Flow Through Collapsible Tubes: Augmented Flow Produced by Resistance at the Outlet

By Simon Rodbard, M.D., Ph.D.

The physical laws describing the character of flow through blood vessels may depart radically from those which have been developed by engineers and physicists for uniform flow through rigid tubes of uniform diameter. These deviations are marked in the case of flow through collapsible tubes, such as blood vessels and valves. At critically high velocities, the flow pattern may be transformed from a quiet, uniform smooth-flowing stream to an interrupted series of jets with the production of audible sound and with marked energy losses. The present study deals primarily with the "paradoxically" increased flow which may take place through collapsible tubes when a resistance is added to the outlet from the system. This marked deviation from the laws for rigid tubes is attributed to the vessel-distending effects of the added resistance, and to the inhibition of the phenomenon of recurrent collapsibility. The present in vitro experiments are used to attempt to explain certain paradoxical findings in flow through the collapsible tube systems of the body.

When flow takes place at critically high velocities through a collapsible vessel, instabilities appear which bring about fragmentation of the stream, vibrations, and marked energy losses.1 These phenomena result because the distending (lateral) pressure falls at a site of high velocity.* When this pressure drop is of sufficient magnitude, the lateral pressure distending the walls is less than the counterforce; the walls are therefore forced closer together. Consequently to this partial constriction of the tube there is a still greater velocity of the stream in this segment, and there is a further fall in distending pressure; the lumen is thereby further reduced. The process progresses until the tube is almost completely closed. At this point, velocity falls nearly to zero (demonstrated by high speed cinematography), and the entire energy of the stream acts to distend the constricted segment. With reopening of the tube, flow begins again; distending pressure then falls, and the cycle is repeated.

It has been suggested that this process of recurrent closing and opening (flitter) of the tube may be related to the production of murmurs and may explain some of the marked energy losses associated with such vibrations (1). Analysis of the mechanism of flitter suggested that an increased resistance to outflow from a collapsible segment might produce an apparent paradoxical increase in flow. Studies were undertaken to test this thesis.

General Methods

A modification of a previously described hydraulic model was used (fig. 1). This consisted of a water column maintained at a fixed level which served to drive water (15 to 20 C) through a short segment (3 cm. long) of soft walled collapsible tubing (surgical Penrose) with a diameter of 6 mm. The fluid then passed through a length of a thick walled rubber tubing of wide lumen into a hanging reservoir set at a given height.

In order to be able to produce graded narrowings of the collapsible segment, it was enclosed in a glass cuff. Air was pumped into the cuff cylinder by
means of a rubber syringe bulb; cuff pressure was registered with a water manometer. Flow was registered with a rotameter. The frequency of the flitter process was determined with a stroboscope. When indicated, sounds were recorded with a phonocardiographic apparatus.*

The lateral pressure immediately upstream and downstream to the collapsible segment was measured in some instances. As expected, these values were related to the driving pressure head minus a factor related to the velocity of the stream (flow per unit of cross section area). These data are not given in the present report.

Several types of resistance to outflow from the collapsible tube were utilized. These are described in appropriate sections below.

RESULTS

1. Flow Through a Rigid Tube

For base line studies, the rubber segment was replaced by a brass tube of 6 mm. in diameter and 3 cm. long. As expected flow through this system was dependent essentially on the difference in pressures between the inlet and outlet (fig. 1). At a pressure difference of 130 cm. water, 29 ml. per second was delivered. As the distal (outlet) resistance was raised by increments, flow diminished progressively. At 100 cm. water effective pressure head (inlet minus outlet pressure), 25 ml. was delivered per second; at 50 cm., 13 ml. was delivered. Delivery through this relatively rigid system was greater than any of the flows obtained under comparable pressure conditions with the collapsible penrose tubing.

2. Flow Through a Collapsible Tube

For the following experiments the driving pressure head was set at 100 cm. water above the level of the collapsible segment. The level of outflow was set initially at 30 cm. water below the segment. The cuff surrounding the collapsible tube was open to air, that is, under no compression. Under these conditions the flow through the system was 25 ml. per second (compared to 29 when a rigid tube was used).

As the cuff pressure was raised by increments, the flow fell in an irregular fashion. This effect can be seen by noting the flow at the origin (abscissa) of the various lines in

* Twinbeam Cardiette (Sanborn).

![Diagram](http://circ.ahajournals.org/)

**FIG. 1.** Inset gives the design of the apparatus used. PH represents the inlet driving Pressure Head maintained in a hanging reservoir at a fixed height. Flow passes through a segment of tubing under study, shown as the narrowed portion of the tube. This is surrounded by an enclosed cylinder, labelled "Cuff." In some experiments a rigid brass tube was used in this position. In others, a segment of Penrose tubing was used. The Penrose segment could be "constricted" by increasing the air pressure in the cylinder (cuff pressure). The outlet pressure serving as the distal resistance (DR) in these experiments was maintained constant by means of a second reservoir hanging at a fixed level.

The graph shows the effect of the height of the outflow level on delivery. The inlet pressure head was maintained at 100 cm. above the segment of collapsible tube under study. The vertical axis gives the height of the outlet above or below the collapsible tube, labelled as Distal Resistance. The horizontal axis gives delivery in milliliters per second. The line labelled "Rigid" gives the flow when the collapsible tube was replaced by a segment of copper tubing, and provides a baseline. As the outlet height is raised (vertical axis), flow is reduced progressively as expected. The other 12 lines represent flow through the collapsible tube compressed by cuff pressures in centimeters of water as noted with slanted numerals. As the distal resistance (level of the outlet) is raised, flow may increase, decrease, or remain unchanged, depending on the setting of the cuff pressure. Under some conditions, the walls of the collapsible tube can be seen by means of stroboscopic light to be closing and opening (flitter) at regular rates. The repetition rate of these vibrations is given in the upright numerals accompanying some of the dots. The letter "F" indicates the presence of slow or irregular vibrations of the tube which could not be resolved and counted by stroboscope. Absence of a number at a dot indicates that no vibration was discerned. Discussed in the text.
figure 1. For example, at a cuff pressure of 10 cm. water, flow was 23 ml. per second. When the cuff pressure was raised to 20 cm. water, flow fell to 21 ml. per second, and the soft rubber wall was seen by stroboscope to be collapsing recurrently at a rate of 13 times per second. Further increases in cuff pressure caused an irregular but progressive reduction in flow, so that at a cuff pressure of 50 cm. water the flow was only 14 ml. per second; at a cuff pressure of 70, flow was 7 ml. per second and at a cuff pressure of 110, it was only 1 ml. per second.

At the velocities which we studied, delivery is dependent primarily on the viscosity of the fluid and the length and diameter of the pipe system. Since tap water at 15 to 20 C. was used throughout, there were no significant changes in viscosity. The system was arranged so that the length of the various pipes remained unchanged. The only factor which was observed to change in the foregoing experiments was the diameter of the collapsible tube.

In accord with the laws for flow through tubes, the delivery through a system is related to the fourth power of its diameter.* The introduction of pressure into the cuff acts to reduce the diameter of the collapsible tube and in this way can markedly increase the resistance to flow. Very small changes in diameter may produce great increases in resistance, since this is a function of the fourth power of the diameter.

With the onset of recurrent collapsibility the problem is complicated further. Under these conditions the diameter of a portion of the tube is changing rapidly from moment to moment, producing enormous variations in resistance. At high cuff pressures (severe stenosis), flow becomes minimal because of the high resistance to flow through the compressed tube and the flitter phenomenon is suppressed. A seepage flow continues however, even when the cuff pressure is higher than the effective pressure head.

Details of the phenomenon of recurrent collapsibility including energy losses, murmur production, and fragmentation of the stream are given in a previous communication.¹

3. The Effect of a Distal Resistance

An analysis of the mechanism of flitter suggested that under certain circumstances the provision of a resistance to outflow might enhance flow through a collapsible tube. Evidence for this was already available in the work of Holt.² This interpretation was based on the fact that a distal resistance would increase the distending pressure acting on the collapsed segment, and thereby partially eliminate the most effective hindrance to flow: the progressive and recurrent narrowing of the collapsible segment.

Outflow or distal resistances were produced by three different means: (a) provision of an outflow column set at various heights; (b) use of graded orifices at the outflow, and (c) use of a second or distal collapsible segment. These had essentially similar effects on delivery.

a. Distal Resistance Due to Water Column at Outlet. The effect of the height of the outlet on the delivery was first recorded with the collapsible tube exposed to atmospheric pressure. When the driving head was 100 cm. of water, and the outlet was 30 cm. below the level of the collapsible tube (a total effective head of 130 cm. water), the flow was 25 ml. per second. As the level of the outlet was raised, the delivery fell consistently but irregularly (fig. 1). Thus, with the outlet at the level of the collapsible tube (effective pressure head equals 100 cm. water), flow was 23 ml. per second. Further raising of the outflow level

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* The Hagen-Poiseuille formulation is stated mathematically as:

\[ Q = \frac{\pi (P_i - P_o) d^4}{128\mu L} \]

where \( Q \) is the quantity of fluid delivered, \( \pi \) is the constant 3.14, \( P_i \) is the pressure at the inlet, \( P_o \) is the pressure at the outlet, \( d \) is the diameter of the tube, \( \mu \) is the viscosity of the fluid and \( L \) is the length of the pipe. It must be noted that this formulation holds only for steady flow through pipes of unchanging diameter. It is obviously difficult to apply this formula quantitatively to flow through the vessels of the body since the flow may be pulsatile rather than steady, and since the most significant factor, the diameter of the tube, may vary from moment to moment as well as from point to point.
caused a consistent fall in flow until it approached values obtained with the rigid tube.

Effect of Cuff Pressure. As noted in section 2 above, an increase in cuff pressure acted to compress the collapsible tube under study and thereby to reduce the delivery. For example, a cuff pressure of 40 cm. water reduced the flow from 25 ml. per second to 16 ml. per second (fig. 1). Likewise, raising the distal resistance alone acted to reduce flow by virtue of the reduction in effective pressure head. However, a combination of these two flow reducing effects sometimes produced apparent paradoxical results.

When the level of the outlet was raised while the cuff pressure was 40 cm., either there was no effect on flow, or sometimes the flow even increased significantly. Thus, raising the outlet 30 cm., and thereby reducing the effective pressure head from 130 to 100 cm. water caused an increase in flow from 16 to 18 ml. per second, an increase of 14 per cent. A further rise of 30 cm. in the height of the outlet had no effect on flow, even though the effective pressure head was now reduced to 70 cm. water.

These results appear paradoxical in that a greater flow through the system may be obtained for an effective pressure head of 70 cm. H₂O than is delivered for one of 130 cm. water. Similar effects were obtained at other cuff pressure levels (fig. 1).

The enhanced flow is apparently due to the distending effect of the outlet pressure on the collapsible rubber segment. This widening of the lumen of the tube accomplishes a reduction in resistance and energy loss. Despite the increased volume delivered, the velocity of the stream through the collapsible tube is reduced, and the tendency to flitter, which is velocity-dependent, is inhibited. This effect becomes apparent by noting that the flitter repetition rate, which was 26 per second when the outlet was 30 cm. below the collapsible tube, was reduced to 21 per second when the outlet was raised 20 cm.; it had fallen to 16 per second when the outlet was raised to the level of the tube, and with outlet at 30 cm. above the tube flitter ceased entirely. Similar effects noted at other cuff pressures are charted in figure 1. Even at very high cuff pressures (90, 100, 110 cm. water) the flow was relatively unchanged despite marked reductions in effective pressure heads. In these instances there was no apparent vibration of the tube. It would, therefore, appear that the reduction in effective pressure head was balanced almost exactly by the drop in resistance to flow due to the distention of the collapsible tube produced by the distal resistance. Generally, similar results were obtained in other experiments with the inlet pressure head set at 150, 100 and 50 cm. water.

It was sometimes possible to produce rather striking increases in delivery by raising the level of the outlet. One such set of data is given in table 1 in which the inlet pressure head was 100 cm. water. With the outlet set at the zero level, (i.e., at the level of the collapsible segment), the flow through the Penrose segment constricted with 90 cm. water cuff pressure was about 10 ml.; when the outlet level was raised 70 cm. water above the segment, the flow was increased to 17.5 ml. per second.

These data demonstrate that with certain relationships between driving pressure and degree of narrowing (cuff pressure), a rise in

| Table 1.—Effect of Outlet Height on Delivery Through A Collapsible Tube* |
|-----------------|-----------------|-----------------|-----------------|
| Outlet Height Above Collapsible Tube | Cuff Pressure |                |
| cm. H₂O        | zero cm. H₂O    | 60 cm. H₂O     | 70 cm. H₂O     |
| ml./sec         | ml./sec         | ml./sec         | ml./sec         |
| 0               | 40              | 34              | 27              | 18              | 9.7             |
| 5               | 39              | 32              | 29              | 18              | 10.0            |
| 10              | 39              | 33              | 27              | 19              | 10.0            |
| 15              | 38              | 37              | 27              | 19              | 10.0            |
| 20              | 35              | 35              | 27              | 20              | 10.0            |
| 25              | 33              | 34              | 31              | 21              | 10.0            |
| 35              | 30              | 32              | 30              | 20              | 10.0            |
| 40              | 29              | 30              | 29              | 19              | 10.7            |
| 45              | 27              | 29              | 27              | 19              | 12.0            |
| 50              | 26              | 28              | 25              | 19              | 13.0            |
| 55              | 24              | —               | 24              | 18              | 11.3            |
| 60              | 21              | —               | 22              | 17              | 11.0            |
| 65              | 19              | —               | 20              | 24              | 11.8            |
| 70              | 17              | —               | 18              | 19              | 17.5            |
| 75              | —               | —               | 16              | —               | 14.1            |

* Pressure head was kept constant at 100 cm. H₂O. Delivery is given in ml./sec.
outlet pressure can result in an enhanced flow. These effects are most probably due to the vessel distending effects of the distal resistance. Energy losses due to flow through a narrow tube as well as those due to the recurrent opening and closing of the vessel are thereby reduced or eliminated and present themselves as an increased delivery.

b. Distal Resistance Due to an Orifice at the Outlet. In these experiments a fixed orifice was used as the resistance to outflow from a collapsible tube. These orifices were smooth holes drilled into a plate of brass 25 mm. in thickness. The orifice was then fixed to the distal end of the elastic tube by means of a wide lumen brass pipe of 15 mm. diameter (fig. 2). The inlet pressure head utilized in these experiments was 125 cm. water.

When the cuff pressure was set at zero, the flow through the system was markedly affected by the outlet orifices. The flow through the system with outlet orifices of either 9.6 or 8.0 mm. diameter was 55.5 ml. per second. Outlet orifices of these sizes were so large that they imposed no significant resistance to outflow. For small outlet orifices, the flow was significantly reduced. Thus, an orifice of 6.4 mm. diameter permitted a flow of 53 ml. per second; an orifice of 4.8 mm. permitted 43.5 ml.; and an orifice of 32 mm. permitted 28 ml. to flow each second.

Application of cuff pressures less than 30 cm. water had no significant effect on flow with any of the orifices used. As the cuff pressure was raised higher than this level, flow fell off as expected (fig. 2). Thus, flow was progressively reduced as the cuff pressure was raised and the largest orifice (9.6 mm.) was used.

Delivery through the same system with an outlet orifice of 6.4 mm. diameter was unaffected by increases in cuff pressure until it was 45 cm. water. At this cuff pressure level, however, delivery was greater for the system with the smaller 6.4 mm. outlet orifice than for the 9.6 mm. orifice.

Similar effects were found with the smaller outlet orifices. This limited orifice was the apparent sole determining factor in volume delivered until the cuff pressure was raised to a critical level. At this level, however, the flow was greater for the smaller outlet orifices than for the larger outlet orifices.

This effect becomes clear when the data for each orifice was compared at specific cuff pressures. Thus, at a cuff pressure of 60 cm., flow was greatest (44 ml. per second) through the system with the outlet orifice of 4.8 mm., while it was only 28 ml. per second through the same system with the larger outlet orifice of 9.6 mm. By using the smaller outlet orifice, then, there was an increase in flow of over 50 per cent above that obtained by the use of the larger outlet orifice.

These data further clearly demonstrated that an outlet resistance, by acting as a distending force on a collapsible tube, could act "paradoxically" to increase flow.

It could be observed that when the enhanced flow occurred with the smaller outlet
orifices, the flittering of the tube was suppressed. Distal resistances of the orifice type, like those due to the heightened column resistance also appear to operate by inducing a back lateral pressure which distends the elastic segment and thereby inhibits flitter. The resistance to flow through this critical portion of the system is thus reduced, and the over-all resistance of the system is also lessened.

c. **Collapsible Tubes in Series.** Since situations may arise in which two successive segments of a vessel may be narrowed sufficiently so that both may be thrown into recurrent collapsibility (flitter), experiments were undertaken to test the effect of a distal or outlet resistance composed of a collapsible tube (fig. 3). In the description below, the first cuff and collapsible segment will be referred to as the *central* unit, and the second cuff and collapsible segment as the *distal* unit. The pressure head in this series of experiments was set at 136 cm. water.

When the distal cuff was open to atmospheric pressure, increases in the central cuff pressure resulted, after reaching the critical value of 50 cm. water, in the occurrence of flitter in this segment, associated with a progressive reduction in delivery. These data are demonstrated in fig. 3 as values on the horizontal axis (distal cuff pressure equals zero). Under these conditions flow for a central cuff pressure of zero (line at extreme right of fig. 3) was 51 ml. per second. At a central cuff pressure of 75 cm. water, flow was 45 ml. per second; at a central cuff pressure of 85 cm., flow was 37 ml. per second, etc.

In the present study, the central cuff pressure was kept constant at a given value, and the distal cuff pressure was varied. The quantity of fluid delivered gave a measure of the energy losses due to the combined resistances of the two collapsible tubes.

When the central cuff pressure was set at values from zero to 75 cm. water, a rise in distal cuff pressure of 50 cm. water had no effect on flow. The effects of distal cuff pressures in the range 80 to 90 cm. water had special interest. Since the effects in these ranges were almost identical, they are given in fig. 3 as a single curve (labelled 85). As the distal resistance was raised from zero to 50 cm. H₂O, flow was markedly reduced by approximately half. A further increase in distal cuff pressure to 70 cm. water caused an increase in flow to values even greater than had been obtained when the distal cuff pressure was zero. Increases in distal cuff pressure above 70 cm. water caused a progressive reduction in flow.

A somewhat similar effect is illustrated for a central cuff pressure of 120 cm. water. An increase in distal cuff pressure had no effect on flow for the condition when the central cuff pressure was 150 cm. water.

Resonance effects in the flitter rates of the two collapsible segments appeared to be related to the anomalous flows obtained in the

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**Fig. 3.** The effect on delivery of two collapsible tubes in series. The design of the experiment is given in the inset. A driving pressure head of 136 cm. water was maintained throughout. Flow passing through the system was collected and measured. When the cuff pressure in both cuffs was zero (atmospheric), flow was 51 ml per second. The line at the extreme right shows the effect on an increase in only the distal cuff pressure. Values are given for data obtained with the central cuff pressure "C. P." set at various levels as noted. Data obtained at central cuff pressures of 75, 78, 85, 120 and 150 cm. H₂O are given for various levels of distal cuff pressure (vertical axis). Discussed in the text.
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80 to 90 cm. water distal cuff pressure levels. However, these were too complex to resolve with the stroboscope, and will probably require a more sensitive analytical procedure.

These data show, as with the other distal resistance arrangements discussed above, that under certain conditions an augmented flow may be obtained by increasing the resistance to outflow from a collapsed tube. This enhancement of flow is associated with effects on the rate of recurrent collapsibility and with a consequent reduction in the resistance to flow through the central collapsible segments.

**DISCUSSION**

The body may be viewed as a collection of collapsible tubes which conduct fluid to various sites inside or outside the body. Among others, these include the blood vessels, the intestinal tract, the urogenital passages and the tracheobronchial airways. Elucidation of the special laws of flow through such collapsible tubes may have value in explaining some of the anomalous flow patterns and pressures in the various vessels of the body. 1, 2

If the rules for flow through collapsible pipes can be considered to apply to flow through the collapsible tubes of the body, they may serve to uncover mechanisms of energy losses in the transport of fluid and in the production of sounds of various types. In previous studies we have suggested the possibility that occurrence of flitter in blood vessels and other tube systems of the body may be related to the general problems of murmur production. 1, 3, 4, 5

The present results demonstrate that an increase in distal resistance beyond a collapsed or flittering tube can have very important effects on the ability of the pumping mechanism to push fluid through this vessel, as well as producing striking effects on the nature and frequency of the sounds which result. Thus, our data may be interpreted as suggesting that under certain conditions the addition of a second resistance may reduce the energy losses and thereby increase the apparent efficiency of a pumping organ, while incidentally inhibiting a murmur which may have been produced. The present data may thereby provide an insight into certain mechanisms associated with murmur production. 6

The special mechanics of distal resistance may assist in explaining "crescendo-decrescendo" or "diamond shaped" murmurs of outflow stenosis 6 occurring during the rapid ejection phase. Thus, extrusion of blood through a stenotic aortic or pulmonic valve may produce flittering of the leaflets and result in a murmur. As the intraventricular pressure rises early in systole, flow is enhanced and the flitter repetition rate is increased. Toward the latter part of systole, the heightened arterial pressure may act as a distal resistance, reducing the flitter rate (decrescendo). Unpublished work on circulation models support these interpretations. It may also be suggested that the effect of outlet resistance may help explain findings in clinical situations with double stenosis or resistances. 7, 10

Respiratory intrathoracic pressure changes acting on the collapsible great veins also undoubtedly affect the ability of the venous blood to enter the chest and return to the heart, as indicated by the work of Holt, 7 Duomarco 11 and Brecher. 12

The present studies demonstrate clearly that delivery through soft tubes differs significantly from flow patterns obtained with rigid tubes. Application of these mechanical principles to the collapsible tube systems of the body also may help to explain other special problems in the dynamics of flow.

**SUMMARY**

The effect of an outlet resistance on flow through a collapsible tube was determined. When the collapsible tube is completely distended, it behaves similarly to a rigid tube, and an outlet resistance has the same effect as an equivalent reduction in driving pressure head.

However, when the collapsible tube is partially constricted, thereby reducing the flow and resulting in the production of the phenomenon of recurrent opening and closing (flitter) with fragmentation of the stream, murmur production and energy losses, an
outflow resistance may have no effect on flow, or may even enhance flow. This effect is apparently due to distention of the collapsed segment by the heightened lateral pressure; inhibition of the flitter phenomenon also contributes to the enhanced flow. It is suggested that these special dynamics may account for certain paradoxical findings in flow through partially stenosed vessels.

**SUMMARIO IN INTERLINGUA**

Esseva determinate le effecto exercite super le fluxo de liquidos via un collapsible tubo per un resistentia al bucca. Quando le collapsible tubo es completamente distendite, su reactiones es simile a illus de un tubo rigide, e un resistentia al bucca ha le mesme effecto como le equivalentre reduction del propellente altitude manometric.

Del altere latere, si le collapsible tubo es partialmente constringite—de manera que le fluxo es reducite e que consequentemente il occurre le phenomeno de recurrente aperturas e claudituras (palpitation) con fragmentation del fluxo, le production de murmure, e perditas de energia—alora un resistentia al bucca pote remaner sin effecto super le fluxo o pote mesmo accelerar lo. Iste effecto pare resultar del distention del collapsible section de tubo per le augmentate pression lateral. Le inhibition del palpitation etiam contribue al acceleration del fluxo. Nos opina que iste observationes pote possibilmente servir a explicar certe constataziones paradoxe in le fluxo via vasos con stenosis partial.

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SIMON RODBARD

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