Objectives

♦ To provide an overview of the theoretical basis and history of tonometry

♦ To promote discussion of the practical application of tonometry in clinical veterinary ophthalmology

♦ ...in less than 5 hours! 😊
IOP is a measurement not a diagnosis

Glaucoma \[\uparrow\] 25 mm Hg
Normal \[\downarrow\]
IOP Measurement

**DIRECT**
- Manometry
  - invasive

**INDIRECT (estimate)**
- Tonometry
- Contact
- Non-contact
- Indentation
- Applanation
- Rebound
Mercury Column

Manometry

Courtesy C. Delgado
1622 AD: Richard Bannister England described the raised IOP as determined by palpation of the globe as a distinct sign of eye disease.

Many dud tonometers fill the junkyard of history

2016 AD: many "cool" (?), new tonometers "is there an app for that"?
Clinical issues impacting tonometric IOP

- Pressure on eyelids
- Restraint (including collars)
- Blepharospasm and eye movement
- Patient posture and head position
- Sedation, other drugs administered
- Duration of tonometry / multiple measurements
- Time of Day
- Inter –operator variability
- Tonometer type (use consistently)
- The patient - e.g. corneal biomechanical properties
Effects of Eyelid Pressure & Restraint

### Restraint vs. no restraint

<table>
<thead>
<tr>
<th></th>
<th>Mean (mmHg)</th>
<th>SD (mmHg)</th>
<th>Range (mmHg) (avg 3 readings)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck restraint</td>
<td>16.4</td>
<td>6.9</td>
<td>8-33</td>
</tr>
<tr>
<td>Head restraint</td>
<td>10.2</td>
<td>1.9</td>
<td>7-16.5</td>
</tr>
<tr>
<td>No restraint</td>
<td>10.1</td>
<td>0.8</td>
<td>9-13</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Neck vs. head</td>
<td>0.00015</td>
</tr>
<tr>
<td>No restraint vs. head</td>
<td>0.73</td>
</tr>
<tr>
<td>No restraint vs. neck</td>
<td>0.0014</td>
</tr>
</tbody>
</table>

Issues in IOP measurement
Stress & the “White Coat Effect”
Body Position - Supine Vs Upright & Diurnal Curve

Twenty-four-hour patterns of mean IOP in healthy young adults in the sitting (●) and supine (○) positions.

How to evaluate tonometry papers

Accuracy and Precision

- Target analogy

High accuracy, low precision vs Low accuracy, high precision
How to evaluate tonometry papers…

- Are values compared to manometry?

- **Accuracy**
  - Is the correlation coefficient (r square) close to 1?
  - Is the slope of the regression line close to 1?

- Is the under-estimation or over-estimation linear and consistent over a clinically relevant range?

- **Reproducibility and Precision**
  - What is the scatter of data?
  - Are all data points presented or just the means?
  - Inter-observer variability?

- What is the magnitude of departure from “actual” IOP
How to evaluate tonometry papers...

Fig 3—Comparison of in vitro measurements (mean ± SEM) of IOP in horses with eyes open, using a Tono-Pen tonometer vs direct manometry. The solid line represents an ideal 1:1 relationship.

\[ y = 0.724x - 1.713 \]

\[ r^2 = 0.990 \]
Indentation tonometry

- Digital “tonometry”
- Variable indentation tonometers
  - Schiøtz
  - Based on Maklakoff & Fick’s “law”
    - \[ W = P \times A \]
    - For a given weight applied, the greater the indentation, the lower the pressure
    - 1 scale unit approx = 0.05mm indentation
Schiøtz – Practical Use

- Topical anesthesia
- Zero using test block
- Corneal plane horizontal
- Gently touch foot plate to axial cornea
- Plunger Assembly must be oriented vertically
- Add weights to plunger assembly if scale reading < 5, or inconsistent readings
- Avoid prolonged contact with eye
- Conversion table – eg Friedenwald 1955
- Disassemble and clean!
Other Factors
1) Conversion tables - At least 7 in veterinary medicine!
2) Tonometer standardization and maintenance
3) Surface area of indentation
4) Placement on the sclera or nictitating membrane
5) Duration of indentation
6) Sedatives, anesthetics or tranquilizers
Schiøtz – Practical Use

↓ Force
- Gram weight
- Weight of plunger/instrument
- Tear film surface tension (pulls plunger towards eye)
- IOP

↑ Force
- Ocular (scleral) rigidity and corneal resistance to bending
- Steeper or thicker cornea
- Plunger/Tonometer sleeve friction (reduces effect of weight)
- Footplate/corneal friction (doesn’t let cornea relax to indent)
- Eyelid squeezing & / or Globe retraction
- Vascular congestion of the eye (jugular vein compression)
- Non-vertical placement - not all of weight applied to cornea
Applanation tonometry

- **Variable area – fixed weight/ force**
  - Maklakov type

- **Fixed area – variable weight / force**
  - Goldman type – optical detection of applanation point
  - Mackay-Marg type – electro-mechanical detection of applanation point
**Maklakov Tonometer, (Russia, 1885)**

Plunger of a known weight coated with a dye and allowed to *rest* against the eye (supine position / cornea horizontal).

The tonometer end is then pressed onto special paper, producing circle of dye Diameter of circle corresponds to the intraocular pressure.

A scale, based on the plunger weight divided by the area of contact, is placed over the ring converting it into an IOP value.

Tonometers of various weights allow an estimate of ocular rigidity.
Tonomat ( USA 1964 )
Derivative of the Maklakov Tonometer.
The cornea is appplanationed using a standard weighted probe that has a disposable plastic end plate.
An impression is made from the ring which is then measured with a built in scale.
The force (F) required to flatten a circular area (A) of the surface of a container which has a relative internal pressure (P) is given as follows:

\[ F = PA \]

Assumptions - object is spherical, dry, perfectly flexible, infinitely thin and the container wall contributes nothing to the force equation.

Hmmmmmm.........
• measures force required to flatten a known area (diameter = 3.06 mm) of the cornea. (This area may need to be modified in some species)
• Cornea not infinitely thin but, but the resistance of the average cornea to deformation is balanced by the attractive force of the tear film.
• Corneas that are much thicker or thinner than average will affect the reading
• Goldmann applanation remains the gold standard in clinical practice for physician ophthalmologists.
Goldmann applanation tonometry

- Apply topical anesthetic and fluorescein

- A cobalt blue filter is used to produce a blue light, and the tonometer prism is advanced until close to the cornea, then observed through the oculars of the slit lamp.

- The hemi-circles produced by the prism are brought into alignment by the operator.

- When the inner edges of the hemi-circles are in contact, a circle of cornea 3.06mm in diameter is flattened (displacing ~0.5µl of aqueous humor), and 1gm of force corresponds to 10mmHg IOP, assuming an average corneal thickness.
Perkins hand held tonometer

- Endpoint operation of the instrument is the same as the Goldmann
- Doubling prism is used to observe two split semi-circles and a thumbwheel is used to align the fluorescein mires for an IOP measurement.
- An advantage of this type of Goldmann tonometer is that it can be used in any position.
  - Has been calibrated for sheep, cattle, dogs and cats
- Relies on a clear regular cornea
- Maximal scale reading = 5 (maximal IOP ≤ 50mmHg)
Mackay-Marg applanation tonometry

- 1mm central plunger surrounded by circular footplate
- Electromechanical detection of plunger displacement
- Mackay-Marg records this displacement on a paper chart
- Operator reads IOP from the point of the “dip” on the chart – which represents the applanation point when the plunger no longer protrudes from the footplate and the force of IOP is taken off the plunger
Mackay-Marg applanation tonometry

- Topical anesthesia required
  - or IOP about 2 mmHg higher
- Calibrate by gravity (as for tono-pen)
- Use a condom!
- Gently touch probe tip to cornea
- Stages of applanation are reflected on the tracing

Figure 5-5. Mackay-Marg tonometer.
self-contained miniaturized version of the Mackay-Marg
very small “footprint” on the cornea
easier to use with corneal abnormalities and in any position.

sanitized cover is placed over the tip.
Following topical anesthesia, Tonopen is gently tapped against the cornea.
It clicks and shows the pressure reading with every valid contact.
When 3-6 valid readings have been obtained it will beep again and displays the final averaged reading, with an indicator showing the confidence of the reading based on the standard deviation / variance of the averaged values.

NOT ALL TONOPENS ARE CREATED EQUAL (since central plunger reduced to 1mm)
Tono-Pen vs Tono-Pen XL

- Applanation tonometer with 3.2mm tip
- Both the Tono-Pen and Tono-Pen XL are known to underestimate IOP in cats
  - Tono-Pen (slope = 0.73) central plunger 1.5mm
  - Tono-Pen XL (slope = 0.64) central plunger 1.02mm
  - Tono-Pen Vet / AVIA Vet (slope =?) central plunger =1.02mm

Clinical considerations for Mackay-Marg type tonometers

- Mackay – Marg highly accurate in dogs and cats
- Tono-Pen varies by model
  - Highly accurate and precise over normal physiological range
  - Less so at extremes of IOP
  - Overestimates low IOPs, underestimates high IOPs

- Less affected by corneal disease than other types
- Artifactual under-estimation of IOP unlikely – so take the lowest reliable reading
- Viscosity of tear film affects the readings (increasing them by about 15% or more if methylcellulose)
- Off center application doesn’t significantly affect readings
Pneumotonometer

Column of air replaces central plunger as central sensing device.
Not to be confused with air puff tonometer!
Corneal Biomechanics

- Applanation tonometry assumes:
  - cornea offers no resistance to deformation, infinitely thin, completely dry
- 0.1-0.7 mmHg increase in IOP with 10 μm increase CCT
- What about corneal stiffness?

<table>
<thead>
<tr>
<th>IOP&lt;sub&gt;Man&lt;/sub&gt; (mm Hg)</th>
<th>GAT (mm Hg)</th>
<th>Tono-Pen (mm Hg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Control (n = 10)</td>
<td>Corneal Stiffening (n = 10)</td>
</tr>
<tr>
<td>10</td>
<td>2.2 ± 1.0</td>
<td>10.1 ± 3.6</td>
</tr>
<tr>
<td>15</td>
<td>6.8 ± 1.4</td>
<td>15.6 ± 4.1</td>
</tr>
<tr>
<td>20</td>
<td>11.3 ± 1.5</td>
<td>21.1 ± 5.6</td>
</tr>
<tr>
<td>30</td>
<td>20.3 ± 1.5</td>
<td>30.7 ± 5.3</td>
</tr>
<tr>
<td>40</td>
<td>29.0 ± 1.8</td>
<td>40.7 ± 6.0</td>
</tr>
</tbody>
</table>

Effect of Corneal Stiffening on Goldmann Applanation Tonometry and Tono-Pen Measurements in Canine Eyes

Schematic for measuring IOP in mice with an induction-impact (I/I) tonometer, which operates on the rebound principle. Tonometer components and the eye are not drawn to scale.

Danias et. al. (Investigative Ophthalmology and Visual Science. 2003;44:1138-1141.)
Rebound tonometer

- Probe rebounds faster as IOP increases
- Higher IOP - shorter duration of impact.
- Does not require topical anesthesia.
- Similar reliability to Tono-Pen XL and better accuracy
- Systematic overestimation or underestimation of IOP
- Further assessment of rebound tonometry in populations with higher IOP and corneal disease, is needed.
TonoVet

- Studies in:
  - Pigs, Humans, Dogs, Horses, Rabbits, cats
  - Birds (but slopes = 0.8 to 1.6 depending on species)
  - TonoLab (rodents)
- Highly accurate (slope close to 1) in dogs, cats, horses, rabbits and some avian species
- Species differences noted – needs calibration/validation by species

McLellan GJ et al. (2013) Vet Ophthalmol
*Leiva et al. (2006) Vet Ophthalmol, 9,1,17-21 * Compared I-Care to Tonopen XL
Knollinger, AM et al. (2005) J Am Vet Med Assoc 227 (2), 244-248
Reuter A et al. (2009) ECVO Proceedings
Wang, WH et al. (2005) IOVS ; 46, 4617-4621
Morrison JC et al. (2009) IOVS, 50,6
Comparison of TonoVet® and Tono-Pen XL® with Manometry

- TonoVet
- Tono-Pen XL

Regression equations and correlation coefficients:

1. TonoVet vs Manometry:
   - Equation: $y = 1.0322x + 2.2338$
   - Correlation coefficient: $r^2 = 0.9192$

2. Tono-Pen XL vs Manometry:
   - Equation: $y = 0.6222x + 1.4177$
   - Correlation coefficient: $r^2 = 0.9382$

Graph shows the relationship between Tonometric IOP (mm Hg) and Manometric IOP (mm Hg) with points plotted for each method compared to Manometry.
Air-puff tonometry

Non-contact device
flattens the cornea using a jet of air
Optical receiver detects when and how fast the cornea has been flattened to a predetermined degree.
Converts the amount of time it takes for applanation to occur into mmHg

Advantages:
Topical anesthetic is not required
potential cross-contamination prevented

Disadvantages:
not as accurate as Goldmann or Mackay-Marg type tonometers (esp. at high IOP).
Patient movement a problem!!
Goldmann realized that corneal thickness and rigidity were important and might influence measurement of IOP.

Instrument was optimized for an “average” human cornea of 520 µm (underestimated! 540 - 550 µm.)

People who have thin corneas have IOP measurements which are lower than true IOP.

People with thick corneas tend to have an IOP measurement higher than true IOP.
THE RELATIONSHIP BETWEEN CCT AND IOP READINGS

...others report no linear correlation between CCT and IOP, why?
models are dependent on:

- population characteristics
  - presence/absence of ocular hypertension
  - number and type of surgical interventions
  - ethnic groups

- pachymetric technique used
- tonometric technique used
  - each can over or under estimate IOP
(Swiss Microtechnology, CH)

uses a direct transcorneal method to measure the IOP

The device is slit lamp mounted, similar to GAT.

The tonometer tip contact surface is concave Contoured to human corneal surface.

When placed on the eye corneal mechanical effects on IOP measurement are reduced.

The DCT gathers 100 IOP readings per second, thus recording dynamic IOP. TAKES 5 secs!

Gives an estimation of ocular pulsatility i.e. perfusion?
The ORA utilizes an air pulse to apply force to the cornea advanced electro-optical system to monitor the resultant corneal deformation.

Alignment to eye is fully automated.

The difference between "inward" applanation pressure and "outward" applanation pressures defines corneal hysteresis, a measure of ocular rigidity.

“RORA measurement may not be possible in the presence of nystagmus”
The Proview eye pressure monitor has a flat applicator the same diameter as the Goldmann tonometer.

Uses a psychophysical test based on the entoptic phenomenon of pressure phosphenes, a sensation of light elicited by nonphotic stimuli, to evaluate IOP.

Not very accurate!!

Diaton tonometer also measures IOP through the eyelid. The measurement principle is based on the acceleration of a free falling rod with a known weight and its interaction with the elastic eye surface through the eyelid. Tends to underestimate IOP.
The SENSIMED Triggerfish® Sensor is a soft disposable silicone contact lens with a micro-sensor strain gauge that captures spontaneous circumferential changes in the cornea with IOP fluctuation (1).

An adhesive antenna, placed around the eye, receives information from the contact lens. (2)

Data is transmitted through a thin flexible cable from the Antenna to the portable recorder, worn by the patient, that stores acquired data. (3,4)

At the end of the 24 hr recording period, the data is transferred via Bluetooth from the recorder to computer software for review.

www.sensimed.ch
Direct Telemetric Measurement of IOP

Downs, JC et al, 2011. IOVS
Telemetry

- A new frontier?
- Will allow continuous remote measurement of IOP
- IOP variability and fluctuations are “worse” than we think!

- All of the devices thus far tested have their “limitations”
- Watch this space!
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Carol A Rasmussen MS & Paul Kaufman MD
Paul E Miller DVM

…& all the authors & sources I forgot to acknowledge…..