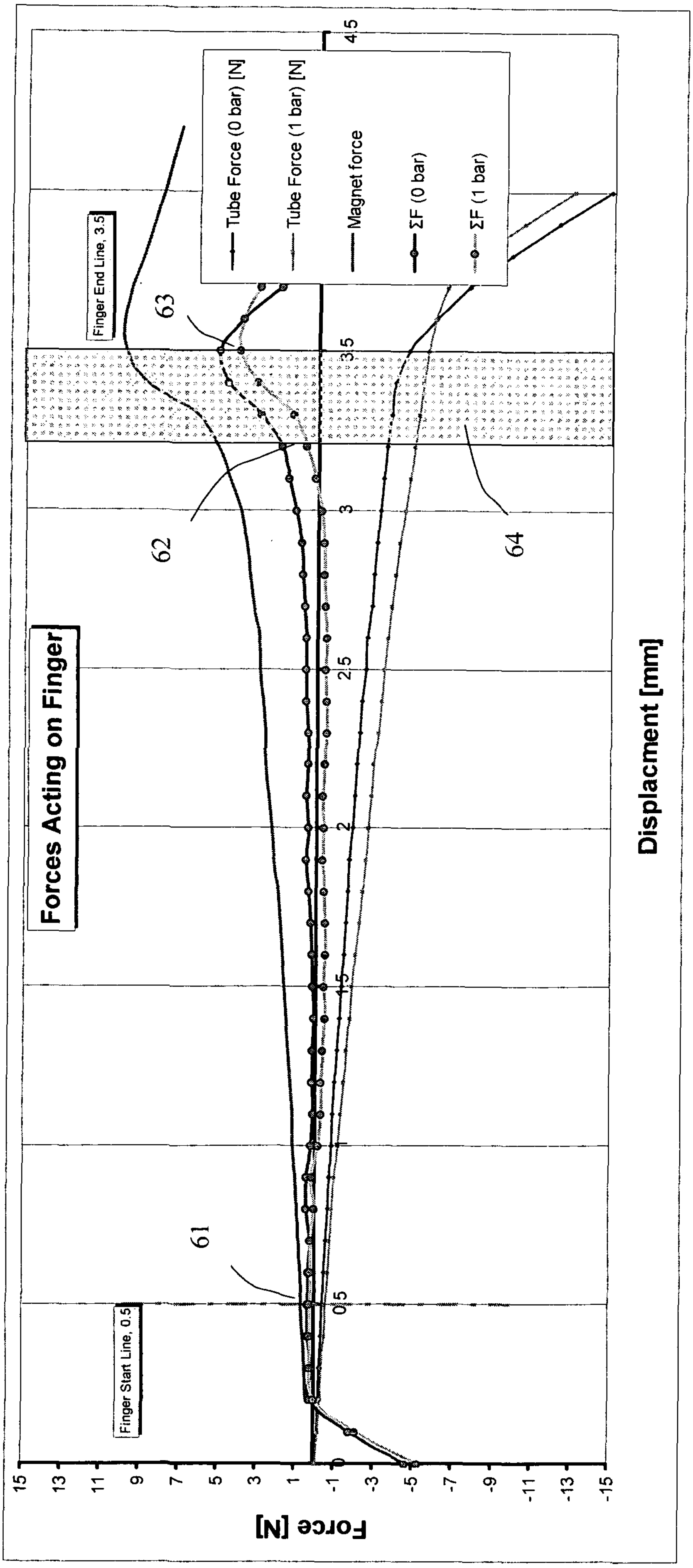



*Fig. 5*



Forces Acting on Finger
Tube Force (0 bar) [N]
Tube Force (1 bar) [N]
Magnet force
ΣF (0 bar)
ΣF (1 bar)
Finger Start Line, 0.5
Finger End Line, 3.5
61
62
63
64
Force [N]
15 13 11 9 7 5 3 1 -1 -3 -5 -7 -9 -11 -13 -15
Displacment [mm]
0 0.5 1 1.5 2 2.5 3 3.5 4 4.5


*Fig. 6*