On the consistency of tonography

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Sixty tonograms of 10 to 40 minutes' duration were analyzed by calculating the outflow facility estimate obtained at each successive minute and during the first 4 minutes with the use of Grant's tonographic equation. The tonographic tracing was found to be a negative exponential function, which, only rarely, is appropriately approximated by a straight line in the first 4 minute segment. It is best delineated by a smooth curve passing through the majority of points in the tracing.

This study showed that the 4 minute estimate of outflow facility is a good representative of similarly calculated estimates of outflow facility prevailing during each individual minute. It also showed that within this framework no modification or alteration can be expected by prolonging tonography for periods longer than 4 minutes, and that such modification should be sought in the basic framework of tonography.

In order to obtain a numerical estimate of outflow facility by tonography, a number of assumptions had to be made; the following are relevant to this presentation:

1. That outflow facility and inflow rate of aqueous are independent of pressure and remain unchanged during tonography.
2. That the progressive reduction in the raised intraocular pressure during tonography is caused by the increased outflow rate of aqueous.
3. That the validity of the Friedenwald calibration of the Schiötz tonometer holds equally well in the prolonged tonography as it does in short-lasting tonometry.
4. That the flow of aqueous through the trabecular meshwork is linearly related to the outflow pressure gradient.

These assumptions permit the use of the Schiötz tonometer calibration to calculate the change in intraocular volume during tonography and to obtain a numerical estimate of aqueous outflow facility with the use of the equation:

\[ C = \frac{\Delta V}{T(\text{average } P_t - P_o - 1.25)} \]

Wherein:

- \( C \) represents outflow facility in microliters per millimeter of mercury per minute;
- \( \Delta V \) represents the change in intraocular volume in microliters;
- \( T \) is the duration of tonography in minutes;
- \( P_t \) is the intraocular pressure during tonography;
- \( P_o \) is the intraocular pressure in the undisturbed eye before tonography; and
- 1.25 is the average increase in episcleral venous pressure during tonography.

The following reported findings have encouraged acceptance of the validity of the above assumptions:

1. The estimate of outflow facility obtained by tonography is similar to that obtained by perfusion.
2. If tonography is prolonged, \( P_t \) approaches \( P_o \).
3. \( C \) values estimated at 2 minute in-
trials from a 6 minute tonogram did not differ significantly from each other or from that calculated from a 4 minute interval. However, experimental evidence has been provided to show that outflow facility and inflow rate of aqueous are pressure dependent, that the formulation of Friedenwald's pressure-volume relationship may not apply to the intact human eye, and that the stress-strain relationship is time and pressure dependent.

The shape of the tonographic tracing has been reported differently by different workers. Grant reports a progressive increase in scale reading which is virtually linear, and, hence, does not hesitate to draw a straight line throughout the tracing in order to determine the appropriate beginning and end of the tonogram. Linner, among others, reports a nonlinear exponential increase in scale reading during tonography, which is exaggerated, but not exclusively produced, by changes in systemic arterial pressure. A detailed analysis of the phenomenology of the tonographic tracing and of the various sources of error was recently reported by Goldmann. The finding that the rate of pressure reduction is greater at the beginning of tonography led to a variety of speculations implicating the reduction in intraocular blood volume at the beginning of tonography, a suppression of inflow rate by increased intraocular pressure, the actual compression and indentation of the cornea by the tonometer plunger, as well as the stress-relaxation of the ocular coats during tonography.

Accordingly, different attempts have been made to improve the tonographic estimate of outflow facility. Goldmann attempted to eliminate the effect of compression on the cornea by the tonometer plunger by using two adjacent lights for fixation. After 90 seconds, fixation is changed from one to a second light in order to bring an uncompressed area of the cornea under the plunger, thus obtaining a measure of corneal compression which he then used in correcting an 8 minute tonographic tracing. Prijot proposes a 6 minute tonography in which the first 2 minutes are discarded, with the expectation that the process of "creep" has been consumed, and uses the 2 to 6 minute interval to calculate the C valve. Leydhecker doubts the physiologic significance of C value in tonography because of the existence of many uncontrolled and unmeasurable variables, and calculates a value from the beginning of the third to the seventh minute of tonography which, admittedly, is devoid of physiologic content but is nevertheless reported as being useful in separating the normal state from glaucoma. Van Beuningen proposes an extension of the linear portion of the tonogram to the left in order to avoid the curvilinear portion and delineate what would have been caused by aqueous outflow only.

The purpose of the present investigation is to ascertain the need for modifying Grant's method of tonography, and to seek, within the framework of tonography, evidence of significant trends of change in parameters not taken into account in the tonographic formulation. This was attempted by examining the C values calculated for each successive minute in tonograms of 10 to 40 minute durations. The results of this investigation revealed a surprisingly good consistency between the tonographic assumptions and the calculated C values, and pointed out that, within the framework of tonography, the above-mentioned processes are not detected nor are they eliminated by prolonging the tonogram, and that the tonographic tracing is primarily a decreasing exponential function which, on occasion, may approach a straight line, when a 4 minute segment is considered.

Sample

The sample consisted of 60 subjects who showed excellent cooperation and tolerance to prolonged tonography, and who had no evidence of past ocular surgery. Of these, 54 had normal visual function and 6 had open-angle glaucoma. All were over the age of 40 except 16 normal subjects whose
ages varied between 20 and 30 years. The ratio of males to females in the entire sample was 3:1.

Procedure

Tonography was performed with the use of the Mueller electronic tonometer coupled to a Leeds and Northrup recorder, in a manner described previously, with proparacaine for topical anesthesia. One long tonogram was obtained on each subject. In 10, the long tonogram was obtained on the second eye after a 4 minute tonography had been performed on the first eye. This was done in order to find out whether the differences in C values between the first and second eyes, reported previously, could be due to a difference in tonographic tracing.

Analysis of records

Samples of tonograms appear in Fig. 1. At the end of each minute the scale readings was calculated from the midinterval of the pulse wave at that time. There was no attempt to smooth the tonographic tracing. Scale readings were recorded to the nearest quarter of a division. For each reading, the $P_t$ value (intraocular pressure during tonography) and the $\Delta V$ (change in ocular volume) were calculated from the tables for $P_t$ and $\Delta V$ published by Moses and Becker; these tables were made to read in intervals of a quarter of a division by using the arithmetic average of the readings at half scale intervals in the published tables. Similarly, the $P_o$ reading at the beginning of tonography was obtained from appropriate tables. For each minute interval, the C value was calculated from the equation:

$$C = \frac{\Delta V}{\text{Average } P_t - P_o - 1.25}$$

Wherein:

$\Delta V$ and $P_t$ represent the change in intraocular volume and the average intra-

Fig. 1. A and B represent samples of long tonograms obtained in the study. Scale readings were read at the end of each minute and converted to appropriate $P_t$ and $\Delta V$ values. The $P_t$ values were then plotted to describe the decay of $P_t$ in Figs. 2 to 9.
ocular pressure, respectively, during that minute; \( P_o \) is the intraocular pressure in the undisturbed eye calculated from the reading obtained at the beginning of the tonogram; 1.25 is the average increase in episcleral venous pressure during tonography.

In addition, the C value was calculated for the first 4 minute intervals in the usual manner employed in tonography. Samples of the results appear in Figs. 2 to 9.

**Comments**

The tonographic tracing. It was evident in all long tonograms that the tonographic tracing is not a linear increase in scale reading. This held true even when only a 4 minute segment of the tracing was considered. Attempts at forcing a straight line over the first 4 minute period of these tonograms leaves one with a variety of alternatives, each giving a different C value, and, yet, each equally well fitting the tonographic tracing. From this standpoint, it seems warranted to caution against such a procedure, where many alternative straight lines can be drawn, and to recommend a procedure of accepting the tracing as it is, attempting to draw a smooth curve throughout the entire record. This is espe-

![Fig. 2. Upper tracing: Decay of intraocular pressure during tonography \( P_t \). Lower tracing: C values calculated for each minute of tonography. Interrupted horizontal line represents the C values calculated in the usual manner from the 0 to 4 minute segment of the tonogram. \( P_t \) ordinate on left-hand side; C value ordinate, right-hand side; abscissa represents time of tonography in minutes.](image)

![Fig. 3. Same as Fig. 2.](image)

![Fig. 4. Same as Fig. 2.](image)
cially warranted since, when the tracing is considered in this manner, the 1 minute C value showed excellent consistency with the average 4 minute reading; a finding which is in agreement with the expectation of tonography.

**One minute versus 4 minute C values.** The C values calculated for successive intervals of 1 minute showed excellent agreement with the 4 minute C value in the vast majority of tonograms. In 54 tonograms, the arithmetic average of the 1 minute C value of the first 4 minutes did not differ from the 4 minute value by more than 6 per cent. This excellent agreement continued to exist when the first 6 minutes were considered. In 5 tonograms, the agreement was within 10 per cent. In all tonograms, it was within 20 per cent. In view of the fact that these tonograms were not smoothed in order to eliminate the effect of respiratory waves and other transients of the tonographic tracing, this finding, indeed, reflects an excellent agreement between the individual 1 minute value and the 4 minute values, and warrants the conclusion that the latter, in tonography, is a very good average value of the prevailing outflow facility estimates throughout the entire period. This also shows that extending the tonogram for an additional 2 minutes does not improve upon the 4 minute estimate.

**The change in 1 minute C values with time.** In considering the variation in the individual 1 minute estimates throughout prolonged tonograms, three trends became apparent:
1. The individual 1 minute determinations varied around the 4 minute value in a random manner. This was the case in 52 tonograms (Figs. 2 to 5).

2. The 1 minute C values became progressively smaller with time (Figs. 6 and 7). This occurred in 3 tonograms.

3. The 1 minute C values became progressively larger with time (Figs. 8 and 9). This occurred in 5 tonograms.

Thus, in the majority of tonograms there was no evidence of a systematic trend or change in the 1 minute values indicative of a change in parameters not accounted for by tonography. This is in agreement with the formulation and expectation of tonography. Thus within the framework of tonography factors such as the reduction in intraocular blood volume, suppression of inflow, stress-relaxation, and compression of the cornea by the tonometer plunger are not detected in the tonographic tracing. For, if these processes were manifest, a progressive reduction in C values with time should then become evident; the reason being that these processes have a time course, beginning with tonography, and are time dependent, so that their effect becomes progressively less with time. If their effect were superimposed on a constant C value, then the 1 minute values should have shown a progressive reduction with time to reach a constant level. This was not the case in the majority of tonograms; only 3 demonstrated this tendency. This absence may be due to the poor sensitivity of tonography, the small magnitude of the effect of these processes, or the simultaneous occurrence of counteracting mechanisms.

There was no difference in the trends manifested in males and females, normal or glaucomatous eyes, different age groups, or first or second eyes. Thus, differences in C values among these groups cannot be explained by differences in the tonographic tracings. The last two trends, occurring in 13 per cent of subjects, are not consistent with the expectations of tonography. Their interpretation within the framework of
tonography implicates a change in the dynamics of the steady state during tonography.

**Extension of pressure decay curves.** In order to check the contention that, if tonography were sufficiently prolonged then $P_t$ would become equal to the steady state pressure, which, in this case, will be $(P_0 + 1.25)$, the decay of $P_t$ curves recorded from the tonographic tracing was smoothly extended until an asymptote was reached. The following two trends were detected:

1. When the 1 minute $C$ values showed no change with time or became progressively less, the extended $P_t$ curve attained a level 3 to 6 mm. Hg higher than the expected $(P_0 + 1.25)$. Stepanik\(^{20}\) reports that when he calculates the $P_t$ at infinity, by treating the $P_t$ curve during tonography as a decreasing logarithmic function, he finds that this value, which he calls $P_x$, is higher than $P_0$.

2. When the 1 minute $C$ values showed a progressive increase with time, the extended $P_t$ curve attained a level 1 to 4 ml. lower than expected.

This finding does not seem to be consistent in tonograms where the 1 minute $C$ values continued to remain constant. However, it should be pointed out that the sensitivity of this method is such that if one were to force a curve ending at $P_0 + 1.25$ and passing through the beginning of the tonogram, the necessary changes in the tonographic curve would still be within ± 15 per cent of the $P_t$ values, a range undesirably large for proper curve fitting, which might prove acceptable when the over-all formulation of tonography is tested. No further attempt at curve fitting was made in this study because of the inherent difficulty in writing, analytically, the expected pressure decay during tonography. This is being investigated in perfused, intact human eyes and will be reported in future publications.

In conclusion, the experimentally demonstrated trends and characteristics of the eye, which are at variance with the tonographic formulation, were not detected when the internal consistency of tonography was examined in prolonged tonograms. Until such trends can be demonstrated and accounted for by a method other than tonography, attempts at their correction or elimination within the framework of tonography are bound to be futile and at best unenlightening.

**REFERENCES**