AO TECHNICAL REPORT

A Noncontact Applanation Tonometer

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Description and Clinical Evaluation

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A new applanation tonometer (NCT) measures intraocular pressure without touching the eye. A central area of the cornea is deformed by an air-pulse of linearly increasing force and the instant of applanation is determined by a monitoring system that senses light reflected from the corneal surface. Clinical evaluation has demonstrated good correlation between NCT and Goldmann tonometer readings, thereby validating this new method of tonometry.

A new applanation tonometer (American Optical Corp.), developed by one of us (B.G.), measures intraocular pressure (IOP) without contact between the instrument and the eye (US Patent 3,585,849, Method and apparatus for measuring intraocular pressure, June 22, 1971). Applanation is produced by a controlled air-pulse of linearly increasing force impinging on the cornea. A monitoring system senses light that is reflected from the corneal surface and records a maximal signal at the instant of applanation. The interval of time required for the air-pulse to produce applanation is proportional to IOP.

Applanation tonometry is based on the Imbert-Fick law, which states that the IOP is equal to the applanation force divided by the area of applanation. The first clinical applanation tonometers were introduced by Weber in 1867 and by Mlakoff in 1885. The Mlakoff tonometer estimated the area of cornea that was flattened by a cylinder of known weight. A more accurate instrument is the Goldmann applanation tonometer, which measures the force that is required to flatten a specific optically determined area. It is the currently accepted standard for evaluation of all clinical tonometers.

The noncontact tonometer (NCT) utilizes the fundamental principles of applanation tonometry. It has been calibrated against the Goldmann tonometer. It is unique in that it flattens the cornea within a few milliseconds by means of an air-pulse instead of by direct mechanical contact. The purpose of this report is to describe the NCT and present the results of an initial clinical evaluation.

Description of Instrument

The NCT consists of three component systems. The first, the pneumatic system, is designed to deliver an air-pulse whose force increases linearly with time (Fig 1). The second, the applanation monitoring system, is designed to detect and identify, with microsecond resolution, the occurrence of applanation (Fig 2). The optical-electronic alignment system is the NCT's third component. It consists of a primary visual alignment system and an overriding automatic alignment verification feature that precludes measurement unless the incorporated spatial criteria are satisfied (Fig 2). A special purpose digital computer, located in the instrument's base, regulates each of the component systems, integrates their interactions, processes the acquired measurement information, and finally, displays the IOP digitally in millimeters of mercury.

Pneumatic System.—As shown in Fig 1, the pneumatic system consists of rotary solenoid (S); connecting linkage (CL); carbon piston (P); seated in a polished stainless steel cylinder (C); with window (W); and modified microscope objective (O); constituting the axial boundaries of plenum (cavity) (PL).

When the solenoid is energized, the piston, riding on an air-film bearing, accelerates at a controlled rate, thereby pressurizing the plenum. Because the objective is broached axially, and has a length of tubing, the positive plenum pressure is transmitted in the direction of the patient's cornea. When a force transducer is substituted for the cornea, the displayed voltage vs time output demonstrates the linearly increasing force characteristic of the air-pulse for the first 8 msec (Fig 3).

When the air-pulse impinges against a properly oriented cornea, it initially causes a progressive reduction of corneal convexity, then instantaneous applanation, then a slight concavity, and finally decay of the air-pulse permits progressive restoration of the cornea to its original shape.

Applanation Monitoring System.—As depicted in Fig 2, the applanation monitoring system (AMS) continuously monitors the status of corneal curvature during the measurement event. It consists of two obliquely oriented tubes (T and R). The transmitter (T) directs a collimated beam of light at the corneal vertex while the telecentric receiver (R) "looks" at
the same area. From the undisturbed cornea, little or no light is captured by the receiver's lens, passed through pinhole aperture (A) (located in the lens' focal plane), or sensed by the detector (D) (Fig 4). As the cornea's convexity is progressively reduced under the influence of the air-pulse, increasing numbers of rays are accepted and sensed. When apllanation is achieved, the cornea acts as a plano mirror and causes a maximum signal to be developed by the detector (Fig 5). When the cornea becomes slightly concave, an abrupt reduction in sensed light occurs. The decay of the air-pulse causes a reversal of the preceding events. Figure 6 is an oscilloscopic recording of the detector's output throughout the corneal deformation event.

At the instant when apllanation is detected, the supply of current to the pneumatic system's solenoid is immediately shut off by the digital computer in order to minimize air-pulse force impinging upon the cornea.

Alignment System.—The third component system has three design features that are intended to facilitate NCT-to-cornea alignment.

Primary Visual Alignment System.—A modified optical spherometer (a system similar to the radiuscope) constitutes the visual system for alignment in three dimensions—axial, vertical, and lateral (Fig 2). It consists of fixation and alignment target (F) (a red dot on a white field); beam splitter (B); front surface mirror (M); collimating lens (TL); beam splitter (B2); microscope objective (O); telescope lens (TL2); and eyepiece (E), with aiming circle reticule (G). Since target F is located in the focal plane of TL1, an image of the red dot is formed in the "working plane" (WP) or front focal plane of objective (O). When the instrument is moved so that WP is coincident with the center of curvature of the central cornea, the corneal virtual image of the red dot is reimaged in the plane of G and viewed by the operator. When alignment is refined so that the optical spherometer's axis is normal to the local corneal vertex, the red dot is centered within the aiming circle, G. For a cornea with a radius of curvature of 7.9 mm, the distance from the pneumatic orifice to the cornea is 11 mm. This distance varies from 11 mm, according to the corneal radius of curvature.

The patient is instructed to fixate the red dot target, located at optical infinity, through the broached orifice of the objective (O). Alignment requires that the patient fixate the red dot target.

Correction of Patient's Astigmatism.—To provide for correction of large refractive errors in patients who have aphakia or high myopia, a five-position turret device (Fig P) is interposed in the collimated space between TL and B2 (Fig 2). Four of the five apertures contain an axially centered 3-mm diameter lens, each of a different power (+14, +4, -3, and -10 diopters). Because light from target F is collimated in the space between TL and B2, each small lens optically modifies only the central aperture corresponding to the orifice through which the patient fixates the target. Optional positioning of the turret by the operator provides the patient, who has a large refractive error, with an adequate image of the target, without altering the position of the objective's working plane.

While precise fixation of the red dot target is not critical, it is important that corrected acuity, adequate to direct the patient's visual axis toward the target, is available. With alignment of the NCT to the cornea, this will insure that the air-pulse, which is
coaxial with the alignment system, will be delivered approximately perpendicular to the corneal vertex.

**Secondary Automatic Alignment Verification System.**—An air-pulse that is delivered obliquely to the central cornea—that is, when the dot lies outside the limits of the aiming circle—would lead to a falsely increased measurement. The automatic alignment verification system (A AVS), therefore, is designed to preclude the possibility of taking a measurement when the red dot alignment (and fixation) target lies outside of the aiming circle.

The AAVS consists of light emitting diode (LED) located in a plane optically equivalent (conjugate) to that of fixation and alignment target F; mirror (M); collimating lens (TLc); microscopic objective (O); telescopic lens (TLt); diroic mirror (B1); and detector (D2), which lies in a plane conjugate to that of the aiming circle (G).

An image of the infrared LED is formed in the WP and superimposed on the red dot image. When the NCT is properly aligned with the cornea, the virtual LED is also reflected back toward G. The infrared light, however, is intercepted by B1 and imaged on D2. The emitter (LED) and detector (D2) aperture sizes are so related that the detector functions automatically, in the same manner as G is utilized visually, to permit IOP measurement only when the visually effected alignment satisfies spatial tolerances bounded by the diameters of G and D2.

The integrated systems are mounted to a slitlamp type base that, with horizontal control lever and separate elevator control, facilitates alignment with the patient's eye (Fig 7).

**Operating Principles**

Consider the interaction of the NCT with the eye. Following alignment of the instrument with the cornea, when the event trigger switch (located in the elevator knob) is depressed, a 3-msec pulse from LED (AAVS) facilitates assessment of the alignment. If alignment is found to be inadequate, no air-pulse will be discharged. If, on the other hand, alignment is found adequate, an air-pulse is initiated, and an increasing linear force-time ramp (Fig 3) impinges upon the cornea, producing a progressive reduction in curvature.

Applanation is sensed by the AMS as a maximum signal (Fig 6) and is identified at the time of occurrence by associated circuitry. The parameter that is measured is the time interval to applanation, as measured from a fixed temporal index related to piston position.
A direct linear relationship has been observed between IOP and time interval to applanation. An oscillator clock of empirically determined frequency, whose every beat advances a two digit numerical display one count, facilitates the translation of the applanation time interval into a digital display in millimeters of mercury. A detailed discussion of the empirical determination of the clock’s frequency is presented under the section “Calibration.”

Figure 8 is a composite representation of three oscilloscope displays that were held in memory and then recorded. Curve No. 1 shows the force transducer output display of the sensed air-pulse. On the left, curve No. 2 is the applanation spike of an eye with an IOP of 17 mm Hg. The next spike signal (No. 3) is that of an eye with an IOP of 36 mm Hg. Intraocular pressure is proportional to the time of the spike and to the height of the air-pulse display at the instant of the spike. Intraocular pressure is unrelated to the amplitude of the spike itself, which is determined by the dimensions and reflectance of each cornea at the moment of measurement.

An investigation, using high-speed 16-mm motion picture film was conducted to determine if indeed the applanation spike peak was coincident, in time, with a discrete corneal applanation configuration. A dual optical input high-speed motion picture camera was employed to simultaneously record the corneal profile as well as the time-associated AMS amplified signal, as displayed on an oscilloscope.

Using two subjects, many sequences were filmed, at a rate of 5,000 frames per second. In some of the sequences, the corneal profile was recorded, in others, an oblique view of the corneal vertex was filmed in order to observe the formation of the concavity following applanation. In both cases, the oscilloscope display of the corneal curvature monitor was filmed.

The films demonstrate (with a one-frame uncertainty) that the spike-peak occurs simultaneously with applanation. Further, the oblique-viewing series demonstrates that the concavity starts to develop during the frame immediately following applanation.

The spatial relationship of the alignment and applanation monitoring systems is shown in Fig 2. The intersection of the axes of the transmitter and receiver (T and R) occurs on the common axes of the alignment and pneumatic systems and at a point that is 7.7 mm inside of the working plane (WP) of objective (O). It follows, then, that when the NCT is aligned with a cornea having a central radius of 7.9 mm, the vertex of the applanation monitoring system lies at the planated surface. For corneal radii longer than 7.9 mm, the intersection occurs inside the cornea; for shorter radii, it occurs in front of the cornea. The consequence, in either case, is that the area of the monitored applanated surface is shifted laterally from a nominal central position, even overlapping parts of the undisturbed cornea in extreme corneal curvatures.

Clinical experience and deliberate study have shown that, within the range of curvature and astigmatism that has been encountered, NCT measurement is independent of corneal curvature. This independence is largely due to two factors: (1) While the applanation spike amplitude is dependent upon corneal reflectance and total planated area monitored, temporal detection of the occurrence of applanation—the spike-peak—is virtually independent of amplitude. (2) Figure 9 is a shear interferogram of the air-pulse. It demonstrates that the air-pulse undergoes minimal dispersion in cross-section over a considerable axial range, at a distance of 11 mm from the orifice. To enhance phase contrast, dichlorodifluoromethane (Freon) was used instead of ambient air and the time of photographic exposure was 40 msec. Both factors contribute to exaggerating the actual dispersion that takes place. In short, the brief air-pulse is well "collimated."

While we have not, in the clinical situation, encountered the limits of
curvature that may be measured, geometric and signal-to-noise considerations indicate that the NCT has the capacity to measure corneas having a radius of curvature that lie between 6.4 and 8.8 mm. The NCT alignment procedure in cases of high corneal astigmatism is to effect axial focus between the two meridional foci.

**Calibration**

Random populations offer a low incidence of elevated pressures. In order to facilitate a full pressure-range calibration, a technique using the ophthalmodynamometer to artificially elevate IOP was employed on normal subjects. The resources of the Glaucoma Clinic of the Edward S. Harkness Eye Institute, Columbia-Presbyterian Medical Center, were also utilized to provide high IOP data.

In the first technique, a Baillart ophthalmodynamometer was successively applied to the temporal side of the globe at three force levels (dial indicator settings). At each setting an NCT measurement was executed. The same three force levels were again successively applied to the globe, while determinations using the Goldmann tonometer were made. With normal IOP included, four measurements were obtained from each normal eye. Topical anestheia was applied for all measurements.

Comparative data were also collected in the Glaucoma Clinic. In this procedure, NCT measurement, made without anesthesia, preceded routine Goldmann applanation tonometry.

The NCT has been calibrated by determining the time interval associated with any given IOP, as identified by Goldmann applanation tonometry. With the linear time vs IOP relationship established for the specific air-pulse ramp slope (Fig 3), a quartz crystal-driven oscillator (clock) was designed so that its period—the interval between two beats—was equivalent to the increment of 1 mm of IOP. The oscillator is employed to drive the two-digit display so that each “beat” advances the numerical readout one count, or 1 mm Hg.

During the accumulation of calibration data, an oscillator frequency higher than the anticipated requirement was used to assure adequate temporal resolution. From the accumulated data, a regression equation was computed in the form, $NCT = aG + b$, where $NCT$ is readout in counts; $G$ is intraocular pressure, measured by Goldmann applanation tonometry; $a$ is the ratio by which NCT and $G$ are related; and $b$ is the NCT intercept in counts at zero $G$, due to inappropriate initial temporal location of the counting index.

For each count of NCT to be equivalent to a 1 mm Hg increment, the counting frequency employed in these studies had to be modified by a factor of $1/a$. For the air-pulse ramp depicted in Fig 3, this empirically determined frequency is 8,789 counts per second, or approximately 9 counts or 9 mm Hg/msec. The counting index was adjusted to commence after an offset indicated by the value of $b$ so that the normalized regression curve passes through the origin (0,0), with NCT = $G$.

A feature is incorporated in the NCT to enable the operator to quickly determine at any time whether the integrity of the instrument’s calibration is intact. Calibration integrity ultimately depends on exact repeatability of the air-pulse ramp slope. The slope of the ramp depends, in turn, on the velocity of the piston. A solid state emitter and detector pair, facing each other across a chord in the cylinder’s inner diameter, are utilized to indicate the traversal time of a fixed length of the piston past the monitoring station. When the NCT is used in its self-test mode, the traversal time is digitally displayed, using a counting frequency higher than that used in the normal operating mode in order to provide better resolution. Appearance of a specific number assures the integrity of the pneumatic system, as well as all of the associated logic circuitry used in IOP measurement.
Clinical Evaluation

Starting in April 1972, a clinical evaluation study was conducted in the Glaucoma Clinic and in the private practice of one of us (M.F.). In this study, all NCT measurements were made by a new technician who had no previous experience or background in the ophthalmic field. She required approximately one hour of instruction in the use of the NCT and was then able to obtain satisfactory readings. In general, three NCT readings were taken on each eye, without use of anesthesia. This was followed by routine Goldmann measurements made by one of us (M.F.), with use of anesthesia. The averages of the NCT measurements were used in the statistical computations. Patients who were unable to see the target or who had corneal scarring were excluded from the study.

Data on 570 eyes were collected; the findings are shown on the scattergram (Fig 10) where NCT is plotted on the ordinate and Goldmann measurements on the abscissa. The standard deviation of differences (SD) is a measure of the error or difference between pairs of NCT and Goldmann measurements. In the computation of the SD, all error is attributed to the NCT; Goldmann tonometry is considered to be the error-free variable. The data demonstrate very close agreement between the means, a high coefficient of correlation (0.9), and a relatively small SD (2.86 mm Hg). It is evident that the NCT has been successfully calibrated against the Goldmann tonometer.

Observations

Several studies were conducted to determine if the impact of the air-pulse upon the eye produced any adverse effects. The following are some of the results obtained:

1. Exposure of one eye of each of four rabbits to 24 successive NCT measurements produced no change in the tenacious blood-aqueous barrier of these animals, as determined by aqueous humor protein content. The second eyes were used as controls.

2. Slitlamp fluorescence examination of human corneas, following at least 12 successive NCT measurements, showed no epithelial disturbance.

3. Thirty successive measurements, made 5 to 10 seconds apart, produced no statistically detectable reduction in human IOP. Evidently, the extremely brief impact time of the air-pulse does not cause any significant increment in outflow.

From the high-speed motion picture studies (described in the section "Operating Principles," it was determined that the diameter of the applanated corneal area is 3.6 mm (with an uncertainty of 0.2 mm). Calibration of the force transducer used to produce Fig 3 led to the determination that 1.4 gm is utilized to applanate each 10 mm Hg of IOP. Since the NCT applanated area is approximately 40% greater than that applanated in Goldmann tonometry, which employs 1.0 gm/10 mm Hg, the force per unit area is approximately the same for both instruments.

Examination of clinically acquired data, as well as data from studies of the repeatability of IOP measurements, reveals that the average total spread of six successive determinations on a given eye lies between 2 and 3 mm Hg. Because the measurement is randomly made during a very small interval of the cardiac cycle, a large component of the total spread appears to be due to unpredictable sampling of the pulse pressure variation.

Throughout our clinical experience, we have encountered a small number of patients who have manifested large spreads in a series of measure-
ments on the same eye. Some were clearly tense, anxious "squeezers." In some of these cases, repeat measurements after the patient became relaxed demonstrated considerable reduction in the spread. This phenomenon may be encountered in any method of tonometry.

It is worth noting that, within the accumulated experience of the authors, discomfort was very rarely reported. In some instances, patients expressed surprise after the measurement, and a few said they had been startled. This reaction can be minimized by allowing the patient to experience the discharge of an air-pulse against his finger prior to NCT measurement on his eye.

**Comment**

Our experience clearly demonstrates the validity of this new method of applanation tonometry. The time interval required for an air-pulse to applanate the cornea can be determined, and this time interval is, in fact, proportional to IOP. Furthermore, the procedure can be accomplished within a few milliseconds and is therefore completed long before intervention of the blink reflex. This type of extremely rapid measurement does not induce any significant effect upon intraocular pressure, even when repeated several times. In essence, it has been proven that applanation tonometry can be accomplished by an instrument which does not touch the eye.

The specific instrument described in this report effectively utilizes this new approach to applanation tonometry. It can be safely used on a routine clinical basis, without use of topical anesthesia. It has been calibrated against the Goldmann applanation tonometer, and the clinical results demonstrate a close correlation between NCT and Goldmann readings in eyes having clear, smooth corneas and ability to see the fixation target. The greatest discrepancies occur at very high pressure levels, where the NCT tends to produce a reading somewhat higher than the Goldmann tonometer. This type of discrepancy has little, if any, clinical significance. It is evident that the NCT yields measurements which are valid for routine clinical tonometry.

Certain characteristics of the NCT provide advantages over other tonometers for specific purposes. First, there is no contact between the instrument and the eye, and measurement is painless. Hence, topical anesthesia is not required and there is no risk of microbiological contamination due to transmission of infections such as epidemic keratoconjunctivitis. Second, the procedure can be easily and rapidly learned by any individual of average intelligence and dexterity, even in the absence of previous ophthalmic experience. Third, repeated measurements produce no significant alteration in corneal integrity or IOP.

The NCT is clearly a superior instrument for glaucoma screening programs, and it will be very attractive to the optometric practitioner. There are several potential applications for the NCT in ophthalmology. Tonometry could be easily delegated to technician-assistants in eye clinics and busy offices; this procedure would be a time-saving device for ophthalmologists. The NCT could also be used by ancillary personnel to obtain around-the-clock tensions, whenever such data are needed. The NCT is preferable to other tonometers with certain types of patients, such as patients who will not submit to instillation of eyedrops, "squeezers," those with infected eyes, and children (willing and able to fixate). In clinical studies where frequent measurements are required to monitor some type of effect on IOP, the NCT would be an ideal choice because repeated use of other tonometers would tend to disrupt the corneal epithelium and reduce IOP.

There are certain limitations to the applicability of the NCT that must be stressed. It was designed primarily for eyes with clear, smooth corneas able to see the fixation target. It is not the best tonometer to use on eyes that do not meet these requirements. It must be regarded as inaccurate whenever it deviates from the Goldmann applanation tonometer, which served as the standard for calibration of the NCT.

NCT measurement of eyes with corneal edema, scarring, or other irregularity has proven to be difficult and, at times, impossible. Often, in these cases, the corneal reflectance is inadequate to satisfy the requirements of the AAVS. In those cases where such corneas still provide adequate reflectance to allow visual alignment, the NCT can be operated in an optional override mode that disables the AAVS, thereby permitting measurement. Clinical experience in such cases has shown that where measurement is possible, there are often large discrepancies between repeated readings on the same eye, and the IOP cannot be determined with any degree of confidence.

An eye whose corrected vision is inadequate to see the fixation target presents a problem in alignment. Where a measurement is made on a misdirected eye, the air-pulse is delivered obliquely, and part of the force is ineffectively vectored tangential to the cornea, thereby requiring greater force (or time) to achieve appplanation. Therefore, misalignment causes erroneously high NCT readings. For the unilaterally blind patient, an external fixation light may be presented to the sighted eye, in order to assist in alignment of the blind eye. Multiple measurements should be made with the blind eye in slightly different positions. Since errors are always on the high side, the lowest reading is the best determination.

It is worth repeating that the NCT is not the best tonometer for use on eyes with cloudy corneas or low visual acuity. In patients with clear corneas and vision, the NCT has proven to be an accurate and reliable instrument.

**References**