

Evaluation of the basic validity and clinical usefulness of the Mackay-Marg tonometer

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The present form of the Mackay-Marg tonometer consists of a 1.5 mm. diameter flat-based plunger mounted essentially flush with a flat footplate. The rubber mounting of the plunger acts as a stiff spring. Pressure measurements are derived from intraocular pressure acting through the flattened cornea against the plunger and causing microplunger movements. It has been shown that the response of this instrument is directly related in a linear fashion to hydrostatic pressure on the rubber membrane covering the plunger and to open-manometer pressure in enucleated eyes of various species. The slope of the linear relationship appears to vary slightly with the species. Clinical comparison was made between estimates of intraocular pressure obtained with the Mackay-Marg tonometer and the Goldmann applanation tonometer. Anesthesia was used for all examinations. There was a highly significant correlation between the results with the two instruments, the Mackay-Marg results being systematically greater and the Goldmann results systematically lower than their mean results. Comparison was also made between Mackay-Marg tonometer readings on the same eyes without and with corneal anesthesia. When anesthesia was not used the mean pressure was about 2 mm. Hg higher than when anesthesia was used. Potential errors and advantages were discussed.

A number of reports on the Mackay-Marg tonometer have been published.¹⁻⁵ These have been concerned with the theory on which it is based, the mechanical and electronic methods of satisfying the theory, and interpretation of the resulting curves. Several potential advantages over previous forms of tonometers were discussed.

The purpose of this investigation was evaluation of the basic validity and clinical usefulness of the new tonometer.

The Mackay-Marg tonometer

A form of the Mackay-Marg tonometer which is described in detail elsewhere was used.⁶ It is based on the same theory and is functionally the same as the previous mechanical feedback form. However, it avoids the use of feedback which allows the probe to be smaller, sturdier, and free from difficult mechanical adjustments.

The present tonometer consists of a 1.5 mm. diameter flat plunger mounted in silicone rubber so that it protrudes 5μ beyond the flat footplate. Movements of the plunger of less than a micron are sensed by a linear transducer and recorded electronically (Fig. 1). In use, the tonometer tip is covered by a thin disposable rubber membrane.

The silicone rubber in which the plunger is mounted acts as a stiff spring. When the tonometer is pointed vertically upward or downward the plunger displacement is that caused by its own weight. The electronic amplification of the plunger movement may be adjusted to a suitable magnitude, at which setting the scale deflection of the recording instrument between the two opposite vertical tonometer positions represents the force of twice the weight of the plunger.

As the cornea is flattened against the 1.5 mm. transducer surface, the curve recording plunger displacement rises to a crest which represents

This study was made at the request of the Committee on Standardization of Tonometers of the American Academy of Ophthalmology and Otolaryngology.

Supported in part by the Aerospace Medical Laboratory, Air Research and Development Command, United States Air Force Contract AF 33(616)-7664.

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intraocular pressure plus bending force of the cornea. At the passing of the corneal bend beyond the transducer surface onto the surrounding coplanar area, the curve descends to form a trough (Fig. 2). It is the height of the initial trough above the base line which is the measure of the intraocular pressure. As the probe is advanced the curve rises again to a central maximum at which point the probe is removed from the eye and the curve is retraced as an approximate mirror image of the first part.

Evaluation of basic validity

Response to a directly applied water column.

The tonometer, covered by its rubber membrane, was fixed pointing upward and a plastic tube was forced onto the circumference of the footplate. Water placed in the tube exerted a force on the plunger equal to the weight of a cylinder of water the diameter of the plunger and the height of the water column.

In the tonometer tested, the weight of the plunger was approximately 0.35 Gm. and its diameter 1.5 mm. The recording system was adjusted to produce 20 mm. scale deflection for twice the effect of gravity on the plunger (tonometer pointing up and pointing down). If the silicone rubber acted as a perfect spring, 1 mm. scale deflection was produced by 0.035 Gm. force. Water on the plunger, when expressed in millimeters of mercury, would be equivalent to mm. Hg/0.024 Gm. Therefore, the ratio of scale deflection to the fluid on the plunger is

$$\frac{\text{mm. scale deflection}/0.035 \text{ Gm.}}{\text{mm. Hg}/0.024 \text{ Gm.}}$$

or 0.68 $\frac{\text{mm. scale deflection}}{\text{mm. Hg}}$

If millimeters of mercury are plotted on the abscissa and millimeters of scale deflection on the ordinate, the slope of the line relating these values should be 0.68. This, of course, ignores pressure on the rubber in the space between plunger and footplate.

Open manometer measurements on enucleated eyes. Intraocular pressure was established by communication through a 16 gauge cannula in the vitreous to a column of water. Cannulation of the anterior chamber was avoided because a large lumen was required to maintain the intraocular pressure constant without much time lag, despite changes of volume during the flattening, and the large needle might distort the cornea. Pressure was raised from 5 to 60 mm. Hg in 5 or 10 mm. Hg steps. Calibration was usually completed by returning to 5 mm. Hg for a confirmation of that point. Freshly excised eyes of rabbits, cats, cynomolgus monkeys, and man were used. The



Fig. 1A. Mackay-Marg tonometer.

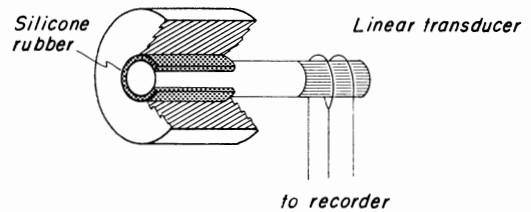


Fig. 1B. Schematic diagram of the probe of the Mackay-Marg tonometer used in this study. The thin rubber covering for the probe is not shown.

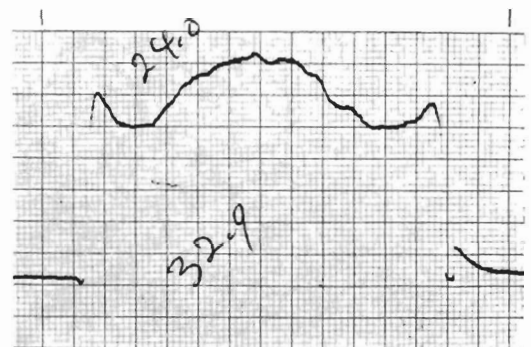


Fig. 2. Typical recording made with Mackay-Marg tonometer.

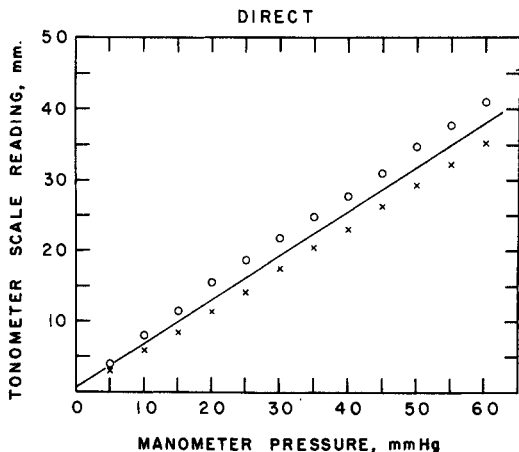


Fig. 3. Relationship between scale reading and hydrostatic pressure applied directly to the probe of the Mackay-Marg tonometer.

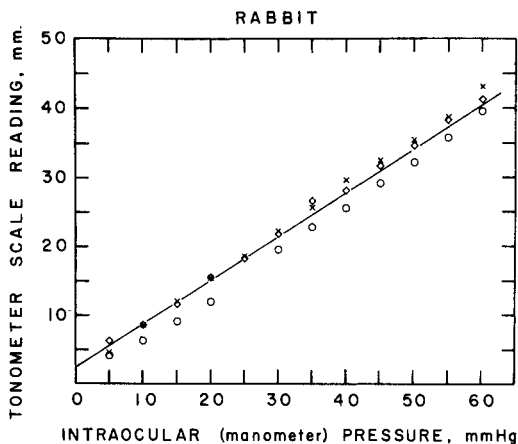


Fig. 4. Relationship between scale reading of the Mackay-Marg tonometer and open-manometer pressure, rabbit eyes.

eyes were partly embedded in a silicone rubber matrix. The cannula could be plunged through the rubber and into the globe without plugging the lumen.

Results of manometric studies. In each case the response of the tonometer to manometric pressure was essentially linear. Fig. 3 shows the response from direct hydrostatic pressure. Figs. 4, 5, 6, and 7 show the graphs for the eyes of the rabbit, cat, monkey, and man, respectively. Each symbol represents the mean of three values from a given eye. Curves were fitted by the method of least squares.

The slopes and intercepts are presented in Table I. If the curve is forced through the origin, the slope is slightly shifted as shown in the last column.

Discussion of manometric studies. It is clear from Table I that the slopes of the calibration lines are all similar. The intercept of the rabbit eye line is obviously much higher than that of the other curves because in these early studies we had not recognized the importance of air

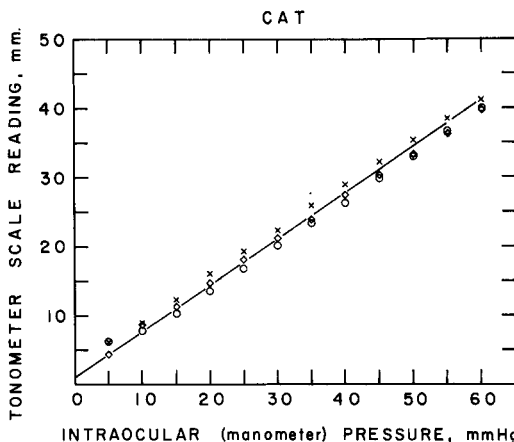


Fig. 5. Mackay-Marg tonometer scale reading versus open-manometer pressure, cat eyes.

Table I

	Slope	Intercept scale reading (mm.)	Slope forced through origin
Direct	0.62	0.7	0.65
Rabbit	0.64	2.5	0.72
Cat	0.67	1.0	0.71
Monkey	0.67	0.9	0.70
Man	0.72	0.9	0.75

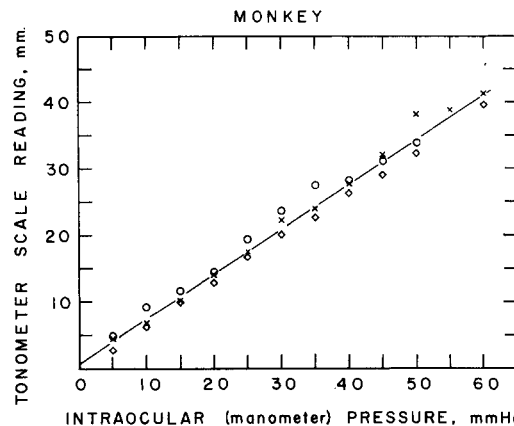


Fig. 6. Calibration of Mackay-Marg tonometer with open-manometer pressure in monkey eyes.

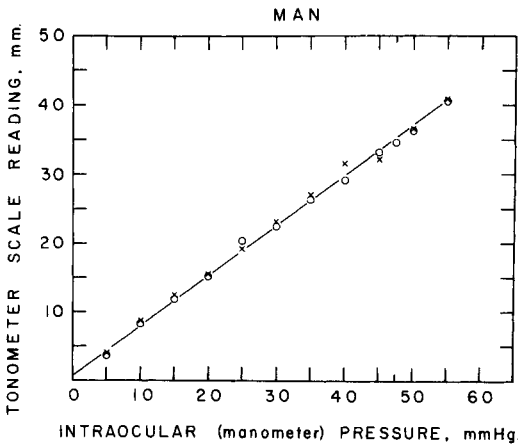


Fig. 7. Scale reading of Mackay-Marg tonometer as related to open-manometer pressure in fresh human eyes.

trapped between condom and probe. Despite wrinkles in the side of the rubber film covering the tip of the probe, enough air could be trapped to raise the intercept as much as 5 mm. Hg. Subsequently, a small puncture was made in the front of the receptacle-end condom with which the end of the probe was covered. Stability of the intercept after puncture indicated the validity of the technique to avoid a small but constant error for a given covering by a rubber film.

The range in slopes from 0.62 for hydrostatic pressure directly on the rubber film cover to 0.72 for the human eye shows a change of 15 per cent which in itself appears significant. Furthermore, even when the line is forced through the origin, the slopes still appear to show the same range and kind of differences. We tentatively conclude that second-order corrections must be made to the first-order theory, and that these corrections vary with the species. Calibration may be undertaken with a simple water column on the tonometer but for application to the clinic, direct values should be increased by 15 per cent.

In earlier publications it was stated that the response of the tonometer was linear above 10 mm. Hg.^{1, 5} In our present series of measurements we often found that values recorded at a manometer pressure of 5 mm. Hg were higher than predicted as shown in the earlier papers. However, if the eye was deflated and allowed to rise to 5 mm. Hg, the departure from strict linearity was no longer observed. It was clear that the low pressure of 5 mm. Hg was not adequate to overcome blocking of the needle when descending to that pressure. Whenever extraneous factors—such as needle blockage—are eliminated, the tonometer response is linear up to 60 mm. Hg, at least.

Clinical evaluation

The clinical value of a tonometer rests on the accuracy and stability of its estimate of intraocular pressure and on the convenience and speed of its application. Since the Goldmann is recognized as a tonometer of relatively high clinical accuracy, it was chosen for comparison with the Mackay-Marg instrument. No clinical instrument measures intraocular pressure, but merely permits estimation from some physical factor believed to be closely associated with pressure. A clinical comparison must rest on a statistical analysis of the scale readings of the instruments compared. A high correlation is taken to indicate that the two instruments measure the same thing; a small variability, that the results are stable; and a difference between the means, that the scale of one is displaced with respect to the other. Two sets of comparisons were made: (1) Mackay-Marg tonometer compared with Goldmann tonometer, all eyes anesthetized, the order of instrument used first and the order of eye tested first randomized according to a prearranged plan; (2) Mackay-Marg tonometer on unanesthetized eyes followed by corneal anesthesia and repeat Mackay-Marg tonometry. The order of eyes tested was randomized.

In comparison (1), the Mackay-Marg tonometer was mounted in a horizontal position on a slit-lamp mount and was brought against the cornea by manipulation of the control stick. A helper watched the paper tape as it emerged from the recorder and indicated when several records of satisfactory shape had been obtained. An unlimited number of measurements were made, and when the record was read later, all tracings of typical form were analyzed and incorporated in the results. An average of 9.4 readings were made on each eye.

Three measurements utilizing the Goldmann tonometer were made on each eye. The operator did not read the scale but withdrew the tonometer from the eye when the tonometer was in adjustment. The scale reading was then recorded by an observer and the adjustment knob was turned to an arbitrary position. All three readings are included in the results in each case.

For comparison (2), the tonometer was held by hand. No assistant was employed. An average of 4.0 readings were made per determination.

All Mackay-Marg determinations were made by R. O., all Goldmann by R. A. M.

Results of clinical evaluation

Scale reading of the Mackay-Marg tonometer was converted to millimeters of mercury by assuming that when twice gravity displacement of the plunger = 20

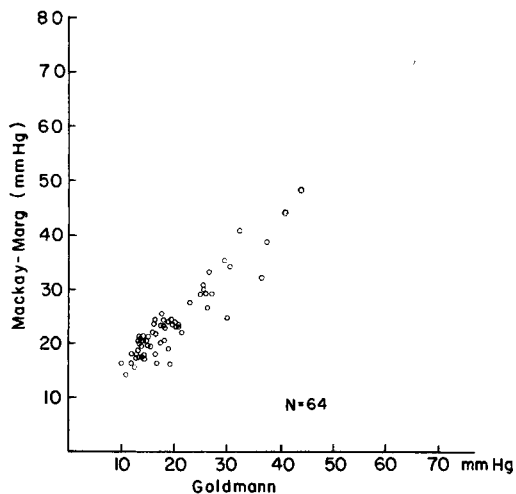


Fig. 8. Scattergram of values for intraocular pressure obtained with Mackay-Marg and Goldmann tonometers. Corneal anesthesia was used in all cases.

mm. scale displacement, the slope of mm. displacement/mm. Hg = 0.73.*

1. When an anesthetic was used for all measurements (64 eyes), the results of the two tonometers were highly correlated. A scattergram (Fig. 8), with the mean of the Mackay-Marg readings for each eye on the ordinate and the mean of the corresponding Goldmann readings on the same eye on the abscissa, shows a straight-line relationship with very little scatter around the slope.

Comparisons of the variability of measurements made by the two instruments on the same eye were made in 32 cases. In 3 cases, the variability was significantly greater for the Mackay-Marg instrument (1 at the 0.01 and 2 at the 0.05 level). The difference in the remaining 29 cases was not significant; in the majority of cases the Mackay-Marg was the more variable.

In every comparison of the two methods, there is a constant difference. The Mackay-Marg mean reading is significantly higher or the Goldmann mean reading is signif-

icantly lower. This difference can easily be taken care of in the calibration of the instruments when the correlation is high.

2. Fig. 9 is a scattergram of the results of pressure estimates made with the Mackay-Marg tonometer without and with anesthesia on 64 eyes. (Satisfactory tracings could not be obtained on one eye.) The means of the readings with anesthesia are significantly higher than those without anesthesia ($P < 0.05$) but there is no way of knowing whether this difference is due to the order of testing or to the anesthesia. The correlation is significant ($P < 0.001$) but not as high as in Series 1.

Comparison of variability of measurement made by the Mackay-Marg instrument without and with anesthesia was made in 32 cases. In 2, the variability was significantly greater with anesthesia (1 at the 0.01 level and 1 at the 0.05 level). In 6 the variability was significantly greater without anesthesia (4 at the 0.01 level and 2 at the 0.05 level). In the remaining 26 cases the difference was not significant; in the majority of cases the results without anesthesia were more variable. Statistical analysis of the results is given in Table II.

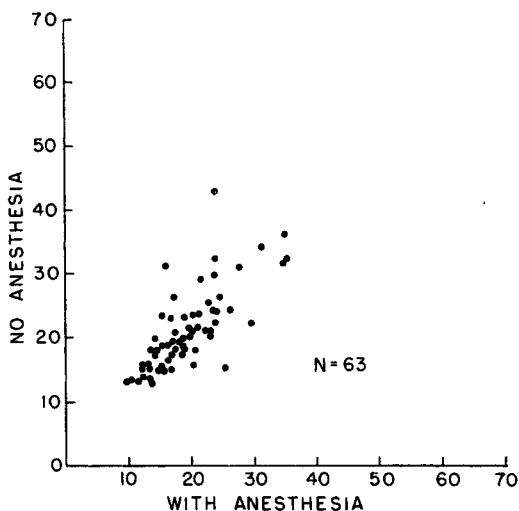


Fig. 9. Scattergram of values for intraocular pressure obtained with Mackay-Marg tonometer without corneal anesthesia versus Mackay-Marg tonometer with corneal anesthesia.

*The slope 0.73 scale units per millimeter of mercury for the human eye was an early estimate made before more accurate curve fitting was done. This in no way affects the correlation studies but only the equations for the regression lines.

Table II

No. of eyes	Mean of Goldmann	Mean of Mackay-Marg	Difference in means (P)	Correlation coefficient (r)	Probability (P)	Slope (b)	Equation*
<i>Series 1†</i>							
a) Goldmann first, Mackay-Marg second, both with anesthetic							
40	20.61	24.36	0.001	0.934	0.001	0.8954	$M = 0.8954 G + 5.91 \pm 2.79$ $G = 0.9751 M - 3.14 \pm 2.92$
b) Mackay-Marg first, Goldmann second, both with anesthetic							
24	19.36	24.80	0.001	0.965	0.001	0.9966	$M = 0.9966 G + 5.51 \pm 3.10$ $G = 0.9338 M - 3.80 \pm 3.00$
<i>Series 2</i>							
Mackay-Marg without anesthetic (Y), then with anesthetic (X)							
	Mean, without anesthetic	Mean with anesthetic					
63	21.14	19.40	0.05	0.742	0.001	0.8128	$Y = 0.8128 X + 5.37 \pm 4.34$

*Mackay-Marg reading is estimated as 0.8954 times the Goldmann reading plus the constant 5.91 with a standard error of estimate of 2.79. This means that approximately two thirds of the estimates will be within 2.79 units of the true reading.

†Although the results with Goldmann first and those with Mackay-Marg first appear to be very much the same and the slopes are highly significant in each, the slopes differ from each other significantly at $P = 0.05$, so that the equation used for predicting a Mackay-Marg reading from a Goldmann reading should be selected according to the method used first.

Discussion

There are no known errors of application of the Mackay-Marg tonometer which would yield an underestimate of intraocular pressure. Decentration of the Mackay-Marg probe parallel to a normal to the cornea should lead to slightly higher estimates of intraocular pressure since more aqueous would be displaced before the corneal bend reached the edge of the plunger than if the probe were centrally placed and parallel to the axis of the eye. The possible magnitude of this potential error has not yet been experimentally determined. However, decentration of the probe also leads to a degradation of the crest. It should be possible to study the relationship of crest height, decentration, and increase in tension so that the importance of this potential error can be assessed and, if necessary, avoided. Air trapped under the intact condom produces an overestimate of pressure. This may be avoided by a pinhole in the front of the rubber film.

A low Mackay-Marg reading, compared to a Goldmann, could occur if the cornea were stiffer than the amount arbitrarily compensated for in the applanation instru-

ment, or the reverse could occur with a less stiff cornea.

It should be noted that clinical practice and experience with the Mackay-Marg tonometer have been extremely limited relative to the Goldmann tonometer.

The time required for application of the Mackay-Marg tonometer is very short in most cases. Several records can be made in rapid succession. However, these records must be evaluated later, which brings the total time required by a single operator for tonometry up to the same range required for other types of tonometry.

Abrasion was not caused in any case in this series. In instances where the Mackay-Marg tonometer was applied first, fluorescein staining of the cornea was not more apparent as a result of tonometry than after application of a Goldmann tonometer.

Since the Mackay-Marg tonometer registers rapidly, it records the greater variability of intraocular pressure during tonometry without anesthesia than with it. Despite this variability, the indications of this instrument are thought to be clinically useful. As with any tonometer, care must be exercised to have the patient as relaxed as possible. It is noteworthy that

the average values without anesthesia are about 2 mm. Hg higher than those with the drug.

Several distinct advantages of the Mackay-Marg tonometer appear:

1. There is no danger of transfer of infection from patient to patient. The tip of the tonometer is covered with a disposable rubber membrane.

2. The Mackay-Marg tonometer estimate of pressure is virtually independent of ocular rigidity and corneal stiffness.

3. The ease of application in any position and rapidity of use should make this tonometer very useful for pressure measurements of the eyes of laboratory animals, and, perhaps, of children.

4. Recording is automatic and permanent.

No explanation of the average difference of intraocular pressure obtained with the Goldmann and the Mackay-Marg tonometers when anesthesia is used for both is offered at this time. However, intraocular pressure when measured with the Mackay-Marg tonometer appears to be higher when no anesthesia is used than when the cornea is anesthetized.

Discussion

Dr. Elmer J. Ballintine, Cleveland, Ohio. When the discussion of tonometry by Drs. Mackay and Marg appeared in *Acta ophthalmologica* in 1959, the Committee on Standardization of Tonometers was impressed with the rigor and completeness of the theoretical discussion and were eager to examine a tonometer based on the principles presented. The committee welcomed, therefore, the invitation of Dr. Marg to conduct a cooperative evaluation of the new instrument under clinical conditions. The present report is the result of this effort. It shows that the Mackay-Marg tonometer is a precise and reasonably convenient instrument for indicating the intraocular pressure both in man and in experimental animals.

I wish to emphasize that devising more precise and elaborate tonometers is not likely to increase significantly either our knowledge of glaucoma or to improve our treatment of it. Intraocular pressure is a biologic variable and the instruments already available are more than adequate to indicate the normal biologic variation as well as the

We wish to thank Dr. Robert Shaffer and Dr. Michael Hogan and their staffs, as well as Dr. Arthur Jampolsky, for their aid in obtaining clinical material and freshly enucleated human eyes, Mrs. Barbara Hixon for her aid in planning the clinical trials and evaluating the results statistically, and Professor Frank W. Weymouth for his valuable suggestions.

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departures from normality. Progress toward solutions of the problems of glaucoma does not depend on constructing more precise tonometers but on instruments, experiments, and observations which will increase our knowledge of the fundamental disease process, of which elevations of intraocular pressure are only one indirect manifestation.

There are several small points that I hope Dr. Marg will clarify for me. First, the slopes of the lines on the plots that relate tonometer reading to intraocular pressure measured manometrically vary among the species and depart from the expected slope obtained by direct calibration with a water column. If I were to buy a Mackay-Marg tonometer to be used in experimental work on rabbits, for instance, what calibration curve should be used?

The authors state that the indicated intraocular pressures on intact human eyes were more consistent when the Mackay-Marg tonometer was held in the hand than when the tonometer was

held mechanically on a slit-lamp attachment, yet much of the data was obtained with a mechanically held tonometer. Why was the apparently more reliable method of manual holding used?

It is not clear to me why the possibility of transfer of infection is reduced by the Mackay-Marg instrument when it was necessary to perforate the rubber guard membrane to obtain maximum reproducibility.

Dr. Marg (closing). Dr. Ballantine asks why we held our tonometer mechanically rather than manually. Our tonometer is rather new and we have been experimenting with various methods of application. At that stage of our work we thought that the mechanical presentation might be better,

but, as the results became available, we soon changed our minds and returned to the manual method.

We are not certain that the small differences in the slopes from the various species are significant. If these are significant second-order effects, they may be minimized by raising the gain of the tonometer probe, not the over-all gain. Work is in progress which we believe will elucidate this point.

Putting a pinhole in the rubber membrane cover to release any air that may be trapped does not cancel the protection it gives from infection. The pinhole is on one side and the eye secretions do not reach it.