During the last fifty years a number of physical theories have been proposed in an attempt to describe analytically the behavior of pulsatile flow in the mammalian arterial system. In order to make such an approach to a system of nonuniform, viscoelastic vessels containing a non-Newtonian fluid at all possible, it becomes necessary to introduce simplifying assumptions, the judicious selection of which represents one of the most critical points of departure for any analysis and requires considerable insight into biological phenomena. Womersley's theory, although similar to those developed earlier by Witzig and Lambossy, has been the most widely applied because of its refinements and because he provided the tables necessary for a solution of the linearized Navier-Stokes equations with minimal labor.

Due mainly to the unavailability of adequate instrumentation for accurate measurement of blood pressure and flow, experimental verification of these theories and their underlying assumptions has become possible only during recent years. In a careful study, comparing experimental data with those predicted by theory, evidence was presented that Womersley's theory underestimates the viscous losses associated with pulsatile blood flow by a factor of three or more. In view of the assumptions underlying the theory, the authors suggested that this discrepancy may be due either to nonlaminar flow characteristics or to convective acceleration associated with a decrease of vessel cross section along the distance over which the pressure gradient is measured. Model experiments in which flow patterns are visualized by means of birefringence techniques have shown the presence of a large number of small disturbances at various points in the cycle during pulsatile flow and at points of branching or changes in vascular cross section during steady flow. However, these experiments did not indicate whether the pressure-flow relations associated with these instabilities of flow differed significantly from those expected for laminar flow. The present study was undertaken in an attempt to evaluate the effects of these disturbances on flow dynamics.

Methods

Commercial polyvinyl tubing (radius 0.87 cm at 125 cm H2O distending pressure, wall thickness 0.28 cm, static elastic modulus 3 x 10^7 dynes/cm², wave velocity about 30 m/sec) was cut in pieces approximately 7 m long. The individual pieces were softened to various degrees (static elastic modulus 0.5 to 3 x 10^7 dynes/cm²) the day before the experiment and were used as a model for the dog aorta, which has similar wall characteristics. The tubing selected for study was inserted between a pump and a reservoir (fig. 1). The outlet of the reservoir was joined to the pump inlet by means of Tygon tubing. The pump, consisting of two rubber chambers in parallel, each enclosed in a plastic housing and equipped with ball valves at the inlet and outlet, was driven by air pressure and provided pulsatile flow. The air pressure was monitored as an index of the driving force. The driving pressure had the form of a square wave and the flow pulse at the pump outlet resembled that in the ventricular outflow tract. The stroke volume could be varied from 10 to 40 cm³ and the frequency from 0 to 3 cycles/sec. A total of 39 experiments was done on five pieces of tubing.

In order to avoid entrance effects, all the parameters were evaluated at a distance of approximately four meters from the pump. Volume flow was monitored by means of an electromagnetic flowmeter (Medicon 2004 K with extracor-
FIGURE 1
Model for study of pulsatile flow. Bentonite solution is driven by a pump through a test segment of viscoelastic Tygon tubing while flow, pressure, diameter and birefringence are measured simultaneously.

FIGURE 2
Arrangement for measurement of birefringence. Five phototubes ($B_1$-$B_5$) are arranged to sense changes in light intensity across the tube diameter. A sixth phototube ($B_6$) senses motion of the vessel wall.

Flows were evaluated by using a streaming birefringence technique. On the basis of the theory outlined in the discussion, this method permits a quantitative evaluation of flow profiles. A birefrigent liquid in motion undergoes internal stresses due to viscosity and velocity gradients and its optical properties are changed. The velocity of light propagation through the fluid is no longer independent of the direction of propagation and the liquid becomes temporarily anisotropic. The incident light emerging from the light source through a lens is polarized in one direction by the polarizer (fig. 2). When it passes through the birefringent fluid it is broken into two perpendicular components which, traveling at different velocities through the birefringent fluid, arrive at the analyzer with a relative retardation. The analyzer transmits only components perpendicular to the initial polarization direction and the recorded values for transmitted light intensity are related to the rate of strain in the fluid. Zero light intensity occurs if the angle of isocline (referring to an orientation of the axes of the polarizer such that plane polarized light passes unmodified through the birefringent medium) is an integral multiple of $\pi/2$ or if the relative retardation between the two polarized rays in the medium is equal to an integral number of wave lengths of the incident light. The change in light intensity across the tube was sensed by five phototubes. A sixth phototube was placed behind the tube wall and measured the intensity of a light beam, which did not pass through the analyzer and polarizer plates. Its output was therefore proportional to radial wall movement. Appropriate corrections were made to compensate for the differences in direction and length of the light paths arriving at the six phototubes. The output of the phototubes was measured in arbitrary units (see Results).

A bentonite solution (0.2% bentonite per weight, viscosity = 0.0105 poise at 25°C) was used as perfusion fluid. At this concentration the fluid behavior is Newtonian. All transducers were calibrated statically and dynamically for each experiment. Their response was flat to at least 25 cycles/sec and the measurement errors were ±0.2 cm H$_2$O for the pressure transducers, ±0.1 cm$^3$/sec for the flowmeter and ±3 x 10$^{-4}$ cm for the radius measuring device.

Flow patterns were evaluated by using a streaming birefringence technique. On the basis of the theory outlined in the discussion, this method permits a quantitative evaluation of flow profiles. A birefringent liquid in motion undergoes internal stresses due to viscosity and velocity gradients and its optical properties are changed. The velocity of light propagation through the fluid is no longer independent of the direction of propagation and the liquid becomes temporarily anisotropic. The incident light emerging from the light source through a lens is polarized in one direction by the polarizer (fig. 2). When it passes through the birefringent fluid it is broken into two perpendicular components which, traveling at different velocities through the birefringent fluid, arrive at the analyzer with a relative retardation. The analyzer transmits only components perpendicular to the initial polarization direction and the recorded values for transmitted light intensity are related to the rate of strain in the fluid. Zero light intensity occurs if the angle of isocline (referring to an orientation of the axes of the polarizer such that plane polarized light passes unmodified through the birefringent medium) is an integral multiple of $\pi/2$ or if the relative retardation between the two polarized rays in the medium is equal to an integral number of wave lengths of the incident light. The change in light intensity across the tube was sensed by five phototubes. A sixth phototube was placed behind the tube wall and measured the intensity of a light beam, which did not pass through the analyzer and polarizer plates. Its output was therefore proportional to radial wall movement. Appropriate corrections were made to compensate for the differences in direction and length of the light paths arriving at the six phototubes. The output of the phototubes was measured in arbitrary units (see Results).

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The transducer output was recorded on a 14-channel tape recorder, under continuous monitoring on two 8-channel Sanborn oscilloscopes. During experiments, the cycles to be analyzed were coded on analog tape by means of a signal generated from a LINC computer. The LINC determined simultaneously the period of the marked cycles from a trigger generated by the

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pump. The data were then played back through the A-D converter of the LINC and subjected to Fourier analysis. The applicability of Fourier analysis to the cardiovascular system and its limitations are discussed in detail elsewhere.9

The results of the Fourier analysis were used to calculate the power spectra of the different variables. For periodic signals this method is considerably faster than that based on correlation techniques, because the Fourier transforms of the individual frequency components are obtained directly from the Fourier coefficients as follows:

If two periodic signals \( f_1(t) \) and \( f_2(t) \) are represented by their Fourier series:

\[
f_1(t) = \sum_{n=0}^{\infty} a_n \cos n\omega t + \sum_{n=1}^{\infty} b_n \sin n\omega t \tag{1a}
\]

and

\[
f_2(t) = \sum_{n=0}^{\infty} A_n \cos n\omega t + \sum_{n=1}^{\infty} B_n \sin n\omega t \tag{1b}
\]

the Fourier transforms of the \( n \)th harmonics of the two signals can be written as

\[
F_{1,n}(i\omega) = \frac{1}{T} \int_0^T f_1(t) e^{-i\omega t} dt = \frac{1}{2} (a_n - jb_n) \tag{2a}
\]

\[
F_{2,n}(i\omega) = \frac{1}{T} \int_0^T f_2(t) e^{-i\omega t} dt = \frac{1}{2} (A_n - jB_n) \tag{2b}
\]

The value for the \( n \)th harmonic of the cross power spectrum, \( \Phi_{f_1f_2}(n) \), of the two signals then becomes (* indicates the conjugate transform and \( j = \sqrt{-1} \)):

\[
\Phi_{f_1f_2}(n) = F_{1,n}^* \cdot F_{2,n}
= \frac{1}{4} (a_n + jb_n) (A_n - jB_n) \tag{3a}
\]

which separates into a real and an imaginary part:

\[
\Phi_{f_1f_2}(n) = \frac{1}{4} \left[ (a_n A_n + b_n B_n)
+ i (B_n A_n - a_n B_n) \right] \tag{3b}
\]

where: \( a_n, b_n, A_n, B_n \) are the Fourier coefficients of \( f_1(t) \) and \( f_2(t) \) respectively.

\( F_{1,n} \) and \( F_{2,n} \) are Fourier transforms of the \( n \)th harmonics of the two signals \( f_1(t) \) and \( f_2(t) \).

**Results**

Figure 3 shows a sample tracing obtained with a driving pressure of 300 cm H\(_2\)O in a tube with a static elastic modulus of 0.91 x 10\(^7\) dynes/cm\(^2\) and a wave velocity of 14.6 m/sec. On the left are illustrated from top to bottom: the two radius measurements \( (D_1 \) and \( D_2) \), driving pressure to the pump \( (P_r) \), upstream and downstream pressure \( (P_1 \) and \( P_2) \), the pressure difference between the two, obtained by electrical subtraction of the two pressure signals \( (\Delta P) \), radial wall motion as measured by the phototube \( B_0 \) and volume flow \( (Q) \) by electromagnetic flowmeter. The panels on the right represent from top to bottom: driving pressure \( (P_r) \), birefringence pattern from left to right \( (B_1 - B_5) \) corresponding to the position of the phototubes shown in figure 2, wall motion \( (B_0) \) and volume flow \( (Q) \). In this particular experiment the two pumping chambers were arranged in such a way that one pump cycle produced two flow pulses. Directing the attention first to the left-hand panel, one notices that the downstream pressure pulse is larger than the upstream pulse, and that the latter is considerably smoother. Since we are dealing with a uniform tube the change in shape of the pressure pulse is due to wave reflections originating at the reservoir inlet. The pressure gradient leads the flow pulse in phase, indicating the predominance of the inertial over the elastic forces in this model. Changes in radius are small (approx 1.4%, corresponding to the high elastic modulus) and in phase with the pressure change. The radial motion as estimated by the coils is very different from that measured by the phototube. While the first indicates only changes in radius, the latter monitors the overall radial motion of the wall with respect to a fixed reference point. From the right-hand panel it is apparent that the output of the phototubes measuring the birefringence is smooth and very similar in shape to that of the electromagnetic flowmeter (polarity in \( B_2 \) is reversed). By direct observation the patterns resemble those described earlier for classical laminar flow in viscoelastic tubes, which is characterized by steady, smooth shear lines and the absence of irregularly appearing spots of increased light intensity.6

These tracings are shown again in figure 4 and compared against those obtained with a driving pressure of 500 cm H\(_2\)O (symbols as in
Figure 3. Sample tracing obtained with driving pressure of 300 cm H2O. Flow is laminar and shapes of the volum flow tracing (Q) and of the five birefringence tracings are similar. No high frequency components are present.

In the panel on the left (driving pressure 300 cm H2O, mean volume flow 28 cm³/sec, pump frequency 1.2 cycle/sec, Reynolds number calculated on the basis of mean flow 2900) the birefringence pattern is smooth and similar to that of the electromagnetic flowmeter. In the panel on the right (driving pressure 500 cm H2O, mean flow 52 cm³/sec, pump frequency 1.2 cycle/sec, Reynolds number 5500) the outputs from the two phototubes, which sample the birefringence close to the wall, are very similar to that obtained at the lower driving pressure. However, the patterns obtained from the three phototubes placed behind the central core of the flow channel are quite irregular. There are large high frequency components, confirming the conclusions obtained earlier on the basis of qualitative visual interpretation of motion pictures. These motion pictures show the appearance of irregular spots of high illumination, particularly during flow deceleration, throughout the central core, while the continuity of the shear lines close to the wall is maintained.

The harmonic content of the central birefringence is compared with that of the electromagnetic flowmeter in Figure 5. With a driving pressure of 300 cm H2O, the harmonic content of the electromagnetic flowmeter (panel a) is very similar to that of B3 (panel c). Note that in both cases the second harmonic is largest. This is so because the Fourier analysis was done over one pump cycle, which contains two flow pulses, as pointed out under Methods. Above the fourth
PULSATILE FLOW PATTERNS

FIGURE 4

Comparison of volume flow and birefringence patterns at two driving pressures. At left (driving pressure 300 cm H$_2$O), flow is laminar; at right (driving pressure 500 cm H$_2$O), eddies appear in the central core of the moving fluid (disturbed laminar flow). These eddies are characterized by their higher frequency components, and are not detected by the electromagnetic flowmeter. Note that outputs of the phototubes, B1 and B2, sampling the peripheral sleeve indicate undisturbed flow in the vicinity of the wall.

harmonic there are no frequency components of significant magnitude. The 52nd harmonic, which occurs in the output of B3, (panel c) corresponds to 60 cycles/sec noise in the circuitry of the phototube. The implication of such artifacts for Fourier analysis (aliasing errors) is discussed in detail elsewhere. With a driving pressure of 500 cm H$_2$O the harmonic content of the electromagnetic flowmeter is still limited to five harmonics (panel b). In contrast, the output of the phototube B5 shows a wide spectrum of frequency components, as expected from the analog tracing. Similar spectra are obtained in this case from B2 and B4, while the output from the two peripheral phototubes (B1 and B3) remains unaltered. If the driving pressure (or the flow rate) is further increased, the higher frequency components appear also in the output of the latter two phototubes. Note that B4 shows a large first harmonic in its output, in contrast to the electromagnetic flowmeter. This indicates that this frequency component arises from the flow in the center of the tube, but that its contribution to volume flow is too small to be measured by the electromagnetic flowmeter. The difference in the frequency spectra between the flowmeter

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Frequency spectra of volume flow and birefringence patterns in pulsatile flow. Electromagnetic flowmeter, panels a and b; central phototube B3, panels c and d. In undisturbed flow (panels a and c; frequency 1.2 cycle/sec, driving pressure 300 cm H2O, mean flow 28 ml/sec) the frequency content of the two monitoring devices is similar. With the appearance of eddies (panels b and d; frequency 1.2 cycle/sec, driving pressure 500 cm H2O, mean flow 52 ml/sec) the frequency content of the volume flow does not change (b), while that of the phototube (d) is greatly increased.

and the phototubes is not due to the frequency limitations of the flowmeter, but rather to the small contribution of these components in terms of volume flow.

Figure 6 illustrates the real and imaginary parts of the cross power spectrum of input pressure and volume flow associated with the two driving pressures. The real part (lower panel) indicates the actual power drawn from the source, the imaginary part (upper panel) the power which oscillates between the source and the system. The power losses in the system depend on the real part of the power spectrum. It will be seen that the main fraction of the power spectrum corresponds to the second harmonic of the pump (i.e., the fundamental frequency of the flow pulse) and that a smaller fraction corresponds to its fourth harmonic. The pressures and flows associated with the other frequency components are so small that their product is negligible in comparison. Hence more than 95% of the power losses due to the pulsatile flow components are contained within the first two harmonics. The power input for the mean flow (DC component) is 1160 g cm sec⁻¹ for 300 cm H2O driving pressure and 2620 g cm sec⁻¹ for 500 cm H2O driving pressure. Only the first flow pulse requires a power input greater than 10% of the steady flow power (18 and 11%, respectively).

Discussion

As indicated in the section on Methods, streaming birefringence is related to the internal stresses in the flowing liquid. For simple flows these relations have been well...
established, and quantitative measures of either the strain rate or the stress pattern can be obtained. In the case of plane laminar fluid motion the shearing stress ($\sigma$) in a viscous fluid is given by:

$$\sigma = \mu \frac{\partial \delta}{\partial n}$$  \hspace{1cm} (4)

where:  
$\mu$ = coefficient of fluid viscosity  
$\delta$ = fluid velocity  
$n$ = distance normal to the plane flow lamina.

It has been shown\(^{10}\) that under these conditions the amount of birefringence ($n_1 - n_2$) is proportional to the velocity gradient $\partial \delta / \partial n$. Therefore the following flow optic relations are valid:

$$\delta = sf\left(\frac{\partial \delta}{\partial n}\right)$$  \hspace{1cm} (5)

$$f(0) = 0$$  \hspace{1cm} (6)

where:  
$\delta$ = relative retardation between the two light beams produced by the birefringent fluid  
$s$ = length of the light path through the fluid element  
$f$ = functional notation.

Wayland\(^{11}\) has emphasized the significant theoretical difficulties in transferring the results from two-dimensional flow to three-dimensional situations. The rheological properties of a model fluid must be fully understood in order to avoid an unjustified extrapolation of such data to the behavior of blood. Although the flow pattern of the macromolecular suspension used in our experiments may not be too different from that of blood in large vessels, the presence of formed elements which are large compared to the flow channel can introduce a stirring action leading to a modification of the flow profile in smaller vessels in a manner similar to that of turbulent eddies. It should be pointed out that the Reynolds number is characteristic only for steady flow. Its validity as a parameter describing pulsatile flow remains to be established. The critical Reynolds number specifies the conditions under which it is impossible to introduce turbulence in a flow channel. However, laminar flow may be present at much higher Reynolds numbers in smooth flow channels with appropriate entrance conditions. Our data indicate that, in general, turbulence occurs in distensible tubes at higher Reynolds numbers than in comparable rigid tubes.

Because there is considerable confusion in the biological literature about the hydrodynamic terms laminar and turbulent flow, it seems appropriate to explore their meanings in this context. Laminar flow is characterized by the important property that the flow at one point is correlated with that at every other point. Poiseuille flow with its parabolic velocity profile is a classical example of laminar flow. However, it is also valid to classify the intermittent shedding of vortices downstream from an aortic stenosis as a type of laminar flow because of its regular, predictable character. In order to distinguish between these two types, we call laminar flows containing such eddies and vortices “disturbed” laminar flow. The patterns illustrated in the right-hand panel of figure 5 belong to this class. In fact, even when the eddies were distributed throughout the whole flow channel, we were still able to correlate them with the decelerating flow phase by means of correlation techniques.

Turbulent flow, on the other hand, is characterized by complete random motion of the individual fluid elements. There is only a statistical correlation between the velocities measured at two points in the flow sufficiently removed from each other. Although a well-defined mean velocity may be present, random fluctuations of the velocity occur about the mean at each point. In our experiments we have never observed such flows, although the Reynolds numbers based on mean flow ranged from 1000 to 7000.

Lindgren\(^{8}\) has shown that the transition from smooth laminar flow to fully developed turbulent flow is not sudden. At first small zones of instability appear which alternately grow and dampen out as the flow velocity increases in a given geometry. These zones.
then become larger and more persistent, until a sufficiently random motion is superimposed on the forward progress of fluid to classify it as true turbulence. In this transition zone there is a sudden change in the pressure-flow relation. This discontinuity appears in the region between two limiting values of the Reynolds number, the lower value characterizing the first appearance of turbulent flashes and the higher value the presence of fully established turbulence. The critical Reynolds number may vary within wide limits, indicating that it depends on several, as yet unknown, flow properties. One of the major effects of turbulence on the overall flow profile is related to the transfer of momentum from one part of the flow to another in a manner very different from the action of simple viscous drag in laminar flow, leading to marked changes in the profile of the average forward velocity.

Although a cylindrical tube is three-dimensional, the flow within can be reduced to two-dimensional flow because of axial symmetry. However, even so, some doubt surrounds the applicability of the above theory to the disturbed flow patterns observed in this study with the higher driving pressures. The stress-strain rate relations associated with the higher frequency disturbances noted in these experiments may be of a different nature than those associated with the lower frequency component.

Figure 7 shows the velocity profile which

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**FIGURE 7**

Velocity profiles over one pulsatile cycle calculated from outputs of five phototubes during laminar flow. The asymmetry may be related to nonuniform distension along two perpendicular radii in a tube of not strictly circular cross section.
was derived from the birefringence pattern using the flow optic relations (equations 4, 5) for an experiment under conditions of laminar flow in a tube with a static elastic modulus of \(0.97 \times 10^7\) dynes/cm\(^2\) (driving pressure 200 cm H\(_2\)O, mean flow 20 cm\(^3\)/sec, Reynolds number 2100). It will be seen that its general shape is similar to that predicted from Womersley's theory.\(^{12}\) The asymmetry in the motion is unlikely to be due to small errors in the geometrical arrangement of the relative position of the two phototubes with respect to the flow channel and the light source. It appears more probable that it is related to unequal distension of the tube, whose cross section was not strictly circular. Under these conditions a circumferential helical motion of the fluid would be expected and the radial motion in two perpendicular directions would not be identical.\(^0\) The difference in extension in the two directions was 20\% and the phase angle between the respective motions increased from 2\(^\circ\) for the first harmonic to 100\(^\circ\) for the fourth harmonic in this experiment, which tends to support this interpretation.

The higher frequency components characterizing the output of the phototubes sampling the central core of the flow (\(B_2 - B_4\)) appear under visual observation as irregularly shaped spots of high light intensity, associated primarily with the period of decelerating flow. They indicate that the central core is less stable than the peripheral sleeve, where the shearing stress is largest. As the flow rate is increased, the region of instability becomes progressively larger until it includes finally the peripheral sleeve. Using equations 4 to 6 and integrating the velocities throughout the cross section the contribution of these components to total volume flow has been estimated and found to be less than 5\% of the average flow. However, since the stress-rate of strain relations in these eddies may be different from those described by equation 4 the validity of this estimate is doubtful, although the evidence discussed below indicates that it may represent an upper limit.

In no instance have we been able to obtain corresponding frequency components in our pressure measurements, even when we used a Statham SF-1 gauge, whose frequency range is similar to that used for the analysis of the output of the phototubes. On the other hand, these components could easily be recovered by monitoring the wall vibrations by means of a sensitive phonocartridge. This means that the observed high frequency disturbances are transmitted from the central fluid core to the wall without disrupting the smoother flow in the peripheral sleeve. The energy associated with this transfer is below the sensitivity of our electromechanical transducers, but not below that of the receptors in the skin and ear. In terms of the measurable power losses, the losses due to the observed transient flow disturbances must be negligible.

Although the results of these model experiments cannot be applied directly to the mammalian circulation they are helpful for the interpretation of previous findings. It has been shown\(^{13}\) by cinematographic techniques that a complete disruption of dye patterns occurs in the rabbit aorta during peak systolic ejection. At the aortic bifurcation dye could be seen to impinge on the wall and eddies were set up near the orifices of the two branches. The dye nearest the wall was disturbed only minimally and flowed smoothly around the bends. The eddies persisted through systole and disappeared early in diastole. As pointed out above, such flow should not be classified as turbulent.

On the other hand, a study of the frequency spectrum of arterial pressure pulses\(^a\) in dogs at various sites revealed no high frequency components and the pressure-flow relations were found to be linear in the large arteries. Hence it would appear that the flow disturbances reported for the aorta are similar in character to those observed in the present studies. While disturbed flow in the arteries may be important for proper mixing, it is unlikely to play a significant role in terms of energy losses. This indicates that the discrepancies between experimental and theoretically predicted results observed by Fry
et al.\textsuperscript{4} are not due to nonlaminar flow patterns.

**Summary**

Pulsatile flow patterns in polyvinyl tubes were visualized by means of streaming birefringence and compared with those obtained using an electromagnetic flowmeter.

At low flow rates the frequency spectrum of the birefringence pattern is similar to that of volume flow. As the flow rates are progressively increased, irregular eddies appear, particularly during deceleration of flow, first in the central core and later spreading into the peripheral sleeve. They are characterized by a wide frequency spectrum.

The concepts of laminar and turbulent flow are reviewed and evidence is presented which indicates that the power losses associated with the observed eddies are negligible with respect to the losses due to the average flow and its pulsatile components of low frequency.

Flow disturbances observed in the arterial tree appear to be similar in character to those found in the present study. It is unlikely that they can account for significant discrepancies between experimental and theoretically predicted pressure-flow relations.

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Pulsatile Flow Patterns in Distensible Tubes
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