Reports


The Mackay-Marg, pneumatonograph, TonAir, and EMT-20 tonometers were evaluated in the normal dog eye. Tonometric scale readings were compared to the manometric recordings from the anterior chamber. The Mackay-Marg tonometer evaluated in open and closed systems was the most reliable (goodness of fit \( r^2 = 0.96 \)) with intraocular pressure up to 100 mm Hg. The pneumatonograph also exhibited high reliability \( r^2 = 0.92 \) but tended to underestimate intraocular pressures above 40 to 50 mm Hg. The TonAir and EMT-20 tonometers were the least satisfactory for the dog, with \( r^2 \) of 0.77 and 0.86 to 0.81, respectively. The Mackay-Marg is the most satisfactory tonometer for the dog.

Applanation tonometers, in contrast to the indentation types, estimate intraocular pressure (IOP) by measuring the force required to flatten or applanate a constant area of the corneal surface visually with split-field prisms and fluorescein, electronically with special linear transducers, by gas-suspended probes, and by air-pulse noncontact sensors. Applanation tonometers, particularly the Goldmann, are generally accepted as the most reliable in man. \(^1\) \(^4\) Recently, the Mackay-Marg tonometer has been demonstrated superior in estimating IOP after keratoplasty and in the presence of corneal edema and other corneal abnormalities. \(^1\) \(^4\)

The utilization of Schiötz tonometric conversion tables obtained from human eyes has not been accurate when used for the rabbit. \(^5\) \(^6\) The rabbit differs from man in ocular volumes and corneal radius and exhibits a variable ocular rigidity. \(^6\) Use of human-derived Schiötz tables results in gross underestimation of IOP.

Because of the occurrence of hereditary buphthalmia in the rabbit as well as the emphasis on this species for several types of ophthalmic research, study of tonometers has been limited mainly to this animal species. The Mackay-Marg tonometer was also evaluated and found reliable in the rabbit, cat, and monkey eyes. \(^1\) The recent establishment of a strain of beagles with spontaneous glaucoma necessitates tonometric studies in this species. \(^7\) Determination of the accuracy of the Schiötz tonometer was essential for the estimation of ocular rigidity as well as for tonography in the dog. As in the rabbit, use of human calibration tables for the dog results in underestimations of actual IOP. \(^8\)

The present study was undertaken to evaluate the accuracy of several applanation tonometers in the normal dog eye. The applanation tonometric recordings were compared to those obtained by simultaneous anterior chamber manometry.

Methods. The applanation tonometers evaluated were the Mackay-Marg (Model 12; Biotronics, Inc., Redding, Calif.), TonAir (Computer Instruments Corp., Hempstead, N. Y.), pneumatonograph (Alcon Laboratories, Ft. Worth, Texas), and the EMT-20 (Electro-Medical Technology, Redding, Calif.). The EMT-20 tonometer uses an electronic sensor probe similar to the Mackay-Marg instrument but has only a digital display and calibrates within the control module. The Mackay-Marg tonometer was evaluated in 18 eyes (nine dogs); the TonAir tonometer, 38 eyes (19 dogs); the pneumatonograph, 18 (nine dogs); and the EMT-20, 14 eyes (seven dogs).

The laboratory dogs weighed between 8 and 20 kg and ranged in age from 6 to 18 months. The eyes, examined by slit-lamp biomicroscopy and indirect ophthalmoscopy, were clinically normal, and the dogs in good health.

After subcutaneous atropinization (0.05 mg./kg.), general anesthesia was induced and maintained with intravenous pentobarbital sodium. After intubation, the dog was placed in dorsal recumbency. The eye was prepared with a lateral canthotomy, retraction of the eyelids by speculum, and placement of fixation 4-0 silk sutures in the dorsal episclera and conjunctiva and in the nictitating membrane. The cornea was intermittently moistened with 1 percent methylcellulose.

The anterior chamber was carefully cannulated 2 mm. posterior to the lateral limbus with a 21-gauge hypodermic needle connected by polyethylene tubing to a transducer (P-23B; Statham Laboratories, Hato Rey, Puerto Rico). The transducer was connected by polyethylene tubing and a stopcock to a microliter delivery system (Hamilton Company, Reno, Nev.), calibrated 0.1 ml. pipette, and a graduated-column reservoir. An adjustable stopcock could isolate the transducer, tubing, and globe from the calibrated pipette and saline column. Heparinized physiologic saline filled the system. The transducer recordings were transmitted into an amplifier (Model 8870A, Hewlett Packard Co., Waltham, Mass., or Model 7, Grass Instrument Co., Quincy, Mass.) and recorded.

The system was calibrated before and imme-
Fig. 1. Relationship of the scale readings (y) of the Mackay-Marg tonometer to the open-manometer (A) pressure or the closed-manometer (B) pressure (x).
Fig. 2. Relationship of the scale readings (y) of the pneumatonograph tonometer (A) and the TonAir tonometer (B) to the closed-manometer pressure (x).
Fig. 3. Relationship of the scale readings ($y$) of the EMT-20 tonometer (early model a, circle; later model b, +) to the closed-manometer pressure ($x$).

Immediately after examination of each eye to the column of saline, converted to millimeters of mercury. Each tonometer was also calibrated according to the manufacturer's instruction.

IOP was varied from 5 to 100 mm. Hg by 3 to 5 mm. Hg increments from 5 to 50 mm. Hg IOP and 5 to 10 mm. Hg increments from 50 to 100 mm. Hg by the microliter syringe or by varying the height of saline in the reservoir column.

Each application tonometer was placed gently on the center of the cornea, and three recordings taken and averaged. The EMT-20 recordings selected were the two lowest identical or repeatable readings. All tonometers were evaluated with the system closed to the column and micro-liter delivery system, except for the Mackay-Marg tonometer which was tested with both closed and open systems.

The averages for each tonometer recordings were compared to the manometric results with the use of the regression model by the method of least squares. Goodness of fit ($r^2$) was determined for each tonometer, i.e., the proportion of the variance of the tonometric recordings attributed to its linear regression with the manometric results.

**Results.** The scale readings of the Mackay-Marg tonometer in the open and closed manometric systems are shown in Fig. 1, A and B. The scale readings for the pneumatonograph, TonAir, and EMT-20 (models a and b) in the closed manometry systems are depicted in Figs. 2, A and B, and 3. The response of each tonometer to increases in manometric pressure was essentially linear, although at higher pressures the pneumatonograph, TonAir, and EMT-20 scale readings progressively indicated pressure less than actual manometric IOP. Fig. 4 summarizes the slope, intercept scale readings (mm.) and goodness of fit ($r^2$). Comparison of the scale readings of the Mackay-Marg tonometer in the open and closed system indicated no significant differences ($p = 0.94$).

The goodness of fit ($r^2$) for the Mackay-Marg tonometer was superior to all others with either the open or closed manometric results. The pneumatonograph was second highest in goodness of fit, but after about 40 mm. Hg, manometric pressure began to progressively underestimate IOP. The EMT-20 tonometer (models a and b) underestimated IOP above approximately 25 to 30 mm. Hg with progressive variance. The TonAir tonometer tended to underestimate IOP at all manometric levels of pressure.

**Discussion.** Calibration of application tonometers has not been reported for the normal dog.
eye. Only the portable applanation tonometers were evaluated in the dog because the Goldmann tonometer mounted on the biomicroscope cannot be used conveniently. Evaluation of several applanation tonometers for the dog is essential and timely for studies in aqueous humor dynamics, diurnal variations, and other anatomic, physiologic, and pharmacologic investigations in the glaucomatous beagle. Manometric methods for the calibration of tonometers have used recordings from either the anterior chamber or the vitreous body. The insertion of the recording needle through the clear cornea may produce distortion and alterations of its curvature. Leakage of aqueous humor may also occur with anterior chamber manometry. Recording from the vitreous body can avoid these difficulties but also records the ocular pulse. The oblique insertion of the needle 2 mm. caudal of the limbus through the sclera and sclerociliary cleft into the anterior chamber avoids leakage of aqueous about the needle and produces no detectable corneal distortion.

Of the tonometers evaluated, the Mackay-Marg and pneumatonograph are most satisfactory. Manometric studies in the rabbit, primate, and cat also demonstrate high accuracy of the Mackay-Marg tonometer in contrast to the Schiötz tonometer. Comparison of the Mackay-Marg tonometer with both open and closed stopcock manometry indicated no significant changes as expected for an applanation tonometer. Use of the Mackay-Marg tonometer in the conscious dog in the sitting or recumbent position requires only topical anesthesia. The pneumatonograph is also an accurate tonometer for the dog for IOP's up to 40 to 50 mm. Hg as demonstrated in the rabbit. However, use of the pneumatonograph in the conscious dog is more difficult than of the Mackay-Marg tonometer because of the several seconds of corneal contact required in a frequently moving eye; in addition, the probe sound may distract the animal. Movement of the eye beneath the pneumatonograph probe frequently causes corneal abrasions.

The TonAir and EMT-20 tonometers are less reliable for the dog. The more recent model EMT-20 tonometer (model b) was superior to the earlier instrument, especially within the normal physiologic range of IOP for the dog.

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Enhancing fluid secretion by the corneal epithelium. **STEPHEN D. KLYCE.**

Swollen rabbit corneas incubated in vitro with their posterior surfaces blocked with silicone oil maintained fairly constant thickness over an 11 hr. period. Increasing the simulated intracorocular pressure from 10 to 30 mm. Hg did not produce stromal thinning. When theophylline was added to stimulate epithelial Cl secretion by increasing the Cl permeability of the tear-facing epithelial membrane, corneas thinned at the average rate of 1.3 μm/hr. over a 6½ hr. period. When the epithelial perfusion solution was made Cl-free by SO₄ substitution to favor the passive flow of Cl from the cells to the tear solution, thinning of 3.91 μm/hr. over a 7 hr. period was observed. When corneas were perfused with Cl-free medium plus theophylline, thinning at the average rate of 6.20 μm/hr. over an 8 hr. period was achieved. Therefore, the corneal epithelium is capable of thinning a swollen stroma by transport of fluid coupled to its Cl secretion, which can be enhanced by simple substitutions in the tear-side bathing solution.

The rabbit corneal epithelium is the site of an active Cl secretory process which, when stimulated, can thin a swollen cornea in vitro.¹ Since the transepithelial Cl secretion is stimulated by catecholamines and phosphodiesterase inhibitors, it appears to be mediated by cyclic AMP.² With the use of epinephrine stimulation to analyze the mechanism of Cl transport at the cellular level, it was found that the Cl permeability of the tear-facing membrane and the Cl electrochemical potential gradient across that barrier determined the rate and direction of transepithelial Cl transport.³ These findings suggest a simple means to enhance the fluid secretion associated with the epithelial Cl pump by making substitutions solely in the tear-side solution, using the isolated rabbit cornea to model this process.

**Methods.** Corneas were obtained from New Zealand white rabbits following intravenous administration of a lethal dose of Na pentobarbital. They were mounted in a Lucite chamber⁴ exposing 1 cm² of tissue, permitting microscopic observation and eliminating evaporation.³ The endothelium was removed, and the stroma was swollen from the aqueous humor side for 8 to 10 min. prior to final chamber assembly. During the swelling, the epithelium was frequently rinsed with Ringer solution to prevent evaporative damage. Finally, the endothelial surface was covered with silicone oil to prevent further fluid movements across that surface. Normally a simulated intraocular pressure of 10 mm. Hg was used as a precaution against its ever exceeding the stromal swelling pressure, since otherwise the barrier properties of the epithelium would be compromised.⁵

The thicknesses of the stroma and epithelium were determined with a specular microscope⁶ fitted with an automatic attachment⁷ allowing the continuous measurement of thicknesses without subjective error. In analyses reported here, data were read to the nearest 1 μm. Statistical comparisons were made of average rates of stromal and epithelial thickness changes in sequential 20 min. intervals. Rates of change were directly related to the influence of epithelial ion transport on hydration.

Ringer solutions used consisted of a balanced salt solution (Cl-Ringer) and a SO₄-substituted, Cl-free solution with or without the addition of 1 mM theophylline.¹ They had a pH of 7.4, an osmolality of 305 mOsm. and a temperature of 35° C. In every experiment the osmolarity of the solution used to swell the stroma was identical with that subsequently used to perfuse the epithelium, and the swelling solution was composed of the normal Ringer solution with or without theophylline.

**Results.** After the corneas had been mounted, they swelled (especially those treated with theophylline) for up to 90 min. (Fig. 1), which may be a recovery period. Following this, the epithelium was able to prevent any further considerable stromal swelling for an additional 8 to 10 hr. of incubation. Differences in initial thicknesses among the experiments shown in Fig. 1 were caused primarily by variations in the ages of the donor rabbits.

When the epithelial surface was perfused with normal Ringer solution, stromal thickness was constant for 5 hr. following initial swelling (Fig. 2, A). In the subsequent 6 hr. stromas swelled