Contact Lens Tonometry—Application in Humans

Beatrix Entenmann, Yves C. A. Robert,* Peter Pirani,† Hartmut Kanngiesser,† and Peter W. Dekker *‡*

Purpose. To establish a standard clinical procedure for measuring intraocular pressure (P_O) with the contact lens tonometer (CLT), to demonstrate possibilities for analyzing ocular pulsation and performing ophthalmodynamometry.

Methods. A reliable histogram-based analyzing system for determining P_O is used. First, the ocular pressure was registered with the CLT method and compared with the Goldmann applanation pressure, measured immediately beforehand. Second, ocular pulsation was studied by recording P_O for 30 to 70 seconds, and the pulse amplitude was then analyzed. Third, an ophthalmodynamometry method during slit-lamp examination was tested. The central retinal artery was observed through the contact lens while the appositional force was elevated. A mark was set at the systolic and diastolic pressure while observing arterial pulsation (similar to the Korotkoff sounds).

Results. Compared with the Goldmann method measurements, P_O obtained with the CLT method yielded a linear regression of $r = 0.7$ (right eye) and $r = 0.68$ (left eye), and was therefore highly significant ($P < 0.0001$, two-tailed). Analysis of the pulse amplitude showed great variability (range, 1 to 9 mm Hg; means, 2.9 mm Hg [right eye] and 3.0 mm Hg [left eye]). The dependence of the pulse amplitude on P_O and age was shown with a correlation coefficient of $r = 0.55$ and $r = 0.59$, respectively. The difference between the right and left eye of the person was <0.5 mm Hg.

Conclusion. The CLT can be used during slit-lamp examination and permits tonometry during ophthalmoscopy, ocular pulsation assessment at different intraocular pressures, and ophthalmodynamometry. Invest Ophthalmol Vis Sci. 1997;38:2447–2451.

There are two primary reasons for performing tonometry over time: the study of intraocular pressure (IOP) pulsation and the so-called provocation tests. Pulsation is measured with special tonometers, including the Perkins[1] recording instrument, the ocular blood flow system,[2] and the Krakau device[3]; in patients with elevated IOP, suction cup devices[4] are used. Provocation tests (e.g., flicker stimuli,[5] warm and cold stimuli,[6,7] or pressure elevation[8]) have been proven useful for evaluating circulatory disturbances of the eye.

To combine the pressure increase with the signal measurement at the eye fundus, a transparent pressure-measuring device is needed that can be brought into the measuring beam of the imaging apparatus. Fulfillment of this criterion means that the applanation area of such a tonometer can no longer be observed. The contact lens tonometer (CLT) has this capability.

A study in which the CLT was used to measure the pressure in eye bank cadaver eyes found a correlation of $r = 0.98$ between the extraocular and the intraocular measurement.[9] By analyzing this study, we established a procedure to allow measurement in living patients. This procedure allows a single examiner to perform the measurement and immediately know the real-time IOP over time while observing the fundus of the eye. In this article, we discuss use of the CLT and software for rapid determination of the baseline pressure (P_O) and describe the standard slit-lamp procedure for correct measurement. We compare the P_O values measured with the CLT with the values obtained with a Goldmann applanation tonometer.

METHODS

This study was approved by the Ethics Committee of the University of Zürich. Informed consent was ob-

*From the *University Eye Department, Universitätsspital, Zurich, Switzerland; †AFIF, Federal Institute of Technology (ETH), Zurich, Switzerland; ‡now affiliated with the Eye Department, Kantonsspital, Aarau, Switzerland.*
Supported by Hartmann-Müller Foundation, Zurich, Switzerland.
Submitted for publication January 30, 1997; revised May 31, 1997, and July 14, 1997; accepted July 14, 1997.
Proprietary interest category: N.
Reprint requests: Y. Robert, University Eye Department, Universitätsspital, CH-8091 Zurich, Switzerland.

tained from the subjects, and the procedure did not deviate from the tenets of the Declaration of Helsinki.

Standard Procedure for Continuous Measurement of IOP in Humans

The technical details of the CLT have been previously described.[9,10] After the measurement is made, the lens is disinfected with alcohol.

The cornea must be anesthetized with oxybuprocaine, as in Goldmann applanation or the three-mirror contact lens examination. No contact gel is needed, in contrast to other contact lenses (e.g., for performing funduscopy). By looking through the slitlamp microscope, the examiner can see if the space between the contact lens and the cornea is filled with fluid.

To obtain the P_O, the examiner looks for the point where the lens is just fully covered with fluid without using high appositional forces, which would artificially elevate the IOP. In this phase, the examiner can easily record the ocular pulsation at P_O. If the lens is not perfectly centered on the cornea or if it is not held vertically, the three pressure sensors will measure very different appositional forces.

The examiner can observe the recorded trace on a computer screen. The values of the actual pressure and the summary of the appositional force (mean of the signals from the three sensors inside the lens) are also shown, both as actual digital values and graphically. By pushing a button, the examiner can display the baseline IOP at the end of the measurement.

A maximal deviation of the three sensors for the appositional force of 10 g is allowed. If they differ by more than 10 g, the pressure values have been shown to be unreliable and are not considered for the P_O computation.

Although the measuring frequency can be varied, all of our traces were recorded with a rate of 10 Hz. Recording time was typically 30 to 70 seconds.

Intraoccular pressure is defined as the lowest measured pressure value of the trace with low appositional forces. If high appositional forces are used, the IOP is artificially raised. The pressure values are also artificially raised if the space between the contact lens and the cornea is not totally filled with fluid, as is the case when the appositional forces used are too low. This might be caused by the capillary pressure of the tear film, which gives erroneously high values if the interface is not completely filled.[11]

To determine the lowest measured pressure value, a histogram of all pressure values registered during one recording is calculated. Values <5 mm Hg are considered artifacts and ignored. Intraoccular pressure is found to be the lowest eye pressure that is registered at least five times during the measurement and is followed by pressure values registered more than five times, so that the slope of the histogram is positive. In this case, the diastolic value of the IOP is considered to be the correct value for P_O.

CLT Pressure Measurement Versus Goldmann Applanation Tonometry

All measurements were made by the same examiner. Immediately before the CLT recording, the IOP was measured using the Goldmann applanation method. The standard procedure was performed in 70 volunteers who had no known ocular disease. Refraction errors in a range of ±3 dioptres (spherical equivalent) were allowed. The CLT recording was performed two or three times for each eye. The values of the three measurements varied within 2 to 3 mm Hg, and the mean of these values was used for comparison.

Pulse Amplitude

To study the behavior of ocular pulsation at P_O, 25 subjects' eyes were again measured using the standard procedure. Ocular pulse curves were recorded three times per eye.

Ophthalmodynamometry

Contact lens tonometer pressure values increase when the real eye pressure is elevated by pushing the CLT against the eye or, in other words, by elevating the appositional force. By doing this during slit-lamp examination with the CLT, the examiner can observe the pulsation of the central retinal artery. If the pressure is further increased until the blood flow just stops, the systolic pressure is obtained. By releasing the pressure on the eye (lowering the appositional force), the pulsation reappears. The diastolic pressure is recorded when the pulsation of the central retinal artery just stops. The blood pressure of the ophthalmic artery can be determined by using these two values.[12] This procedure is similar to measuring a patient's blood pressure at the brachial artery, where the examiner listens for the Korotkoff sounds. While performing ophthalmodynamometry as described, the examiner can place a mark, using a foot pedal, at the point where pulsation of the artery begins and where it stops again.

RESULTS

Standard Slit-Lamp Procedure

Figure 1 shows the trace of the continuously recorded pulsation at P_O over a period of 70 seconds. It is overlaid by a wave due to respiration. The other trace represents the appositional force. Some fluctuation in the appositional force can be observed. This might be due to the tremor of the examiner or blinking of the volunteer; in some cases, the examiner does this

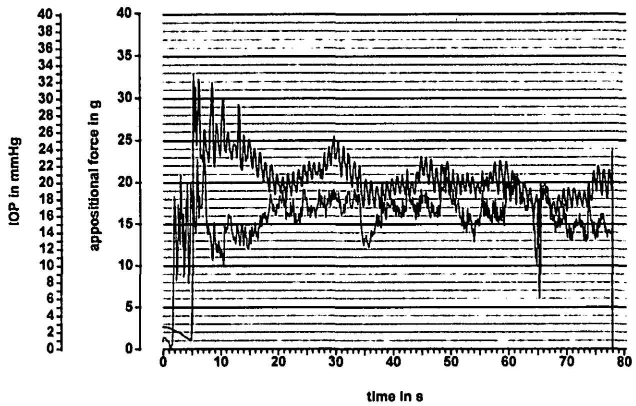

FIGURE 1. On-line trace for 70 seconds. The upper trace shows the eye pressure with its pulsation. The lower trace shows the mean of the three force sensors.

intentionally to find P_O. Within a certain range, this fluctuation of the appositional force does not seem to influence the IOP.

Figure 2, a histogram of all measured values, shows how often the different IOPs of the tracing in Figure 1 are registered. The computer calculates the histogram and gives the P_O, as described above, immediately after the measurement.

Eye Pressure With CLT Compared With Goldmann Applanation Tonometry

Figure 3 shows the diagram for the right eye. With a correlation of $r = 0.70$ for the right eye and $r = 0.68$ for the left eye and $P < 0.0001$ (two-tailed), this represents a statistically very significant correlation between these two methods. The positive offset value is due to the electronic amplification to obtain positive values only.

Pulse Amplitude

The pulse amplitudes of the 25 subjects with normal eyes showed great variability: amplitudes between 1

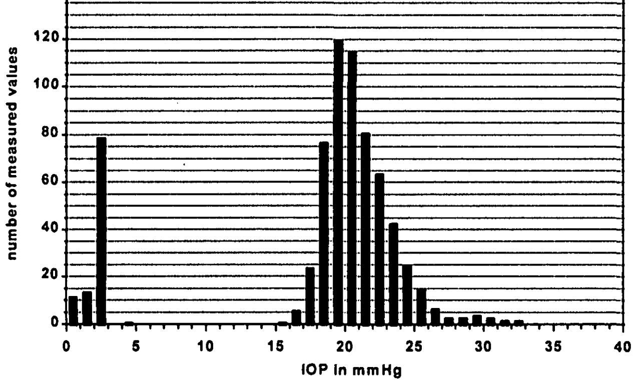

FIGURE 2. Histogram of the values from Figure 1. The lowest value found more than five times is 16 mm Hg. The zero values represent values from the start of the measurement.

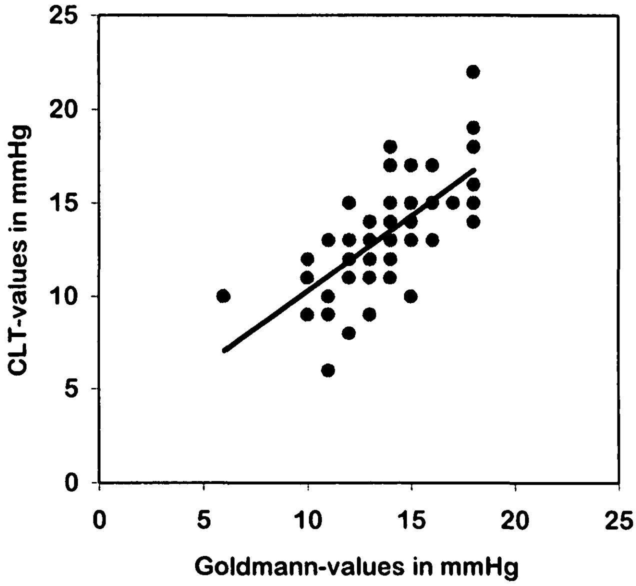

FIGURE 3. Contact lens tonometry versus Goldmann applanation method (for the right eye). $N = 70$ normal subjects. Points duplicated are overlapping.

and 9 mm Hg were observed. Most of the subjects, however, had an amplitude of 2 to 3 mm Hg. The mean values were 2.90 mm Hg for the right eye and 3.02 mm Hg for the left, with a standard deviation of 1.2 and 1.79, respectively. The medians were 2.85 mm Hg for the right eye and 2.3 mm Hg for the left. The difference between the right and left eye of one subject was ≥ 0.5 mm Hg (mean, 0.28 mm Hg). With regard to the height of IOP, a linear, statistically significant dependence on the pulse amplitude was noted with a correlation coefficient of $r = 0.55$ ($P < 0.01$). Even with regard to the age of the subjects, a linear, statistically highly significant dependence was observed, with a correlation coefficient of $r = 0.59$ ($P = 0.001$).

Ophthalmodynamometry

Figure 4 shows a trace from a normal subject with an eye pressure of 12 mm Hg. The blood pressure measured at his left arm in upright position was 120/80 mm Hg.

With an increase in the appositional force, the IOP rose and marks (arrows) were set with the foot pedal when, after compression, the central retinal artery just began to pulsate and when the pulsation just stopped. In this case, the systolic value was 90 mm Hg and the diastolic value 70 mm Hg.

DISCUSSION

The standard CLT procedure described can be used to record ocular pulsation of the uninfluenced IOP (P_O) as long as required.

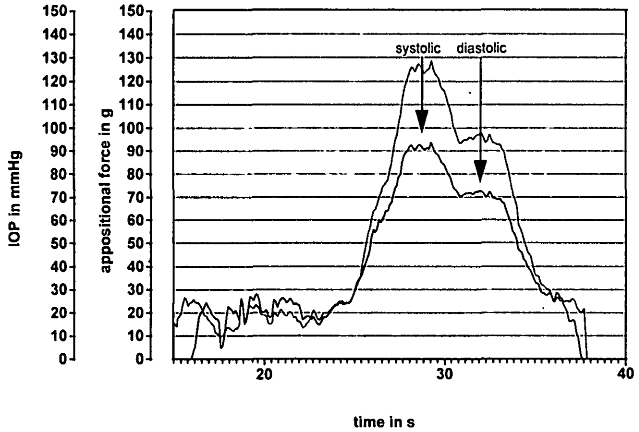

FIGURE 4. Ophthalmodynamometry. Dark trace is pressure; light trace is force. Arrows point to the systolic and diastolic values.

Because low appositional forces (when the lens is not totally filled with fluid) produce incorrectly high pressure values and high appositional forces also produce high pressure values, the algorithm that looks for the lowest measured value to obtain P_O works very well. If the appositional force is too high throughout the entire measurement, in most cases the contact lens is not held in a vertical position and the three sensors for the appositional force show different values. In these cases, a range of 10 g difference is not enough to obtain any value for P_O, and the measurement should be repeated.

Because the IOP constantly fluctuates over seconds, the reliability of the measurement increases with longer registration and the sources of error diminish (e.g., respiration cycles, pulse fluctuation, Valsalva maneuver).[13–17] By analyzing the trace after the measurement, the appositional force applied and the fluctuations can be assessed.

The standard procedure for contact lens tonometry can easily be performed at slit-lamp examination. If needed, the CLT could also be used as a tonometer in the supine position (e.g., to examine patients in bed or in the operating room, to examine obese patients, or to avoid errors in measurement due to the Valsalva maneuver).[16,17] To check whether the lens is filled with fluid, a flashlight or a head ophthalmoscope can be used.

Contact Lens Tonometry Versus Goldmann Applanation Tonometry

In a study of 70 subjects with normal eyes, pressure values measured using contact lens tonometry were compared with those obtained using Goldmann applanation tonometry. The possibility of remembering data that could influence the values[18] can be excluded because Goldmann applanation tonometry was performed first and the ensuing values for the CLT are shown as numbers on the screen and are not seen before the end of the examination. With a correlation coefficient of $r = 0.70$ for the right eye and $r = 0.68$ for the left eye, the correlation between these two methods is statistically highly significant (see Fig. 3).

However, the correlation to in vivo Goldmann values was not as impressive as seen in an in vitro setting, where the CLT values correlated to intraocular measured pressures with a correlation coefficient of $r = 0.98$. There are several possible explanations. One reason for the lower in vivo correlation could be due to the limited range of IOP in this normal population. Respiratory effects, blinking, vertical gaze, or accommodation of the subjects might be sources of errors for both methods.[14,16,19–21]

Goldmann tonometry is the most widely accepted method in clinical testing of IOP, and new tonometers must be compared to this method. However, the Goldmann tonometer itself has many sources of errors. One is the fact that the values are measured in steps of 2 mm Hg; odd numbers are interpolated and partially underlie the examiner's interpretation. Even if the examiner in this study tried to use the correct procedure for Goldmann applanation, errors from incorrect fluorescein concentration,[22] width of the rings,[23] and illumination[24] must be taken into account. There are also variations between measurements using two different Goldmann tonometers and between measurements taken by two examiners.[18,25]

Pulse Amplitude

The pulse amplitudes in the normal eyes of the 26 subjects in this study were variable, with a range of 1 to 9 mm Hg. However, the interindividual variability, as well as the variability of the values for the right and left eye, was very slight and varied by ≥0.5 mm Hg.[1,3] The mean pulse amplitude of about 3 mm Hg is in agreement with the findings of Perkins et al[1] using the modified Goldmann applanation prism. They also reported that their pulse amplitudes were remarkably higher than the pulse amplitudes recorded using pneumatonography. A positive correlation between the pulse amplitude and IOP has been described.[1,26–28]

Ophthalmodynamometry

The pulsation of the central retinal artery can be seen by elevating the IOP by pressing the contact lens against the eye. When marking the event of cessation and reappearance of pulsation, the systolic and diastolic values of the IOP can be registered on the trace. No further computation is necessary; the instrument gives the actual pressure directly. Using special algorithms based on the work of Bedavanija,[12] the measured values can be compared with those obtained with compression ophthalmodynamometry. Performing ophthalmodynamometry with the CLT is a handy and minimally invasive way to obtain information about the pressure in the ophthalmic artery.

In conclusion, reliable tonometry can be performed with the CLT during ophthalmoscopy. The ocular pulsation can be analyzed at different IOPs, and ophthalmodynamometry can be easily performed during slit-lamp examination.

Key Words

appositional force, contact lens, continuous measurement, ophthalmodynamometry, tonometry

References

1. Perkins ES, Edwards J, Saxena RC. A new recording tonometer. *Trans Ophthal Soc UK.* 1997;97:679–682.
2. Langham ME, To'Mey KF. A clinical procedure for the measurements of the ocular pulse-pressure relationship and the ophthalmic arterial pressure. *Exp Eye Res.* 1978;27(1):17–25.
3. Krakau CE, Lindberg S, Havelius U. An instrument for recording the ocular pulse wave. *Acta Ophthalmol Scand.* 1995;73:472–474.
4. Ulrich WD, Ulrich C. Oculo-oscillo-dynamography: A diagnostic procedure for recording ocular pulses and measuring retinal and ciliary arterial blood pressures. *Ophthalmic Res.* 1985;17:308–317.
5. Buerk DG, Riva CE, Cranstoun SD. Frequency and luminance-dependent blood flow and K^+ ion changes during flicker stimuli in cat optic nerve head. *Invest Ophthalmol Vis Sci.* 1995;36(11):2216–2227.
6. Rojanapongpun P, Drance SM. The response of blood flow velocity in the ophthalmic artery and blood flow of the finger to warm and cold stimuli in glaucomatous patients. *Graefes Arch Clin Exp Ophthalmol.* 1993; 231(7):375–377.
7. Drance SM, Douglas GR, Wijsman K, Schulzer M, Britton RJ. Response of blood flow to warm and cold in normal and low tension glaucoma patients. *Am J Ophthalmol.* 1988;105(1):35–39.
8. Hendrickson Ph, Stöckli HP, Robert Y. Principles of photometry of the papilla. *Arch Ophthalmol.* 1984;102: 1704–1707.
9. Dekker PW, Kanngiesser H, Robert Y. Das Kontaktglastonometer. *Klin Monatsbl Augenheilkd.* 1996;208: 370–372.
10. Kanngiesser H, Robert Y, Dekker P. Das Kontakglastonometer. *Der Ophthalmologe.* 1996;93:549–551.
11. Dreyer M. Kapillarer Flüssigkeitsanstieg zwischen parallelen Platten unter kompensierter Gravitation. *Fortschr. Ber. VDI Reihe 7 Nr 241 VDI-Verlag* Düsseldorf; 1994.
12. Weigelin E, Lobstein A. *Ophthalmodynamometrie.* Basel, New York: Karger; 1962:21–30.
13. Thiel R. Hornhautpulsation, Blutdruck und Augendruck. *Berichte Deutsche Ophthalmol Gesellschaft* 1928; 47:198–206.
14. Moses RA, Carniglia PE, Grodzki WJ Jr, Moses J. Proptosis and increase of intraocular pressure in voluntary lid fissure widening. *Invest Ophthalmol Vis Sci.* 1984; 25:989–992.
15. Cooper RL, Beale DG, Constable IJ, Grose GC. Continual monitoring of intraocular pressure: Effect of central venous pressure, respiration and eye movements on continual recordings of intraocular pressure in the rabbit, dog, and man. *Br J Ophthalmol.* 1979; 63:799–804.
16. Whitacre MM, Stein R. Sources of error with use of Goldmann-type tonometers. *Surv Ophthalmol.* 1993; 38:1–30.
17. Teather TC, Davidovski F. Clinical comparison of the Oculab Tono-Pen to the Goldmann applanation tonometer in obese African-American patients. *Ann Ophthalmol.* 1995;27;153–159.
18. Phelbs CD, Phelbs GK. Measurement of intraocular pressure: A study of its reproducibility. *Graefes Arch Clin Exp Ophthalmol.* 1976;198:39–43.
19. Moses RA. The Goldmann applanation tonometer. *Am J Ophthalmol.* 1958;46:865–869.
20. Moses RA, Liu CH. Repeated applanation tonometry. *Am J Ophthalmol.* 1968;66:89–91.
21. Vernon SA. Reproducibility with the Keeler Pulsair 2000 non-contact tonometer. *Br J Ophthalmol.* 1995; 79:554–557.
22. Smith R. Applanation tonometry without fluorescence [correspondence]. *Am J Ophthalmol.* 1979;87:583.
23. Goldmann H, Schmidt T. Ueber Applanationstonometrie. *Ophthalmologica.* 1957;134:221–242.
24. Schmidt T. The clinical application of the Goldmann applanation tonometer. *Am J Ophthalmol.* 1960;49: 967–978.
25. Berry V, Drance SM, Wiggins RL, Schulzer M. A study of the errors of applanation tonometry and tonography on two groups of normal people. *Can J Ophthalmol.* 1966;1:213–220.
26. Perkins ES. The ocular pulse. *Curr Eye Res.* 1981;1:19–23.
27. Friedland AB. Relationship between arterial pulsations and intraocular pressure. *Exp Eye Res.* 1983;37: 421–428.
28. Phillips CI, Tsukahara S, Hosaka O, Adams W. Ocular pulsation correlates with ocular tension: The choroid as piston for an aqueous pump? *Ophthalmic Res.* 1992; 24:338–343.