References

1. G. Cocconi and P. Morrison, *Nature* **184**, 844 (1959).
2. *Science* **131**, 1303 (29 Apr. 1960).
3. W. M. Sinton and J. Strong, *Astrophys. J.* **131**, 459, 470 (1960).

13 May 1960

Automatic Tonometer with Exact Theory: Various Biological Applications

Abstract. Methods for externally measuring pressure within body cavities exist. In tonometer form they are fast and gentle not requiring anesthetics for the cornea of the human eye. Readings are accurate and independent of tissue tension, corneal stiffness, astigmatic curvatures, and surface tension. There are also separate indications of corneal rigidity and relaxation, and tonographic fluid expression. Other applications include monitoring blood pressure, uterine contractions, and infant intracranial pressure.

The classical methods for measuring the pressure within the human eye have involved a measurement of the force required to flatten a given area or a measurement of the corneal indentation produced by a given weight-loaded rod (*1*). Though ophthalmologists learn to make clinical evaluations from such readings, these procedures are somewhat cumbersome and inaccurate. Inexactness is introduced into the readings by corneal effects such as rigidity and the tension in the tissues tending to resist indentation. The magnitude of this effect seems to be rather variable, and thus an uncertainty is introduced into any reading. On the other hand, the surface tension of the tears tends to pull the probing member toward the eye. In the diagnosis of glaucoma it is desirable to observe intraocular pressure alone: this is made possible by the new tonometer that we have devised and demonstrated, since the aforementioned and other extraneous factors are eliminated (*2*). Besides this increased accuracy, the readings are taken more quickly, more gently, and from any position, without the help of expensive auxiliary equipment such as slit lamps.

In Fig. 1 the principle of one form of our device is illustrated. The end of a small, hand-held probe is pressed against the eye. The tip of the probe carries a pressure-sensitive area approximately 1 mm across. If the eye is momentarily flattened to beyond this sensitive area, then, according to first-order theory, the only pressure that will be recorded is the intraocular pressure of the eye. It will be seen from the figure that a high pressure will press down upon the force transducer, which can be a ferrite core that can move toward or away from a coil, thereby varying the coil's inductance. This variation in the position of the core is detected and amplified, causing a variation in current in a coil whose purpose is to exert a restoring force on a small permanent magnet also coupled to the moving system. Thus an increase in pressure will cause an increase in restoring force which will maintain the pressure-sensitive area rather accurately in the plane of the surrounding plate. The measure of force is the current that is recorded as passing into the restoring-force coil. The sensitivity of the detector is 100 mv/μ, and the deflection of the plunger is 0.6 μ for an intraocular pressure of 40 mm-Hg.

The force required to bend the cornea is exerted beyond the sensitive region and is not recorded. For this reason astigmatism and eye size do not enter: the device can be applied with accurate results to the eye of rabbit or man. Tensions in the tissues are tangential forces that are not recorded by the pressure-sensitive area. Surface tension merely pulls the whole probe against the eye a bit harder and does not influence the reading. The end of the probe can be covered by a thin, disposable, sterilizable, rubber membrance without invalidating the reading, but this membrane must be thin, for its presence slightly decreases the sensitivity of the instrument.

The measurement can be recorded or stored electronically in a number of ways. The most convenient and reliable is simply to record the current that measures the force on the sensitive area, as a function of time, on a strip-chart recorder. A representative recording is shown in Fig. 2. As the hand advances the probe against the eye, the indicated reading increases as the flattened region gradually expands to cover the sensitive area. Once the sensitive area is covered, a further increase in total force applied to the probe will cause expansion of the flattened region out over the surrounding plate which then sustains the bending forces which previously acted on the sensitive region. Thus the increasing reading rises to a crest and then drops down into a trough. A further increase in flattened area will raise the intraocular pressure and thus cause a new rise. The crest amplitude is the result of both pressure and bending forces and thus is the reading that is obtained by the classic aplanation tonometers such as that of Goldmann. The reading at the trough is the true pressure reading for the given flattening without the effect of bending forces. Thus the crest-trough difference is a measure of corneal rigidity. It should be mentioned that minor decentering of the sensitive area with respect to the cornea can result in degrading the maximum into a plateau at trough height. In either circumstance measurement from the baseline to the height of the trough or plateau is a measure of intraocular pressure that is absolute and relatively independent of extraneous factors. As the probe is withdrawn the sequence of events reverses itself. The traced out pattern is essentially symmetrical about its center except that the second trough is generally lower than the first. It is assumed that this results from corneal relaxation and a decreased intraocular pressure during the reduction of aplanation following the expression of some fluid. A comparison of dip height advancing and receding measures corneal relaxation, while comparison of trough height advancing and receding measures the rate of expression of fluid during the interval. The height of the central bump in the tracing is a measure of the elevation in pressure due to the tonometric observation. Measurement of the rate of advancement of the probe against the cornea gives the rate of change of volume of the eye which, in conjunction with the rate of change of pressure, yields more information than classical tonography; we call this metrotonometry.

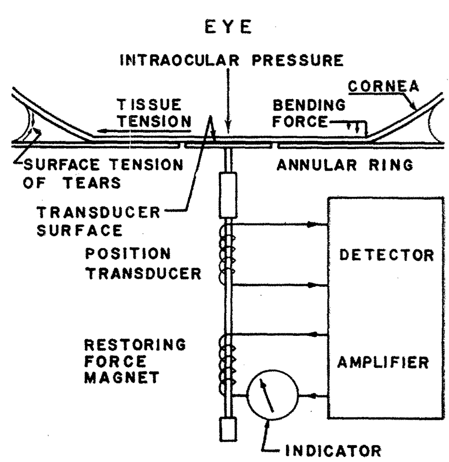

Fig. 1. If the cornea of the eye is flattened against a probe to beyond the pressure sensitive region then the only force that will be recorded will be intraocular pressure, since such factors as corneal rigidity exercise their force beyond the periphery of the sensitive region. Any tendency towards motion in the displacement transducer is detected and amplified to produce a restoring force that holds the pressure sensing piston coplaner with the surrounding region. The restoring-force current is recorded as a measure of intraocular pressure.

In developing this instrument there was some question about the ideal size for the central pressure-sensitive area. Other workers trying to make various extraneous factors effecting the aplanation tonometers cancel out had settled upon a flattened area of 3 mm. Thus our first experiments made use of a

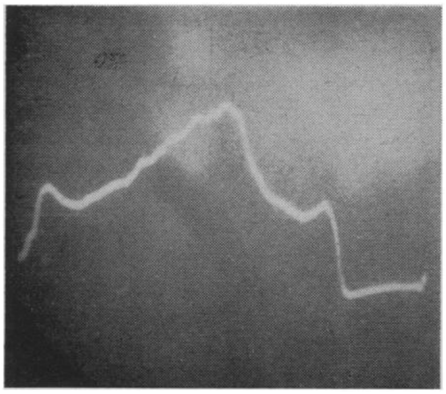

Fig. 2. Representative record traced by a recorder connected in the meter position of Fig. 1 as the probe is advanced against the cornea of a human eye and then withdrawn. The height of the trough measures intraocular pressure and the magnitude of the dip is a measure of corneal rigidity. The first trough indicates 17 mm-Hg, the second, 15 mm, because of the expression of fluid during the interval which was 1 second over-all.

piston 2 mm in diameter and employed a flattening of the eye over a diameter of 3 mm. However, it now seems desirable that both of these diameters be decreased by a factor of approximately two. This is desirable because it is not necessary to cancel extraneous factors which do not enter in the application of this instrument, and because the lessened diameter results in a smaller artificial increase in pressure due to the process of application. To make an accurate interpretation of the cause of the dip in the response curve shown in Fig. 2 it was necessary to perform a series of experiments with specially constructed tonometers having variable piston diameter. From measurements made in this way it was possible to prove that the dip was not caused by buckling of the cornea, in the snap-action fashion of the bottom of an oil can. That is, since the dip was always found to occur at a degree of flattening corresponding to the diameter of the piston, it was proved that the cause of the dip was the expansion of the bent region to a perimeter beyond the margin of the plunger rather than the sudden formation of an inverted vault, which process would be expected to take place at a constant diameter for a given eye or not at all.

Other forms of the tonometer have been tested, and some have proved promising. Thus, forms in which there was no mechanical feedback have been constructed by using a rather stiff force transducer which would record the motion of the plunger while yet keeping the tip of the plunger essentially in the plane of the surrounding area. In any hand-held instrument it is desirable that the mass of all moving parts be kept to a minimum to reduce irregularities introduced by an accelerometer or seismograph effect. Other methods of recording the reading can be employed than the one indicated. Thus electronic circuits can be arranged to store the reading that exists as the current passes through its minimum.

These small probes have many applications in biological experimentation because of their ability to measure intracavity pressure through an intact tissue wall. One of the more obvious examples is the continuous monitoring of blood pressure through the intact wall of a blood vessel. There are sensitivity limitations in every case and these will determine the thickness and stiffness of the wall through which one can measure pressure, and these same factors will influence the most desirable size for the pressure sensitive region. The competing method of performing intracavity measurement is to employ the small swallowable radio transmitters that have been developed in recent years (*3*). But these cannot always be implanted where desired and so the two methods are usually complementary in being applicable to different cases. The primary intention for the present device is to make glaucoma survey more general and routine.

R. STUART MACKAY*
ELWIN MARG
RAYMOND OECHSLI

School of Optometry,
University of California, Berkeley

References and Notes

1. W. S. Duke-Elder, *Textbook of Ophthalmology* (Mosby, St. Louis, Mo., 1938), vol. 1, p. 406.
2. R. S. Mackay and E. Marg, *Acta Ophthalmol.* **37**, 495 (1959); *Electronics* **33**, 115 (1960).
3. R. S. Mackay, *IRE Trans. on Med. Electronics* **ME-6**, 100 (1959); **ME-7**, 250 (1960).
* Address: Radiological Research Laboratory, Univ. of California Medical Center, San Francisco.

18 June 1959

Density of the Lunar Atmosphere

John C. Brandt's paper (*1*) contains criticisms of an earlier note of mine (*2*) dealing partly with the same subject, and I have been invited to reply.

It seems to me that Brandt has greatly oversimplified the issue. The tenuity of the permanent atmosphere of the moon is beyond dispute, but I submit that comparatively large amounts of gas may be held by persorption in the porous or pulverous materials, or both, of the lunar surface (*3*), which is in the condition of permafrost at a depth of the order of 1 m (*4*). Since sorption decreases with rising temperature, some of this gas should be liberated by the heat of sunrays, forming a low atmospheric "skin," which is resorbed in the cold of the night. Thus, the lunar atmosphere in the lower selenographic latitudes may yet have in the daytime the ground density attributed to it by Lipsky, even though it is undetectable by Dollfus's method on the night side of the cusp, close to the first quarter, 200 km above the surface of a polar region (*5*).

There are further objections to this method. The gas is assumed to be CO_2 at 0°C, although the ground temperature in these conditions will be −150°C or less, so that most of the CO_2 would have been precipitated. A Wratten 12 filter was used, which suppresses the blue and violet part of the spectrum. Now, the most likely gas to look for in these circumstances is argon, considerable quantities of which should be produced, as was suggested by Shapley, by the decay of the radioactive isotope of potassium. Since argon is monatomic, as against the triatomic CO_2, an atmosphere of this gas will scatter primarily shortwave radiations and appear much "bluer" than one of carbon dioxide. The use of a Wratten 12 filter should make it largely invisible.

Costain, Elsmore, and Whitfield (*6*) have not published, to date, the full particulars of the method by which they estimated the upper limit of the ground density of the lunar atmosphere. Öpik (*7*) supplies some of the missing reasoning, but he is not very explicit either. The electron density will clearly depend on the assumed chemical composition. If the lunar atmosphere is chiefly composed of argon, an inert gas with a high ionization potential, it may not be ionized to any extent in depth, and this might wholly falsify the result. Moreover, on 12 September 1956, Rishbeth and Little observed an occultation of the discrete radio source associated with Kepler's nova (*8*). There was positive response when the source was still 3′ behind the lunar disk, a figure which is in excess of the previous estimates and which may indicate a refraction far above that found in the occultation of the Crab nebula.

For these reasons one should be chary of ascribing too much importance to these negative estimates, the more so as the density of the lunar atmosphere may vary with phase and lunar latitude.

Not having seen Chamberlain's unpublished paper, I am unable to express any opinion on its merits, but I see no reason to dissent from the results quoted by Brandt (*1*). Brandt's mathematical argument has been omitted from the thermofax copy of his report sent to me, but again I am prepared to accept it as correct within the assumptions he makes. It is his assumptions that I find questionable.

The interplanetary medium may con-