Tooth Pulp Tissue Pressure and Hydraulic Permeability

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If the pulp chamber of a tooth is penetrated, either by dental caries, or by a dental drill, inflammation and eventual death of the pulp tissue usually follows. While a long interval may elapse before degeneration is complete, necrosis is an almost inevitable consequence of pulpal penetration.

A current explanation in the dental literature for this phenomenon is as follows.1 The application of noxious stimuli to the dental pulp is followed by inflammation of pulp tissue and release of fluid into the dental pulp canal. This is supported by histologic evidence of edema, polymorphonuclear leukocytic infiltration, and disorganization of the odontoblastic layer in pulp of teeth which have been diagnosed as suffering from acute pulpitis.2 The inability of the dental pulp to recover easily from noxious stimulation is claimed to be due to the rigidity of the dentin walls surrounding the pulp. This rigidity prevents swelling characteristic of soft tissue inflammation and thus leads to an increase in pulp tissue pressure.3 The pressure eventually becomes high enough to impede circulation, causing pulpal ischemia and subsequent tissue death. The vascular supply of the dental pulp enters and leaves through tiny foramina at the apex of the root and thus is particularly susceptible to the increased tissue pressure. While this hypothesis seems reasonable, it can neither be completely accepted nor rejected due to the lack of information about the mechanical and hydrostatic forces within the pulp chamber.

The object of this paper is to characterize the forces involved in a fluid exchange within the tooth pulp chamber of the dog. Specifically, we have attempted to measure the tissue pressure of the tooth pulp (if pressure is the correct term) under static conditions, i.e., when no net exchange of fluid is taking place, and to measure the dynamic resistance to fluid exchange (in other words, the hydraulic permeability) of the tooth pulp tissue.

Methods

Adult mongrel dogs weighing 10.5 to 15 kg were used. Measurements were made on the maxillary third incisors and the maxillary and mandibular canines. Each tooth was used in only one experiment; however, each animal was employed in several experiments until all suitable teeth had been used.

The animals were anesthetized with pentobarbital sodium (Diabutal, Diamond Laboratories), injected intravenously. Also, the tranquilizer propiomazine hydrochloride (Largon, Wyeth) was injected intramuscularly to reduce the amount of pentobarbital necessary to maintain the anesthetic level. A thermistor probe was inserted rectally for continuous observation of deep body temperature. By means of external heating or cooling, the rectal temperature was maintained at 38°C ± 0.5°C. Room temperature was maintained at 20°C to avoid spurious pressure readings due to expansion or contraction of the fluid in the measuring system.

The enamel was penetrated with a #3 round dental bur driven by a low speed dental motor. Subsequent drilling was done manually with small twist-drills mounted in a watchmaker's pin vise.

The original hole (produced by the bur) was extended 2.50 mm toward the pulp with a #79 drill (diameter 0.37 mm). This hole was enlarged with a #72 drill (diameter 0.63 mm) but only to a depth of 2.25 mm and further enlarged with a #71 drill (diameter 0.655 mm) to a depth of 2.00 mm, forming a tapered hole to produce a tight "jam" fit when the threaded needle was later screwed in.

The #79 drill was then reused, this time with a series of sleeves slipped over it to allow pene-

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The sleeves were constructed from 22-gauge stainless steel hypodermic tubing, and ranged from 0.750 mm to 2.000 mm in length with intervals of 0.050 ± 0.005 mm. Since the mechanical force retarding the advance of the drill is greatly reduced as the pulp chamber was entered, the sleeves were necessary to prevent deep penetration of the pulp and resulting tissue damage. By using progressively shorter sleeves, the hole was extended toward the pulp chamber until either clear fluid or fluid mixed with blood was seen rising in the hole.

At this point a threaded stainless steel cannula was screwed into the hole. The cannula was made from 22-gauge stainless steel hypodermic needle tubing (outer diameter 0.75 mm, inner diameter 0.40 mm) threaded at one end with a jeweler's die. The other end of the cannula was tapered and connected to a 30-cm length of PE 50 polyethylene tubing which led to a pressure transducer (Sanborn model 267B). A microsyringe (Gilmont microburet) with a capacity of 100 µl and a resolution of 0.01 µl was connected to the other inlet of the pressure transducer (fig. 1).

The hydraulic measuring system (syringe, pressure transducer, cannula, and connecting tubing) was originally filled with water, taking care to eliminate all air. On the day of the experiment, about 80 µl of the water were expelled and the needle refilled with an equal amount of mammalian Ringer's solution to avoid introducing a nonphysiological solution into the tooth pulp cavity. During the period of screwing the threaded needle into the tooth, the microsyringe was manipulated to eject fluid continuously and prevent trapping of air in the hole.

The pressure transducer output was amplified by a Tektronix type Q carrier preamplifier; a Tektronix type 133 power supply provided power for the preamplifier and an additional stage of gain. This signal was recorded by a Varian potentiometric recorder. The maximum error in pressure measurement was ± 2 mm Hg, and was due both to drift in the apparatus and to reading error.

Before connecting the cannula to the tooth, the compliance, leakage rate, and response time of the system were checked. The compliance of the measuring system was determined by screwing the cannula into a blind hole, thus producing a closed system. The microsyringe was advanced (or withdrawn) in several steps, recording simultaneously the volume injected and the pressure obtained. The compliance (C) of the system was calculated from the ratio of the volume (V) increment divided by the pressure (P) change, or

\[ C = \frac{dV}{dP} \]  

The compliance was constant over the total range of pressures examined, and had a value of 1.5 x 10⁻⁸ µl/mm Hg. Leakage was checked by elevating the pressure in the closed system to between 90 and 100 mm Hg and allowing it to remain at this level for some time; the rate of pressure drop indicated the magnitude of the leak. By careful attention to all connections, it was possible to reduce leakage rate to 0.2 µl/hr or less. The cannula-tooth junction was tested for leak rate by screwing the cannula into the tooth at the beginning of an actual experiment but with the hole extended only partly through the dentine and not into the pulp; no leaks were found at this junction.

The response time of the measuring system was less than 0.2 second; the actual value was too rapid to be accurately registered by the Varian recorder. (The recorder response was too slow to indicate pulse waves. However, simultaneous observation on an oscilloscope showed a variable pulse pressure of several mm Hg.)

Upon completion of each experiment, the cannula was unscrewed and held at tooth level to obtain the zero base line for pressure measurements. Since the animal was in a supine position, the mouth was approximately at heart level. Hence the pressure measurements may be considered as referred to heart level as well as tooth level. The hole was then sealed with a temporary filling made from eugenol and zinc oxide. Upon recovery, the animal showed no particular discomfort or disability, either of a general nature or of mastication.

Results

After insertion of the threaded cannula into the tooth a few minutes were allowed to elapse. During this interval the pressure in
the system came to a steady value. If no fluid was injected or withdrawn with the microsyringe (or if the transients resulting from such injections or withdrawals were allowed to subside), this pressure level could be maintained with only minor variations (as noted by the random deviation) for extended periods of time. Figure 2 is a typical record of pressure under these conditions. Since there was no net movement of fluid in these circumstances, it was assumed that equilibration had taken place between the measuring system, the tooth pulp tissue, and the pulp vascular system; thus this reading was taken as a measure of the equilibrium pulp pressure ($P_{eq}$). However, this method is open to the criticism that the pressure recorded may not be characteristic of the pulp in the natural state, since the procedure of screwing in the cannula or of injecting fluid may have trapped and compressed liquid which could not escape. If such was the case, this measurement would be more an index of the elastic compression modulus of the pulp tissue than of the pulp tissue pressure.

In order to test this possibility (as well as to calculate the hydraulic permeability), fluid was either injected into or withdrawn from the system using the microsyringe. As shown by the typical record of figure 3, the pulp pressure ultimately returned to similar values following either injection or withdrawal. This was true whether a single injection was made or whether a series of successive injections preceded final equilibration. The final level was also independent of the size of the injection. The equilibration level was close to that originally observed before fluid exchange had taken place. This indicates that the initial results were not caused by "trapping" fluid.

There was some systematic difference in the steady level to which the pressure returned after injection of fluid, compared with withdrawal of fluid. In general, the steady state pressure following injection was higher than the pressure following withdrawal. The magnitude of this "hysteresis" varied with different teeth. In some, the phenomenon was hardly noticeable; in others, the difference in pressures was as high as 10 mm Hg.

The results of the equilibrium pressure measurements in ten teeth from three dogs are presented in table 1. The range of values indicates the highest and lowest steady state pressures recorded in the first 90 minutes after

\begin{table}
\centering
\begin{tabular}{|c|c|c|}
\hline
Teeth & Highest Pressure & Lowest Pressure \\
\hline
Dog 1 & 80 & 50 \\
Dog 2 & 70 & 40 \\
Dog 3 & 60 & 30 \\
\hline
\end{tabular}
\caption{Equilibrium pressure measurements.}
\end{table}
TABLE 1
Hydrostatic Pressure and Hydraulic Permeability of Tooth Pulp

<table>
<thead>
<tr>
<th>Tooth</th>
<th>Pulp pressure</th>
<th>Permeability *</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>mm Hg</td>
<td>μl/hr-mm Hg</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower right canine</td>
<td>58-70</td>
<td>0.59</td>
</tr>
<tr>
<td>Lower left canine</td>
<td>62-76</td>
<td>0.17</td>
</tr>
<tr>
<td>Upper right lateral</td>
<td>48-51</td>
<td>0.20</td>
</tr>
<tr>
<td>Upper left lateral</td>
<td>57-78</td>
<td>0.25</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower right canine</td>
<td>67-77</td>
<td>0.50</td>
</tr>
<tr>
<td>Upper right lateral</td>
<td>45-50</td>
<td>0.50</td>
</tr>
<tr>
<td>Upper left lateral</td>
<td>41-55</td>
<td>0.45</td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lower right canine</td>
<td>52-61</td>
<td>0.12</td>
</tr>
<tr>
<td>Upper left canine</td>
<td>38-47</td>
<td>0.12</td>
</tr>
<tr>
<td>Mean</td>
<td>57</td>
<td>0.33</td>
</tr>
</tbody>
</table>

* Values for which \( P > P_{eq} \) indicate flow into the tooth; for \( P < P_{eq} \), flow is out of the tooth. The permeability measurements are the average \( dQ/dP \) in the range from 0 to 20 mm Hg above or below \( P_{eq} \).

This range includes both random pressure variations, hysteresis effects, and tendency of the mean pressure to drift with time. The average value of pressure for all teeth was 57 mm Hg.

The pressure was not always constant in time, but often rose throughout the experiment. The rate of rise was usually small enough to make detection difficult in measurements made within a one-hour period. However, in a four- or five-hour experiment, the pressure increase could amount to as much as 40 mm Hg, although usually it was about 10 to 15 mm Hg.

Summarizing these results, each tooth exhibited a characteristic \( P_{eq} \) whose mean value was fairly constant over long periods of time (average, 57 mm Hg). Superimposed upon this mean value were random variations (approximately ±3 mm Hg), a systematic deviation if the steady state measurement had been preceded by injection or withdrawal of fluid (hysteresis, average ±3 mm Hg) and a continuous drift with time (average 3 mm Hg/hr).

HYDRAULIC PERMEABILITY

It can be seen from the typical record illustrated in figure 3 (bottom) that ejection of fluid from the microsyringe into the pulp caused an increase of pressure in the system. Following this maneuver, the pressure dropped, finally reaching a steady value. Since the measuring system behaved as an elastic container, and since the volume of fluid in the microsyringe did not change after the initial injection, the drop in pressure could have been due only to the loss of fluid from the measuring system. This fluid must have flowed into the tooth. Similarly, the pressure rose following an initial drop caused by withdrawal of fluid into the syringe (fig. 3, top); this rising pressure could have been due only to fluid passing from the pulp chamber into the measuring system. The rate at which the pressure returned to its steady level was an index of the rate of exchange of fluid with the dental pulp.

A quantitative relation between flow and pressure change can be derived from the following considerations. The flow rate \( (Q) \) is equal to the rate of change of volume \( (V) \) with time \( (t) \) in this system, or

\[
Q = \frac{dV}{dt}
\]  

However, when the volume of the microsyringe is not changing, alterations in volume in the measuring system are reflected in pressure changes, so

\[
Q = \left( \frac{dV}{dP} \right) \left( \frac{dP}{dt} \right)
\]

The first term on the right of equation 3 is simply the compliance of the system, which had been measured previously and found to be \( 1.5 \times 10^{-3} \) μl/mm Hg. The second term on the right, the rate of pressure change, was measured directly from the record by noting the time interval required for the pressure to change a given amount, usually 10 mm Hg. Thus, it was possible to calculate in any interval the average rate of fluid exchange between the system and the pulp tissue and the average pressure at which this exchange occurred.

The relation between pressure and flow is shown in figure 4 for a typical experiment. The system pressure is indicated on the horizontal axis, and the flow, calculated from equation 3, on the vertical axis. Each point represents a separate measurement derived
from a number of determinations within a 40-minute period. These points were fitted by the curve (drawn by eye) shown in figure 5, to indicate the average pressure-flow characteristics of the pulp.

The point at which the curve of figure 5 passes through the horizontal line representing zero flow is a measure of \( P_{eq} \), since at this pressure no exchange is taking place between the pulp and the system. Higher values of pressure are characterized by flow of fluid out of the measuring system and into the tooth; lower pressure values result in flow out of the tooth. The slope of the curve, \( (dQ/dP) \), will be called the dynamic hydraulic permeability of the pulp chamber. This permeability is a measure of the ease with which fluid enters or leaves the tooth pulp.

The slope of the curve is much steeper when the system pressure exceeds \( P_{eq} \) than when it is less; in other words, it is easier for fluid to enter the pulp than to leave it. Thus, the dynamic permeability depends strongly upon pressure (the curve is nonlinear) and, in general is greater when \( P > P_{eq} \) than when \( P < P_{eq} \). For this curve, average values for the slope in the range of pressures 0 to 20 mm Hg above \( P_{eq} \) is 0.25 \( \mu L/hr-mm Hg \); the average permeability in the range of 0 to 20 mm Hg below pulp \( P_{eq} \) is 0.06 \( \mu L/hr-mm Hg \). Values of the mean permeability in this range for this and other teeth tested are listed in table 1.

The flow-pressure curve for a given tooth was reproducible if the measurements were taken within a period of a few hours. However, if the permeability measurements were extended over a long time (4 to 6 hours), the final flows at a given pressure were often appreciably below those initially obtained. This was particularly true for the permeability values for fluid flow into the dental pulp.

Discussion

ACCURACY OF THE EXPERIMENTAL MEASUREMENTS

Besides the usual errors associated with pressure measurements, this experiment had two particular sources of error which could have led to large inaccuracies. The first concerns the great sensitivity of the system to small leaks. For example, it may be seen from figures 4 and 5 that a leak rate of 2 \( \mu L/hr \) (about one average-sized drop per day) would have led to an apparent equilibrium pressure some 40 mm Hg below the true value. This sensitivity is not due to any deficiency of experimental design, but rather is caused

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by the inability of the tooth to furnish even small amounts of fluid without a large pressure drop. The magnitude of the error caused by leaks may be estimated by multiplying the leak rate times the hydraulic permeability of the tooth at $P_{eq}$. By careful attention to all connections, it was possible to get the leak rate below 0.2 $\mu$l/hr, leading to a maximum error of $-4$ mm Hg. Since the pressures throughout the experiment are always positive (greater than atmospheric), the effect of this error is always to cause the apparent $P_{eq}$ to be lower than the true value.

Another possible source of inaccuracy depends upon the system compliance. As can be seen from equation 3, the greater the compliance, the slower the rate of change of pressure for a given flow rate. Thus, a high compliance will lead to a very slowly equilibrating system. The compliance of the system employed in this experiment was very small, usually allowing equilibration in a few minutes even with the small flow rates characteristic of the dental pulp and permitting measurement of flows to a resolution of 0.1 $\mu$l/hr.

RELATION OF $P_{eq}$ TO PULP HYDROSTATIC TISSUE PRESSURE

Drilling into the dentin-pulp border undoubtedly causes some degree of local pulp irritation or injury, perhaps severing capillaries and larger vessels. Thus, it may be argued that despite the precautions taken to minimize tissue damage, the pressures seen here are not due to tissue forces but represent the pressure in capillaries or other blood vessels. Or, at best $P_{eq}$ results from a balance between normal tissue pressure and the pressure of the blood exuding from the severed vessels. The high pressures found here, compared to those found in most other types of tissue, may also be added in favor of this argument. (Note that the low hydraulic permeability implies that even a small amount of blood oozing into the pulp tissue would cause $P_{eq}$ to be much higher than normal tissue pressure.)

Several observations make it difficult, however, to accept this hypothesis. (1) In some experiments, tissue damage was certain, since the fluid seen rising in the hole was seen to be tinged with blood; in other experiments clear fluid was seen rising in the hole, indicating that tissue damage was minimal or absent. Yet, the results in the former experiments were not significantly different from those in the latter experiments. (2) Since blood flowing in the tooth pulp capillaries presumably has not lost the ability to clot, this hypothesis would predict that the initial measurements should be high, later measurements declining toward true tissue pressure as the severed vessels closed. In fact, the opposite was seen, the major systematic trend with time being a steady rise in $P_{eq}$. (3) Blood clots were not usually formed in the needle or tubing even during those maneuvers in which tissue fluid was withdrawn from the pulp. (4) It is difficult to imagine a mechanism whereby a severed vessel can pour out less fluid when unobstructed than it can accept when the surrounding pressure is raised. Yet, the tooth pulp was able to accept fluid much more readily than it was able to exude fluid.

The most probable explanation of these results is that any damaged vessels were closed over rather quickly (in the first few minutes after the pulp had been penetrated), and that any fluid which they had originally discharged into the pulp (or continued to discharge at a much reduced rate) was accepted by the intact capillaries with no appreciable rise in tissue pressure.

Measurements of tissue pressure are subject to a second source of error. Recently Guyton has demonstrated that the customary method of measuring tissue pressure, i.e., the insertion of a needle into the tissue followed by the application of pressure just sufficient to cause fluid influx, usually leads to erroneously high results. This error is most probably due to local tissue distortion and damage caused by the insertion of the needle and the application of hydrostatic forces. However, in the present experiment the cannula was not inserted directly into the pulp; the only physical contact between the measuring system and the tissue was hydraulic. Also, upon initially screwing in the cannula, the pressure in the system rose spontaneously to a high equilibrium level be-
fore any fluid had been injected from the system into the tooth.

In summary, the most likely hypothesis is that the equilibrium pressure represents the normal hydrostatic pressure found in the tooth pulp canal.

DENTAL PULP TISSUE PRESSURE

The experimental measurement of $P_{eq}$ and its identification with pulp tissue pressure leads to the following description of dental pulp forces.

(a) Free interstitial fluid appears to exist within the dental pulp and, thus, the forces within the pulp can be described accurately in part as hydrostatic pressures. The only finding not consistent with this conclusion is the variable degree of "hysteresis." This may imply that hydrostatic forces are not rapidly transmitted to all parts of the pulp, allowing local tissue distortion to produce local pressure alterations. (b) This pressure is relatively stable and is much higher than that found in most other tissues.4 It is noteworthy that high interstitial pressures have also been recorded for renal tissue and that both the kidney and tooth pulp are encapsulated organs.5, 7

DENTAL PULP CAPILLARY PRESSURE

Analysis of the dental pulp fluid of the dog has given a value of 1.2 g/100 ml for the total protein concentration; the protein concentration of the dog blood plasma has been reported at the same time as 6.6 g/100 ml. This indicates that the dental pulpal capillaries are not freely permeable to plasma protein, and consequently, the concentration difference will lead to the development of an osmotic force. This force is equivalent to approximately 22 mm Hg of hydrostatic pressure (although the exact amount depends upon the molecular weight of the proteins involved). Thus, for a mean tissue pressure of 57 mm Hg, the mean capillary pressure must be 79 mm Hg when the tooth pulp is in hydraulic equilibrium. This calculated value of capillary pressure is less than arterial pressure (the systemic arterial pressure averaged 110 mm Hg in those animals in which it was measured) and thus is consistent with the hypothesis of passive exchange of water through the dental capillary wall.

A high capillary pressure implies, however, that hemodynamics of the dental pulp circulation must be considerably different from most other body tissues. In contrast to "typical" tissue in which the major drop of blood pressure occurs in the arterioles and precapillary sphincters, in the dental pulp circulation a major part of the pressure drop must occur in the venules and veins.

The anatomy of the pulp provides a basis for the development of high capillary pressures. The small size of the apical foramina through which the vessels must pass means that a relatively high hemodynamic resistance may be developed at this point. In addition, since the collecting vessels are contained in the same rigid chamber with the rest of the pulp, the high hydrostatic tissue pressure will be transmitted to the venules and veins, tending to make them collapse and raising their resistance to flow.

This view suggests that in dental pulp the circulation of blood may be in a rather precarious position. If for any reason the tissue pressure in the pulp should rise, the veins in the tooth will tend to collapse to a greater extent than will the less easily compressed arteries. This will lead to a further increase of tissue pressure and increased venous collapse, resulting eventually in cessation of flow. Opposing this will be the direct effect of increased capillary pressure which will tend to force open the collapsed vessels and maintain flow. Thus, the net flow through the tooth circulation is controlled by the balance of these two effects; the stability of the flow depends upon which dominates.

INTERPRETATION OF HYDRAULIC PERMEABILITY

For practical purposes, the tooth pulp canal is a chamber of constant volume whose contents are incompressible. When liquid is injected into this chamber, an equal volume of material must leave. Similarly, when tissue fluid is withdrawn, it must be replaced by an equal volume.

One possible mechanism for the displacement of fluid is the alteration of blood volume.
within the pulp vascular system. Thus, each injection from the measuring system into the pulp may compress the tooth vessels, squeezing blood from the pulp canal. However, as the volume which can leave the tooth in such a manner is limited, this explanation is highly improbable since \( P_{eq} \) does not increase significantly following a series of injections, regardless of the number and size of the injections.

The alternative and more probable explanation is that fluid which leaves the tooth upon injection is interstitial tissue fluid. Most of this fluid probably passes into the pulp capillaries and is thus removed from the tooth. However, some fluid may pass out through the apical foramina in the space external to the apical blood vessels.

Thus, the process assumed to generate the curves of figure 3 is as follows. The first effect of rapid ejection of fluid from the microsyringe is an increase in the volume of fluid in the remainder of the measuring system without a significant amount of fluid passing into the tooth. This leads to an increase in pressure in the measuring system and at least part of the pulp; the magnitude of this increase depends upon the compliance of the system. As the pressure in the measuring system is suddenly raised above \( P_{eq} \), sufficient force is generated within the pulp to cause interstitial fluid to flow across the capillary walls either locally at the site of the hole or throughout the tooth and into the general circulation, thereby allowing fluid to leave the measuring system at an equal rate. This results in a continuously decreasing system pressure, and decreasing flow rates, the pressure approaching \( P_{eq} \) asymptotically. Similarly, when the pressure in the measuring system is lowered by manipulation of the microsyringe, fluid passes from the capillaries into the interstitial space. Thus, according to this explanation, the hydraulic permeability is a measure of the ease with which fluid traverses the capillary walls.

The nonlinearity of the pressure-flow curve (figs. 4 and 5) may simply reflect the inherent properties of the capillaries; i.e., the influx of fluid from capillary lumen to interstitial space requires a greater pressure gradient than the efflux of fluid in the opposite direction. The tissue distortion that may result from injection or withdrawal forms another possible explanation for the shape of this curve. Perhaps the increased pressure at the site of injection causes tissue to be pushed away from the hole and even causes fissures to develop disrupting the gelatinous matrix of the pulp, thereby exposing a relatively large capillary surface area to fluid exchange. On the other hand, lowering the pressure at the hole tends to make the pulp collapse against it, thereby decreasing the available surface area. According to this explanation, the nonlinearity is a reflection of the differing surface areas available for the two processes. Implicit in this latter view is the assumption that pressure alterations are not immediately distributed equally throughout the pulp. Which of these explanations is correct cannot be answered from the data at hand but rather requires further investigation of the detailed pattern of fluid distribution.

Summary

The object of these experiments was to evaluate the hydrostatic pressure and hydraulic permeability of the tooth pulp in situ. A small hole was drilled through the enamel and dentin to the dentinal-pulpal junction in canines and third incisors of anesthetized dogs. A threaded cannula filled with mammalian Ringer's solution was screwed into the hole and connected to a microsyringe and a pressure transducer of very low compliance. Pressure was recorded when the cannula was first inserted into the hole; then small amounts of fluid were injected into the system or withdrawn from the system using the microsyringe. The equilibrium pressure \( (P_{eq}) \), measured after transients had disappeared, was fairly constant for a given tooth over long periods of time. Referred to tooth level (which was approximately heart level), \( P_{eq} \) averaged 57 mm Hg (range 38 to 78 mm Hg) in the ten teeth tested. Superimposed upon the steady value was a random deviation (±3 mm Hg), a hysteresis effect resulting in a higher pressure if the measurement had been
preceded by injection of fluid rather than withdrawal (±3 mm Hg), and a continuous drift with time (+3 mm Hg/hr).

The hydrostatic permeability was calculated from the rate of fluid flow when the pressure was above or below its steady state value. When the pressure was high (fluid being forced into the pulp) flow averaged about 0.33 μl/hr-mm Hg over the range $P_{eq}$ to $P_{eq} + 20$ mm Hg. When the pressure was low (fluid being withdrawn from the tooth), flow averaged about 0.14 μl/hr-mm Hg over the range $P_{eq}$ to $P_{eq} - 20$ mm Hg.

It is concluded that $P_{eq}$ probably represents the true hydrostatic tissue pressure normally existing within the tooth pulp. This implies a high capillary pressure and thus a relatively high resistance in the venous side of the pulp circulation. The interpretation of hydraulic permeability is not certain, but this quantity probably is related to the ease with which fluid passes into or out of the pulp capillaries.

Acknowledgment

The aid of George Brengelmann in the experimental design and interpretation of results contributed greatly to successful completion of this project. We acknowledge also the continued encouragement and support of Dr. John Ingle, at whose suggestion these experiments were initiated.

References

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