

TROUGH HEIGHT, PRESSURE AND FLATTENING IN TONOMETRY¹

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Abstract—Our automatic, gentle, electronic tonometer which is based on an exact theory yields a characteristic tonogram. We have shown in a previous paper that the initial crest occurs when the transducer surface is just covered by the flattened cornea and that the trough occurs when it is more than covered. Using rabbit eyes, the relationship was investigated between the degree of flattening and the intraocular pressure by electronic manometry and cannulation. Then the change in manometric pressure was found at the incidence of the initial trough of the Mackay–Marg tonogram. It is demonstrated that a $1\frac{1}{2}$ -mm diameter circular transducer surface area requires a 3-mm diameter flattening of the cornea for the generation of the initial trough. The artificial rise in pressure caused by this applanation is 0.4 mm Hg.

Résumé—Notre tonomètre automatique, léger et électronique, fondé sur une théorie exacte, fournit un tonogramme caractéristique. Nous avons montré précédemment que le ressaut initial se produit quand la surface du palpeur est juste couverte par la cornée aplatie et que le creux se produit quand elle est plus que couverte. On a étudié sur des yeux de lapin la relation entre le degré d'aplatissement et la pression intraoculaire avec une canule et un manomètre électronique. On a alors trouvé que le changement de pression manométrique coïncidait avec le creux initial du tonogramme de Mackay–Marg. On a démontré qu'un palpeur circulaire de 1,5 mm de diamètre nécessite un aplatissement de la cornée de 3 mm de diamètre pour engendrer le creux initial. Cet aplatissement produit une augmentation artificielle de pression de 0,4 mm de mercure.

Zusammenfassung—Unser automatisches elektronisches Tonometer, das auf exakter Theorie beruht, liefert ein charakteristisches Tonogramm. In einer früheren Arbeit haben wir gezeigt, dass das erste Maximum im Tonogramm auftritt wenn die abgeflachte Cornea eben den Stempel des mechanoelektrischen Wandlers bedeckt und dass die Kurve wieder abfällt, wenn die Cornea auch das Führungsrohr des Stempels berührt. An Kaninchenaugen wurde durch elektronische und direkte Druckmessung die Beziehung zwischen dem Grad der Abflachung und dem intraokulären Druck untersucht. Dabei ergab sich, dass die Änderung des Manometerdrucks dem ersten Minimum des Mackay–Marg-Tonogramms entspricht. Es wird gezeigt, dass für einen Wandlerstempel von 1,5 mm Durchmesser ein cornealer Abflachungsbereich von 3 mm Durchmesser erforderlich ist, um das erste Minimum zu erzeugen. Die durch diese Abflachung hervorgerufene artifizielle Drucksteigerung beträgt 0,4 mm Hg.

OUR NEW automatic, gentle, electronic tonometer yields in less than a second a characteristic tonogram (Fig. 1) from which the intraocular pressure may be read (MACKAY and MARG, 1959, 1960a and b; MACKAY, MARG and OECHSLI, 1960). The reading is free from sizeable errors inherent in other tonometers because of its unique design. It has been shown, in accordance with an exact theory, that the initial trough height above the base line gives the measure of the pressure within the eye (MACKAY and MARG, 1960b; MACKAY, MARG and OECHSLI, 1960; MARG, MACKAY and OECHSLI, 1961).

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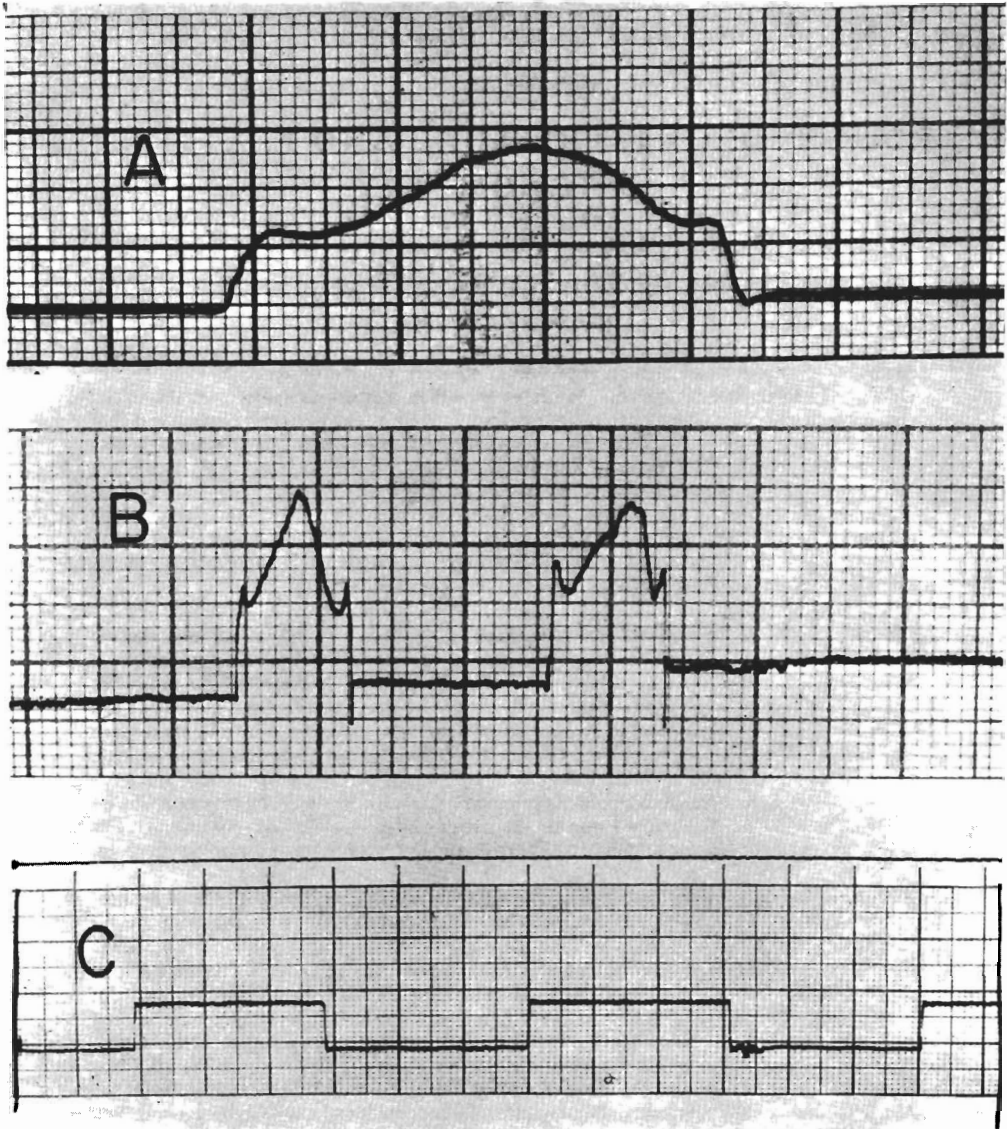


FIG. 1. Mackay-Marg tonograms from the human eye showing the initial crest, initial trough, central maximum and second trough and crest. The intraocular pressure is measured from the initial trough to the base line. The height of the crest above the trough is a measure of corneal stiffness. Chart speed, 2 large divisions or 10 mm/sec.

- A. Tonogram taken with slow movement of probe taking over 3 sec overall. Initial trough obtained in 0.6 sec.
- B. Two tonograms taken in rapid succession. Initial trough obtained in 0.1 sec so that the slight temperature drift indicated by rise of base line is not of significance.
- C. Square wave calibration obtained by shifting the tonometer probe from vertically pointed down to up and repeat (+ and - one gravity). The amplifier may be set for any desired sensitivity. In this instance 1 mm on the chart equals 3 mm Hg ($\pm g = 24$ mm Hg).

We have previously established that the crest occurs when the transducer surface is just fully covered (MACKAY and MARG, 1960b; MACKAY, MARG and OECHSLI, 1960; MARG, MACKAY and OECHSLI, 1961). We also have pointed out that the trough occurs when the transducer surface is more than covered by the cornea. How much more has been unknown up to this time. The purpose of this paper is to establish quantitatively the diameter of the flattened corneal surface at the occurrence of the first trough or plateau. In addition, we wish to determine quantitatively the artificial rise in pressure when various diameters of the cornea are flattened. The increase in pressure at the moment of the development of the initial trough is of special interest for tonometer calibration.

TONOMETER PRINCIPLE

It may be well to review, briefly, the principle and theory of our tonometer. If a low compliance transducer of, say 1½-mm diameter is set flush into a flat plate, one has a unique tonometer. Fig. 2 illustrates the sequence of events as the transducer surface is progressively covered, and more than covered, by the flattened cornea. The trough occurs when the bending forces of the cornea are no longer pushing on the transducer surface but on the surrounding, non-sensitive, coplanar area. In the same way the surface tension forces of tears are also avoided as an artifact in the reading. Corneal astigmatism is of no consequence since only the pressure from the central part of the flattened area is registered. Eye size, condition of the epithelium and ocular rigidity are of no significance nor is the orientation of the subject. Tissue tension forces are tangential in the flattened area so that first order theory dictates that the trough height gives only the intraocular pressure, less a correction for the rise in pressure caused by the volume change from appplanation at the moment the first trough appears. The data providing this small correction value will be examined presently. It should be mentioned that the tonometer probe tip is covered by a thin rubber film (receptacle-end condom) to prevent the transfer of infectious eye diseases from one patient to another. It also keeps the tonometer dry and clean and presents a uniform and smooth surface to the cornea. A thin layer of petroleum jelly over the rubber film keeps it from imbibing water and makes the use of the tonometer without anesthesia more comfortable. The probe may be applied in any orientation and the reading is equally valid as long as it is not shifted between the initial contact and the initial trough, a fraction of a second. The response of the probe to gravity constitutes a built-in calibration device which makes the tonometer calibration independent of amplifier gain and other variable factors.

EQUIPMENT AND PROCEDURE

Tonometer

This investigation was performed with a form of the tonometer without mechanical feedback as illustrated in Fig. 3.² A highly sensitive differential transformer was used. It had a sensitivity of 100 μV output for each volt-micron input. The core was extended to provide a 1½-mm diam. circular area flush with a surround which measured 5-mm diam. overall. Both the transducer core extension and the surround were made of quartz and invar—materials with very low temperature coefficients to minimize temperature transients. The core was potted in silicone rubber which acted both as a bearing and a stiff spring. The spring action was so stiff that the displacement of the transducer in response to pressure was 250 Å/mm Hg, similar to that in previous models of the tonometer with mechanical feedback. This permitted the elimination of a complex feedback mechanism, while maintaining the principle and function of the earlier model. In a phrase, essential co-

² This instrument is manufactured by Biotronics, Inc., 405 14th Street, Oakland 12, California. Patent pending; Regents, University of California.

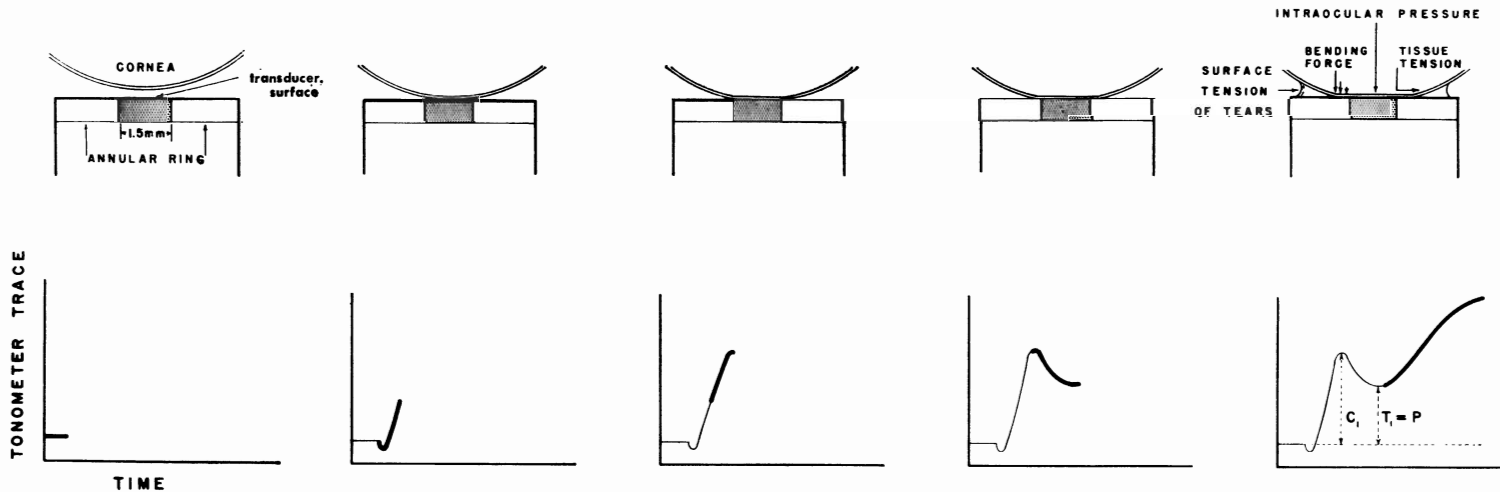
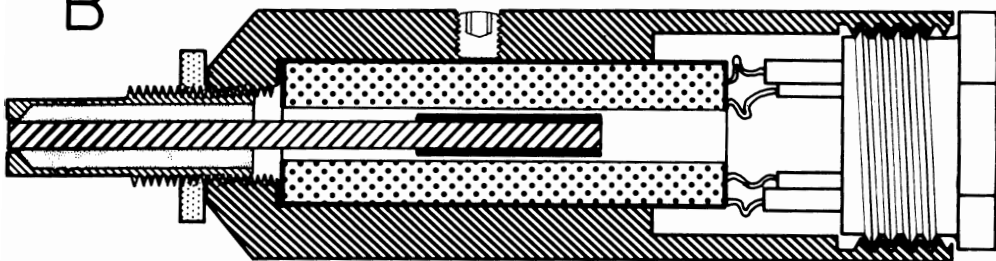


FIG. 2. The sequence of events as the tonometer probe is advanced towards and on the cornea. Note that as the flattening is increased the trough occurs when the bending forces of the cornea are transferred beyond the sensitive transducer surface to the coplanar surrounding insensitive area or annular ring. C_1 = initial crest; T_1 = initial trough which yields the intraocular pressure, P . Occasionally a tiny initial and final dip from the base line is noted, as shown, because of surface tension attracting the plunger before or after actual contact.

A



B



C



FIG. 3. A. Tonometer probe with $1\frac{1}{2}$ -mm diam. transducer surface in the center of the tip (for details, see text).

B. Cross-sectional drawing of tonometer probe construction (for explanation, see text).

C. Scheme of tonometer function. Penwriter must be reasonably fast for clinical application, with a frequency response extending to approximately 100 c/s.

planarity was maintained. The output of the tonometer probe was fed into a carrier-amplifier recorder of adequate sensitivity and frequency response from which the tonogram was obtained.

In more recent models, a "grain of wheat" lamp in the probe provides a beam of light issuing from the transducer surface which may aid in centering the instrument on the cornea.

Electronic Manometer

The pressure of the eye during tonometry was measured by a Lilly electronic manometer (Technitrol Engineering Co., Philadelphia) because its transducer has an insignificant displacement of 1×10^{-7} ml/mm Hg. The output signal of the radio frequency bridge manometer was fed to a standard pen-recorder. Calibration was accomplished by the usual measured water column.

Procedure

A 20-gauge hypodermic needle was inserted into the anterior chamber of a rabbit eye *in situ*. The needle was connected to the transducer of the electronic manometer by a fine, thick-wall polyethylene tube. After the puncture, the eye was restored to normal pressure by means of a water manometer reservoir, or, if the animal were alive, allowed to regain its normal pressure. A polished truncated cone of transparent plastic was advanced toward the eye by means of a micrometer screw until its small end flattened the cornea. By dropping India ink on the cornea, the degree of applanation was clearly seen with good contrast and was photographed for subsequent measurement with a 35-mm camera fitted with an electronic flash. During this time the electronic manometer was continuously recording the pressure.

Various degrees of flattening were produced. Exact values for each of the diameters of the flattened area and the rise in pressure elicited by this flattening were recorded simultaneously. Then the tonometer, registering on a second channel of the recorder, was applied to the eye and the increase of pressure registered by the electronic manometer was noted at the time the trough or crest appeared. These data allowed comparison of the degree of flattening at the time of the trough or plateau by relating it to the same rise in pressure for the previous measurements. An earlier fruitless attempt was made to measure the flattening and the tonometer value simultaneously. A specially designed "transparent" tonometer was constructed so that the flattening could be photographed, but it was not transparent enough to obtain accurate measurements of the diameter. The method finally used was perhaps less elegant but, what is more important, was successful.

RESULTS

The curve displaying diameter of corneal flattening versus rise in pressure is shown in Fig. 4. It is evident that the pressure starts to rise rapidly in the vicinity of a 3-mm diam. area. One may plot on the curve the rise in pressure at which the troughs or plateaus are found with the tonometer. The triangles in Fig. 3 show that it is about 0.4 mm Hg. This demonstrates that the tonometer with a $1\frac{1}{2}$ -mm diam. circular transducer surface area employs a total flattening of 3-mm diameter for the reading of the intraocular pressure.

DISCUSSION

At first glance it may appear that a 3-mm diam. flattening is quite a large extension beyond the sensitive area. A moment's consideration makes it clear that beyond the $1\frac{1}{2}$ -mm diam. transducer area there lies an annulus of flattened cornea only $\frac{3}{4}$ -mm wide. The bending forces of the cornea must be so distributed that they reach a minimum over the transducer

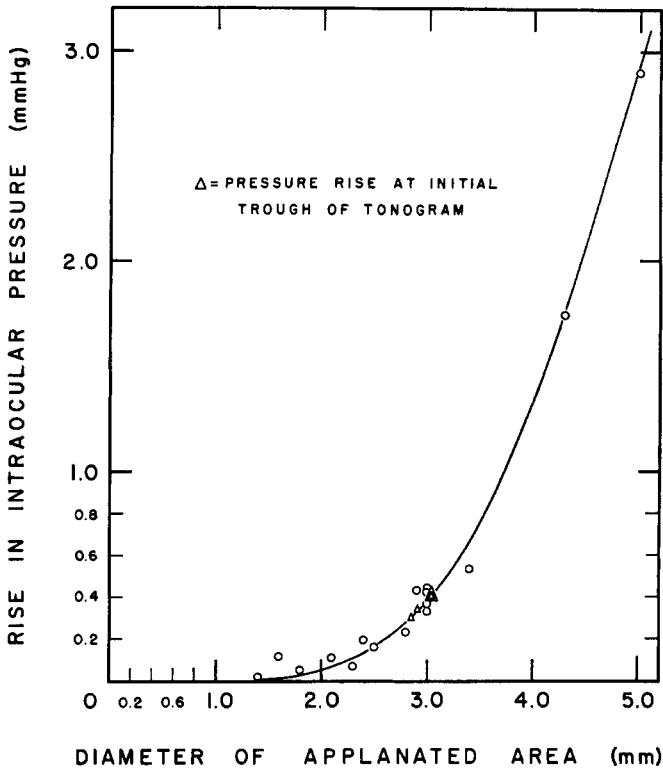


FIG. 4. The rise in intraocular pressure for various amounts of flattening of a rabbit eye. Several tonograms were taken and the rise in intraocular pressure at the moment of the trough is represented on the curve as triangles. Note that it requires 3-mm flattening to obtain the initial trough with a $1\frac{1}{2}$ -mm diam. circular transducer surface area.

in relation to the climbing intraocular pressure when they are maximally about $\frac{3}{4}$ mm away. This value appears reasonable for a corneal thickness of $\frac{1}{2}$ – $\frac{3}{4}$ mm.

A rise of 0.4 mm Hg of pressure at the trough indicates that this value should be subtracted in the calibration of the tonometer probe when made by open manometric tests, i.e. when the pressure within the eye or other hydraulic chamber is maintained regardless of volume changes. The small differences in calibration found among various mammalian species with our tonometer (MOSES, MARG and OECHSLI, 1962) would indicate that this finding is probably valid for other mammalian eyes as well as for those of rabbits.

It is likely that there will be a slightly different actual rise in pressure in eyes with different ocular rigidities and basic pressures. However, the 0.4 mm Hg correction is probably accurate enough for any absolute measurements of pressure for which tonometry can be used. Relative measurements in the same eye would be even less affected.

The curve showing the relationship between change of pressure and diameter of flattened area in Fig. 3 was obtained from a freshly dead rabbit eye *in situ*. Several other similar experiments gave the same results. When the data were obtained from a living rabbit eye, two differences were noted. First, there was much greater scatter of points, presumably largely caused by the moment-to-moment changes of pressure due to the pulse. Second, the

curve was not exactly the same shape, undoubtedly because of the effects of homeostatic or feedback regulation of pressure and perhaps some differences in ocular rigidity. However, the results from freshly dead animals were the same as from the live animals; the trough occurred at a 3-mm diam. flattening.

Some rabbit eyes exhibit little or no crest. This must mean that the corneal stiffness is less than in those rabbit or other eyes in which a sharp crest is observed. The stiffer and the thicker the cornea, the greater the flattening required to reach the trough. This small second or third order correction is of theoretical interest only and may be ignored in clinical measurements.

SUMMARY

The relation between the diameter of flattening and manometric change of intraocular pressure was found and graphed. The change in manometric pressure was determined at the point where the initial trough appears in a Mackay-Marg tonogram. Comparison of these data shows that with a $1\frac{1}{2}$ -mm diam. transducer surface diameter the cornea is flattened to an area of 3-mm. diameter when the first trough appears on the tonogram.

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