Constant-area applanation tonography

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A tonography device, based on the MacKay-Marg tonometer, has been constructed which will applanate the cornea to a preselected area of 5.0 to 6.0 mm diameter and maintain that applanation area. The pressure decrease with time should resemble the pressure decrease following bolus injection of fluid into the eye. In most cases the pressure decreased in a linear slope, abruptly terminating in a pressure plateau. In most cases, the pressure after 4 min of tonography was lower than preliminary Goldmann applanation pressure.

Key words: tonography, intraocular pressure

According to current theory, intraocular pressure is a steady state resulting from passage of aqueous through the eye, with some of the aqueous in transit encountering resistance to its outflow from the eye. Variations in blood pressure cause the intraocular pressure to fluctuate in synchrony with pulse and respiration. One means of investigating the steady state is to produce a perturbation of pressure and observe the eye's reaction to the perturbation. The perturbation frequently has been produced by application of a tonometer, such being called "tonography." Tonography using the Schiötz tonometer has been the commonest procedure but has been shown to be associated with many uncertainties. One serious objection to Schiötz tonography is that the large increase in intraocular pressure caused by application of the tonometer may change the outflow resistance very materially.1 Tonography employing an applanation tonometer would seem to be simpler and more easily quantitated. Moses,2, 3 Thorburn,4, 5 and Pollack et al.6 have reported investigations employing constant-pressure applanation tonography. In this method, intraocular pressure is continuously sensed and kept constant by a feedback system that increases the force (and area) with which the tonometer is applied to the eye, as necessary to keep intraocular pressure at a constant level.

A second type of applanation tonography, constant-area tonography, was reported by Goldmann7 and Goldmann and Schmidt.8, 9 In this application, the diameter of tonometer contact with the cornea is kept constant while the force necessary to maintain a constant contact area is varied. Thus a fixed volume of intraocular contents is displaced and this displacement is maintained. This procedure, in effect, resembles a bolus injection of fluid into the eye.

The primitive question posed in constant-area applanation tonography is: If the intraocular pressure is abruptly raised, what is the pattern of pressure change with time? The present article describes the equipment employed and early results.

Methods

A Brush pen motor was mounted on a slit-lamp carriage with the motor shaft horizontal and at right angles to the subject's line of vision (Fig. 1).
A counterbalanced lever was attached to the shaft of the motor. A Mackay-Marg (M-M) tonometer probe fixed to the lower arm of the lever was used as an intraocular pressure sensor. The foot plate of the probe was enlarged to 8 mm in diameter and much of the handle of the probe was removed. Fine flexible wire, looped over the pen motor, connected the probe to its associated electronic equipment. Current to the pen motor drove the tonometer toward the cornea with a force linearly proportional to the current. The pressure signal from the tonometer probe was fed into a digital computer, which supplied current to the pen motor in proportion to the tonometer signal in order to satisfy the basic relation

\[
\text{Pressure} = \frac{\text{force}}{\text{area}}
\]

where area is held constant. Both pressure signal and force were recorded on strip charts and also on a floppy disk for later computer analysis.

The tonometer probe was calibrated on enucleated human eyes (Fig. 2) giving the relation

\[
\text{M-M chart spaces} = \text{mm Hg} + 2.46
\]

The calibration was incorporated into a computer program that controlled the experiment. The program allowed selection of applanation diameters between 5 and 6 mm. Initiation of the program caused the tonometer to press against the cornea with linearly increasing force to a peak of 14.6 gm to provide a consistent starting point in the experiments. The force then decreased linearly until the force appropriate to the preselected area of applanation was reached.

The tonography device may also be instructed to operate in a constant-pressure mode or in a constant-force mode. Operation in these modes is not discussed in this article.

When in use, the tonometer probe is always covered with a thin rubber sheath (Tonocover).

**Subjects and procedure**

Subjects were unselected patients of the Glaucoma Center of Washington University Medical School, Department of Ophthalmology, and normal volunteers. All subjects gave informed con-
Fig. 3. Examples of tonograms. The upper trace is the force record (gm); the lower trace is the pressure record (mm Hg). The rate of chart travel is 0.5 mm sec⁻¹. The pressure scale is displaced upward 2.46 mm to reflect the intercept of the calibration (Fig. 1). In each case, the force is increased to 14.6 gm and then decreased until appropriate to the diameter of application selected (6 mm in these illustrations), producing the initial sawtooth force peak. In the pressure records, the Mackay-Marg trough or notch used in clinical intraocular pressure measurement with the tonometer is seen on the ascending pressure slope of examples B, C, and D. A, "Exponential pressure decay" type. B, Linear pressure decrease. C, Linear pressure decrease terminating in pressure plateau. D, Linear pressure decrease reversing to linear pressure increase.

Results

Sixty-six technically satisfactory tonograms were obtained in 80 attempts on 39 subjects (76 eyes). Nine of the satisfactory tonograms were performed with an application 5.6 mm in diameter and 57 with a 6.0 mm application diameter.

Four patterns of pressure loss with time were identified among the group of tonograms; (1) monotonically decreasing pressure, concave upward as in Fig. 3, A (two tonograms); (2) decreasing pressure of uniform slope throughout the 4 min (Fig. 3, B) (eight tonograms); (3) a slope of decreasing pressure that abruptly flattened to a pressure plateau (Fig. 3, C) (39 tonograms); (4) a slope of decreasing pressure that abruptly changed to a slope of increasing pressure (Fig. 3, D) (four tonograms). Of the 66 successful tonograms, 53 fell into one of the four aforementioned patterns and 13 received other classifications. The initial segment of several tonograms showed little pressure decrease; for up to 50 sec the tracing was virtually flat, giving the tonogram a somewhat sigmoid form as seen in Fig. 3.

Final intraocular pressure of the tonogram often was lower than the preliminary Goldmann reading.
Discussion

In the average eye with a corneal radius of curvature of 7.8 mm, applanations 5.6 and 6.0 mm in diameter displace calculated volumes of 6.5 and 8.6 mm$^3$, respectively. The increase in intraocular pressure brought about by these volume displacements depends on the pressure-volume (ocular rigidity) characteristics of the eye and the initial intraocular pressure. Ocular rigidity, calculated from the initial force-pressure peak and the beginning of the tonogram 6 mm in diameter, varied from 0.005 to 0.020 (mean 0.0111, S.D. 0.004, n = 75) so that adoption of a "standard" ocular rigidity for facility calculations is meaningless. Study of the accuracy of ocular rigidity measurement by this means is in progress.

The concave-upward, monotonically descending pressure traces tend to be reassuring in that this is the expected form of the pressure decay curve. However, these represent only two of the entire group of 66 tonograms. The eight tonograms with an apparently constant slope could also be part of an exponential decay curve near an asymptote so that the curve is grossly indistinguishable from a straight line. The 43 slope-plateau and V-pattern tonograms (groups 3 and 4) were unexpected and can hardly be attributed prima facie to an exponential decay process arising from a fluid leak from an elastic pressure chamber.

What, then, could cause the "hockey stick" pressure curves of 43 of the 66 tonograms? Several phenomena are known that could be superimposed on the anticipated leak process. One of these is the repeated tonometry effect in which an applanation tonometry repeated at intervals of 30 sec or 1 min is associated with pressure decay. Another is simultaneous contraction of the rectus muscles, a process which might suddenly cease, producing an abrupt change in the pressure slope. Perhaps these phenomena are in actuality the same. The fact that the tonogram of the second eye measured almost always begins at a lower pressure than that of the first eye measured—a fact that is well known in Schiotz tonography—also suggests that some such process is active. It is also possible that some pressure-regulating mechanism varies the aqueous production or outflow in response to ocular pressure. Such variation could account for pressure curves other than those of exponential decay. It is clear that the ocular pressure response to a small-step increase in intraocular pressure is more complex than anticipated.

REFERENCES