Evaluation of two applanation tonometers in cats

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SUMMARY

Comparisons of the MacKay-Marg and Tono-Pen applanation tonometers in open and closed in vitro systems were made for the eyes of cats. Both instruments significantly underestimated intraocular pressure (IOP) vs direct manometry (P < 0.001), but in readily predictable manner, with high coefficients of determination (r² = 0.99). For tonometer 1 (MacKay-Marg), calculated actual IOP = 1.36 × (MacKay-Marg measurement) - 1.67 mm of Hg; and for tonometer 2 (Tono-Pen), calculated actual IOP = 1.37 × (Tono-Pen measurement) + 0.8 mm of Hg, using measurements from 11 enucleated eyes. In vivo comparisons were initially made in 81 clinically normal eyes (n = 41 cats) by applying the Tono-Pen first followed by the MacKay-Marg. Compared with the MacKay-Marg, the Tono-Pen significantly (P < 0.001) underestimated IOP in these cats. When the order of tonometer applanation was subsequently reversed in 73 clinically normal eyes (n = 37 cats) the Tono-Pen again significantly (P < 0.001) underestimated IOP, compared with the MacKay-Marg. Alterations in tonometer order did not result in significant differences in measured IOP for the MacKay-Marg when compared with itself, but Tono-Pen measurements were significantly (P < 0.05) less when its use followed, rather than preceded, that of the MacKay-Marg. Mean (± SD) IOP in clinically normal cats when each tonometer was used first was 22.6 ± 4.0 mm of Hg (range, 14 to 32 mm of Hg) for the MacKay-Marg and 19.7 ± 5.6 mm of Hg (9 to 31 mm of Hg) for the Tono-Pen. The mean (± SD) absolute value of the differences between MacKay-Marg measurements and those obtained by use of the Tono-Pen was 3.2 ± 3.1 (range, 0 to 13 mm of Hg difference).

Materials and Methods

In vitro phase: comparison with direct manometry—Eleven recently exenterated normal feline eyes from 6 random-source cats were cannulated at the limbus, using a branched 26-gauge needle with the aid of a mechanical needle introducer. Leakage around the needle was not observed, and corneal deformation was minimal. One branch of the needle was connected via polyethylene tubing to a 0.9% sodium chloride solution-filled reservoir with adjustable height above the eye, thereby permitting accurate control of IOP. The other branch of the needle was attached to a pressure transducer, a calibrated microvolt-meter, and a continuous physiologic recorder. The system was calibrated to 0 and 30 mm of Hg before and after evaluation of each eye, using 2 saline-filled reservoirs (one set and maintained at 0 mm of Hg and another set and maintained at 30 mm of Hg) and a column of physiologic saline solution. This permitted verification of calibration during the procedure, and ensured consistency in calibration from eye to eye. Eyes were kept moist by frequent administration of physiologic saline solution throughout the test period.

Intraocular pressure was varied from 5 to 50 mm of Hg in 5-mm-of-Hg increments, and from 50 to 80 mm of Hg manufactured, and its performance has not been critically evaluated in cats. Recently, a small hand-held applanation tonometer based on principles similar to that of the MacKay-Marg, the Tono-Pen was developed for use in people. Both tonometers indirectly assess IOP by measuring the force required to flatten (applanate) a constant area of the corneal surface and do not measure IOP directly. Calibration factors designed for the human eye are then used within both instruments to convert this applanating force to millimeters of mercury, thereby estimating actual IOP. Owing to species variations in ocular anatomy, different calibration factors may be necessary for cats, and use of calibration factors designed for people may result in an inaccurate estimation of actual feline IOP, using these instruments.

The purpose of the study reported here was to determine the validity of the MacKay-Marg and Tono-Pen applanation tonometer measurements in cats by in vitro comparison with each other, as well as with results of direct manometry. Additionally, the 2 instruments were evaluated clinically in cats.
in 10-mm-of-Hg increments. The MacKay-Marg\(^4\) and Tono-Pen\(^\text{*}\) tonometers had recently been calibrated by their respective manufacturers and were used and maintained in accordance with manufacturer’s recommendations. Three measurements were obtained, using each instrument at each pressure, and mean values were calculated for each instrument. Measurements were obtained with the eye open and closed to the saline reservoir. Use of the open system permitted IOP to be kept essentially constant when the instrument was placed on the cornea, and use of the closed system permitted intraocular volume to be kept constant when the cornea was applanated. Data obtained were plotted with the independent variable (x) being the manometer measurement and the dependent variable (y) being the tonometer measurement. For both tonometers, measurements were compared with manometric measurements, and tonometric measurements were compared with each other, using a paired Student \(t\) test (with significance at \(P < 0.05\)). Regression lines (first-, second-, third-, and fourth-order polynomials) were constructed for tonometric vs manometric measurements for each instrument, and the best fit was determined, using coefficient of determination \(\left(\hat{r}^2\right)\) values. The absolute values of the differences between MacKay-Marg and Tono-Pen measurements were also calculated for each manometer pressure setting.

**In vitro phase: clinical comparison**—After topical application of an anesthetic agent,\(^6\) IOP was assessed in 81 clinically normal eyes of 41 cats, by first using the Tono-Pen, immediately followed by the MacKay-Marg. Eyes free of discernible lesions in cats not given medications known to alter IOP were considered clinically normal. The IOP was assessed in accordance with the manufacturer’s recommendations in as calm a cat as possible with as little restraint as possible. The 2 tonometers were then evaluated in a different set of 73 clinically normal eyes from 37 cats, using the MacKay-Marg first followed by the Tono-Pen. Data were plotted in similar manner as those for the in vitro phase, comparing measurements between and within tonometers. Paired Student \(t\) tests were performed for each comparison between the 2 instruments when readings were obtained for both instruments from the same eye. Unpaired Student \(t\) tests were done when comparing readings between the 2 sets of cats, because readings were not from the same eye. Because relative over- or under-estimations of IOP obtained using the 2 tonometers would be equally inaccurate, but would tend to produce a mean difference close to zero, the absolute value of the differences in measured IOP was also calculated. The level of significance in all comparisons was set at \(P < 0.05\).

**Results**

**In vitro phase**—Results obtained from use of each instrument and those obtained from use of the direct manometer in the open system were compared (Fig 1 and 2). Both tonometers significantly (\(P < 0.001\)) underestimated IOP, compared with results of direct manometry (Table 1). The underestimation was virtually linear and increased with increasing IOP. The goodness of fit, or \(\hat{r}^2\), value, for each instrument was high \(\left(\hat{r}^2 = 0.99\right)\), using a linear equation. Analysis of the generated lines indicated that the following equations permitted accurate estimation of actual IOP using tonometric measurements from enucleated eyes:

\[
\text{Actual IOP (estimated)} = 1.36 \times \text{(MacKay-Marg measurement)} - 1.67
\]

\[
\text{Actual IOP (estimated)} = 1.37 \times \text{(Tono-Pen measurement)} + 0.8
\]

Significant differences in measurements made with an individual tonometer were not obtained between the open and closed systems. At 5, 10, 15, 25, 35, 40, 45, and 50 mm of Hg, the Tono-Pen significantly \((P < 0.05)\) underestimated IOP, compared with the MacKay-Marg (Table 1; Fig 3).
Table 1—Comparison of measurements obtained using the MacKay-Marg and Tono-Pen applanation tonometers in 11 enucleated eyes of cats

<table>
<thead>
<tr>
<th>Manometer (mm of Hg)</th>
<th>Tono-Pen (mm of Hg)</th>
<th>MacKay-Marg (mm of Hg)</th>
<th>Absolute difference (mm of Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean ± SD</td>
<td>Range</td>
<td>Mean ± SD</td>
</tr>
<tr>
<td>5*</td>
<td>3.8±0.9</td>
<td>3.0 to 6.0</td>
<td>4.9±0.7</td>
</tr>
<tr>
<td>10*</td>
<td>6.8±1.4</td>
<td>5.0 to 10.3</td>
<td>8.6±1.0</td>
</tr>
<tr>
<td>15*</td>
<td>10.7±1.6</td>
<td>8.6 to 14.7</td>
<td>12.7±1.0</td>
</tr>
<tr>
<td>20*</td>
<td>14.3±1.9</td>
<td>11.3 to 18.7</td>
<td>15.7±0.9</td>
</tr>
<tr>
<td>25*</td>
<td>17.7±2.0</td>
<td>15.0 to 22.3</td>
<td>19.7±1.6</td>
</tr>
<tr>
<td>30*</td>
<td>21.3±2.7</td>
<td>18.6 to 27.0</td>
<td>22.5±1.7</td>
</tr>
<tr>
<td>35*</td>
<td>24.8±3.9</td>
<td>21.0 to 39.3</td>
<td>26.5±2.0</td>
</tr>
<tr>
<td>40*</td>
<td>27.4±3.2</td>
<td>23.6 to 34.0</td>
<td>30.0±2.7</td>
</tr>
<tr>
<td>45*</td>
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<td>27.0 to 36.3</td>
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</tr>
<tr>
<td>50*</td>
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<td>60*</td>
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<td>70*</td>
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<tr>
<td>80*</td>
<td>58.7±4.1</td>
<td>52.6 to 65.3</td>
<td>60.4±4.0</td>
</tr>
</tbody>
</table>

* Tono-Pen measurements were significantly (P < 0.05) less than MacKay-Marg measurements at the same manometer settings.

Absolute difference ranges reflect the range in the difference between the mean of 3 measurements with each tonometer at each manometer setting between the 11 enucleated eyes.

Table 2—Clinical comparison of the MacKay-Marg and Tono-Pen applanation tonometers in clinically normal cats

<table>
<thead>
<tr>
<th>Phase*</th>
<th>No.</th>
<th>Mean ± SD (Range)</th>
<th>Mean ± SD (Range)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>41 cats (81 eyes)</td>
<td>21.7±5.3 (9 to 37)</td>
<td>19.7±5.6* (9 to 31)</td>
</tr>
<tr>
<td>2</td>
<td>37 cats (73 eyes)</td>
<td>22.6±4.0 (14 to 32)</td>
<td>18.0±3.7* (12 to 29)</td>
</tr>
</tbody>
</table>

* Phase 1 = Tono-Pen applied first, followed by the MacKay-Marg; phase 2 = MacKay-Marg applied first, followed by the Tono-Pen. * Significantly (P < 0.0001) less than phase-1 or -2 MacKay-Marg measurements. Phase-2 Tono-Pen measurements also were significantly (P = 0.025) less than phase-1 Tono-Pen measurements.

Figure 3—Comparison of in vitro measurements of IOP in cats, using an open system and the MacKay-Marg and Tono-Pen applanation tonometers. Closed-system results were not significantly different. The solid line represents an ideal 1:1 relationship. * Tono-Pen measurements were significantly lower (P < 0.05) than MacKay-Marg measurements.

Observation of the continuous physiologic recordings indicated that the Tono-Pen generally iatrogenically altered IOP less (by several millimeters of mercury) than did the MacKay-Marg when applied to the cornea.

Clinical comparison—Order of tonometer application did not alter the significant (P < 0.0001) underestimation of IOP by the Tono-Pen, compared with the MacKay-Marg (Table 2; Fig 4). Order of tonometer application also did not result in significant differences between measurements obtained with the MacKay-Marg. A statistically significant (P = 0.025) greater underestimation of IOP was obtained by use of the Tono-Pen, however, when its use followed that of the MacKay-Marg vs when its use preceded that of the MacKay-Marg (Table 2). When the Tono-Pen was applied first, the mean (± SD) absolute difference in measurements obtained, using the 2 tonometers, was 3.2 ± 3.1 mm of Hg (range, 0 to 13 mm of Hg). The Tono-Pen measurements differed by as much as 8 mm of Hg overestimation to 13 mm of Hg underestimation of IOP, relative to the MacKay-Marg.

Discussion

Applanation tonometry is based on the Imbert-Fick law that states that an external (applanating) force against
a sphere equals the pressure within the sphere multiplied by the area flattened by the external force. For the law to be valid, however, the sphere must be perfectly spherical, flexible, dry, and infinitely thin. Because the cornea fails to satisfy any of these requirements, modifications of this law are necessary for an aspherical cornea, tear surface tension, corneal thickness, and corneal rigidity. Proper selection of the size of the area applanated could allow certain ancillary forces, such as tear film surface tension and corneal resistance to bending, to balance each other or to become clinically negligible. The area of application with the tonometers evaluated in this study, however, has been selected by the manufacturer for normal human eyes, and hence, the aforementioned forces may not balance out in animal eyes. These unbalanced forces can have considerable impact on IOP estimates. In one study of the Tono-Pen on human eyes treated topically with methylcellulose, which increases tear film surface tension, > 30% overestimation of IOP was obtained.

Results of several in vitro studies, including this one, also indicated that the MacKay-Marg and Tono-Pen tonometers, when applied to nonhuman corneas, underestimated actual IOP perhaps because of variations in corneal physiologic factors, rigidity, curvature, and thickness. Because the Tono-Pen and MacKay-Marg tonometers are based on the same physical principles, it is not surprising that similar underestimations of actual IOP were obtained by use of the 2 instruments on the eyes of cats. The in vitro underestimation, although increasing slightly with increasing IOP, was essentially linear, and given the MacKay-Marg or Tono-Pen values, predictive equations for experimental purposes could be developed permitting estimations of actual IOP. This numerical manipulation, however, probably would not be necessary in clinical situations because actual IOP is a direct linear function of measured IOP and direct measurements can be compared with normal clinical values. Significant variations between tonometers of similar or the same type, however, may be observed, indicating that corrective equations may need to be developed for each individual tonometer.

The in vitro data would seem to indicate that the MacKay-Marg tonometer may be somewhat more accurate at estimating IOP than is the Tono-Pen at IOP within the physiologic range, but the 2 instruments were not significantly different at IOP > 60 mm of Hg. The lower IOP measured clinically by use of the Tono-Pen in clinically normal cats would tend to support the overall validity of the in vitro testing as a way of predicting a tonometer’s clinical performance if proper technique is applied in a clinical setting. During a clinical and in vitro study of the eyes of horses, significant differences were not observed between the Tono-Pen and MacKay-Marg tonometers in either setting, further bolstering the validity of in vitro comparisons in predicting a tonometer’s clinical performance.

Tonometers intended for clinical use, however, should be compared with each other in a clinical setting, as well as in vitro because minor variations in application technique in living, conscious animals may alter the measured IOP from predicted IOP and in vitro studies do not generate normal clinical values. It is possible, in a clinical situation, that the smaller size of the Tono-Pen’s sensitive tip and the tonometer as a whole, may permit subtle alterations in tension on the eyelids or more precise placement on the cornea, thereby altering measured IOP slightly from that assessed, using the larger MacKay-Marg tonometer. The lack of differences between the 2 instruments in horses, and the significant underestimation of IOP by the Tono-Pen vs the MacKay-Marg in cats may be attributable to differences in the sensitivity of the 2 instruments to subtle variations in feline corneal anatomic and physiologic characteristics. It would appear to be inappropriate to extrapolate the validity of clinically useful tonometers across species lines (ie, tonometer equivalency in one species does not necessarily mean the 2 tonometers are equivalent in another species).

It is also clinically inappropriate to extrapolate normal values across species lines because comparisons with previous studies from our laboratory, using the same individual tonometers in horses, indicate that by use of either tonometer, horses have a significantly (P < 0.001; Student t test) greater mean IOP than do cats. This information further supports the recommendation that not only do normal values need to be determined for each tonometer, but that normal values also need to be determined for use of each tonometer on each species. Clearly, erroneous diagnosis of either glaucoma or globe hypotony would result in many clinically normal cats and horses if normal canine values were to be applied to these species.

The statistically significant, but small (2 to 4 mm of Hg), underestimation of IOP obtained by use of the Tono-Pen on clinical feline patients does not automatically invalidate the Tono-Pen for clinical use. Even the most accurate tonometer used in people, the Goldmann applanation tonometer, has an assumed inherent variability of approximately 2 mm of Hg when 2 readings are taken on the same eye by the same examiner. Undoubtedly this variation increases in uncooperative patients. The critical feature of a clinically useful tonometer is that it be able to evaluate IOP in a reliable, predictable way, as is associated with the MacKay-Marg and the Tono-Pen tonometers.

The Tono-Pen appears to lack a tonographic or pseudofacility effect in normal clinical use in cats, because MacKay-Marg measurements were not significantly different when tonometer order was varied in living, conscious cats. The small (1.7 mm of Hg) difference in Tono-Pen measurements when the Tono-Pen was used first, rather than second, indicates that the MacKay-Marg may have a small, but statistically significant, tonographic effect in reducing IOP via increased aqueous outflow through the pressure-dependent trabecular meshwork. The several millimeters of mercury greater iatrogenic alteration of IOP by the MacKay-Marg when applied to the cornea in vitro would also support the possibility of a tonographic effect for the MacKay-Marg.

In the clinical setting, the Tono-Pen had several advantages over the MacKay-Marg in addition to the fact that it is currently being manufactured and the MacKay-Marg is not. It was portable, automatically averaged 3 to 6 readings, gave a percentage variance between the highest and lowest readings, and gave a more easily interpreted digital readout than the graph generated by the MacKay-Marg. The smaller sensitive tip also permitted precise application to the cornea, which may be useful in some patients with diseased corneas. The smaller transient alterations in IOP when the cornea was applanated...
by the Tono-Pen would seem to indicate that use of the Tono-Pen may be slightly less traumatic than use of the MacKay-Marg and hence, may be a better choice to measure IOP after corneal or intraocular surgery. Disadvantages of the Tono-Pen include the need for multiple applications in some cats to obtain a reading, and in measuring IOP < 5 mm Hg (although in the later cases, it was usually easy to clinically assess the eye as soft). The Tono-Pen averaging feature made it somewhat more difficult, compared with the MacKay-Marg, to obtain a reading in fractious cats or those with continual ocular motions. A new model of the Tono-Pen, the Tono-Pen II, displays each measurement, as well as a final average. In our experience, it also may be necessary to specifically request recalibration of the Tono-Pen when it is returned to the manufacturer for cleaning because recalibration may not be routinely performed after cleaning by the manufacturer.

References