between the outer medium and the inner medium is smallest. For example, at temperatures of 0° C and higher, an ice bath for the outer medium is most economical; for temperatures of $-78°$ C and higher, solid CO_2 in alcohol or acetone works well; for temperatures of $-196°$ C and higher, liquid nitrogen can be used as the outer medium.

When only a set temperature, such as that of liquid nitrogen or solid CO_2, is desired, the metal chamber (*F*) between the Dewar flask and the aluminum cup can be eliminated from the device, thereby allowing the outer liquid to bathe the aluminum cup directly. This reduces boiling, particularly of the liquid nitrogen, and allows longer periods of irradiation without the necessity of replenishing the nitrogen.

For irradiation problems in which it is impossible to use a vacuum because of the type of material to be irradiated, but in which it is necessary to control contact with the atmosphere, one may simply insert the cup and close all connections, thereby assuring a definite, limited amount of air for all samples. One may flush the chamber with special gases, or one may irradiate with a flow of gas through the chamber.

The problems to which one can adapt this device are, in fact, many.

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An Oscillographic Plethysmograph Using a New Type of Transducer

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In recent years, several devices have been described for studying the circulation in the human digit (*1–5*). In order to detect the small pulsations in the digits of patients with obliterative arterial disease of the extremities, it was found that an instrument of much higher sensitivity than those previously developed was necessary. Since the mechano-optical systems already in use appear to have reached the limits of sensitivity for that type of recording, it was decided to explore the possibility of transducing mechanical into electrical changes and of magnifying such changes by means of vacuum tube amplifier techniques.

The high sensitivity of the RCA transducer tube (No. 5734) looked attractive at first, and it was incorporated into a suitable sensitive bellows. Although such a system had the desired sensitivity, the electric circuits for it required such a high degree of stabilizing as to make the system impractical for clinical use. The available unbonded pressure strain gauges were next explored. Although these possessed high degrees of sensitivity, they lacked necessary ruggedness, and at high amplifications artifacts commonly resulted from minute mechanical vibrations of the freely suspended resistance wire forming the bridge arms.

The principle of the bonded strain gauge was finally adopted in order to avoid the artifacts of the unbonded gauge. Since such a transducer suitable for plethysmography was not available, efforts were directed toward developing one.

A suitable cantilever beam was constructed of 24ST aluminum (selected for its low modulus of elasticity). Four sets of resistance wires were bonded to the cantilever, two sets on each side of the beam, and connected as a Wheatstone bridge.[1] Deflection of the beam in one direction or the other causes pairs on the opposite sides of the bridge to increase or decrease their resistances, thereby unbalancing the bridge. This electrical unbalance was the quantity amplified and measured. Rugged stops in the transducer prevented movement of the diaphragm and cantilever beyond safe limits.

At first the gauge, too, was attached to a sensitive bellows. After clinical testing, the bellows was rejected because it lacked adequate mechanical stability, was too easily excited by vibration, and had a highly undamped low frequency resonance. It became apparent that what was needed was a membrane or diaphragm that would move in only one plane, would have low inertia and low hysteresis, would be flexible linearly over a large range, and would have a low spring constant. Many diaphragms, both metallic and plastic, were studied, until one was finally built which met the requirements. It was made of bakelite-impregnated woven nylon thread shaped according to the general suggestions of the Bureau of Standards for barometer diaphragms. When this diaphragm was connected to the cantilever bearing the bonded strain gauge, a transducer was produced that fulfilled the desirable qualities outlined above (Fig. 1).

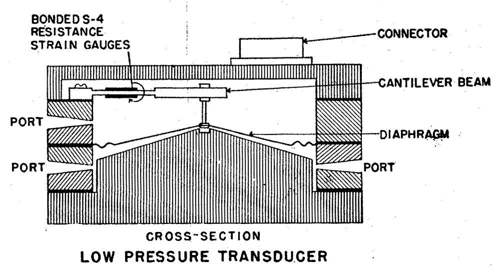

FIG. 1. Diagram of the Grass low-pressure transducer.

The transducer described is very rugged; serious damage does not occur even if it is dropped or otherwise mishandled. Mechanical resonance is in one direction only and is well above the frequency range of components of the circulatory pulse wave. It is inherently properly damped so that liquid transmission can be employed in most situations if indicated. Even with

[1] The process of bonding the resistance wire to a sensitive cantilever beam is intricate and requires long experience to obtain a hysteresis-free linear gauge. A. C. Ruge, who developed the Baldwin S-4 gauge, cooperated in performing this all-important operation.

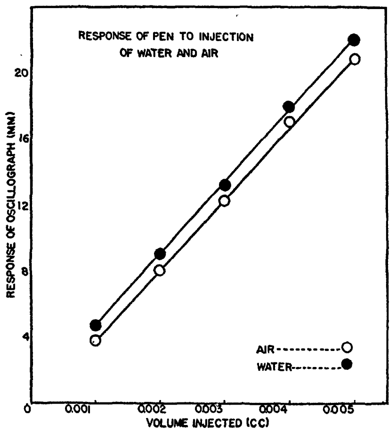

FIG. 2. Curves relating oscillographic response (ordinates) to volume changes within the transducer (abscissae). The curves show linearity of response at high amplification and close similarity of response when air (circles) and when water (dots) are used as transmission media. The same linearity and relationships are demonstrable when larger volumes of air or water and lower amplifications are used.

amplification to noise level no hysteresis can be detected. The transducer is stable, extremely sensitive, and is linear in response from pressures at least as low as 0.1 mm Hg to pressures of 20 mm Hg, the mechanical limit of the present transducers (Fig. 2). The over-all spring constant of the instrument and its large effective pressure area permit displacements of the diaphragm by large changes in volume without developing high pressures (Fig. 3). The transducer is therefore "volume-sensitive" and is particularly suited to studies of the peripheral circulation, because no back pressure is created that would interfere with the capillary circulation or would produce artifacts by pressure-displacement of the oncometer.

Because of the low spring constant of the transducer, and because of its large volume, there is little difference between the responses of the gauge when a compressible (air) or a noncompressible (water) transmitting medium is used. The ratio between air-medium and water-medium responses is 8 : 9 and is

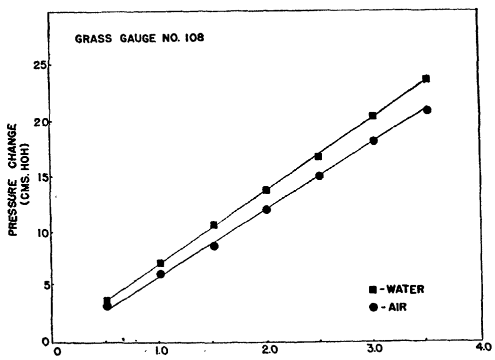

FIG. 3. Curves relating pressures developed within the transducer (ordinates) to volume of air (dots) and of water (squares) injected (abscissae). In dealing with such large volumes extremely low amplification had to be used (pre-amplifiers out of the circuit).

nearly constant over the whole range of responses (Figs. 2 and 3). Similar ratios for commercially available unbonded gauges, designed to measure relatively large pressure changes with very small changes in volume, vary from 1 : 10 to 1 : 2. When using the transducer described above, it matters little whether water or air is used as the transmitting medium from the oncometer to the gauge. Air is usually the more convenient.

The Grass Electroencephalograph was chosen as the amplifier recording system, since it is the most sensitive multichannel instrument that has the proper frequency range, and since it is generally available in medical facilities. It is modified by the addition to the standard instrument of a balance-demodulator unit which permits the recording of absolute electrically transduced volume changes by converting the electroencephalograph to a carrier frequency system. The unit contains the necessary balance for the strain-gauge bridge and energizes it with line frequency alternating current. The combined apparatus takes advantage of the high stability of this type of strain gauge and avoids the use of inherently unstable high-gain d-c amplifiers.

The demodulator eliminates the carrier alternating current from the signal after high amplification and at high signal level. The envelope of the carrier is the signal corresponding to the initial mechanical modulation of the transducer in response to changes in volume within the oncometer. The demodulated signal is direct-coupled to the grids of the last stage of the power amplifier which drives the oscillograph. The electrical sensitivity of the instrument is such that at high amplification a bridge unbalance of 0.1 μv results in a pen deflection of 1 mm. Unlike the electroencephalograph without demodulators, this instrument will record absolute values for volumetric changes with linearity of frequency response to at least 20 c/sec.

Three Luer-type ports are provided on the transducer (Fig. 1), any or all of which can be fitted with accurately machined plungers that can introduce known volumes (0.002 ml, 0.005 ml, and 0.010 ml) into the transducer which holds 5.0 ml, in neutral position. To avoid the difficulties of reading the calibration signal superimposed upon the pulse waves from the digit in the oncometer, the calibration may be done with the digit out of the system and the oncometer replaced by a syringe, the plunger of which is set at a volume corresponding to the volume of the oncometer minus the volume of the digital part being studied. The oscillographic response to the injected calibration volume will then be the same as would obtain if the known volume were injected into the system with the oncometer containing the digit, but minus the digital pulse (Fig. 4). In fact, since this is a volume-sensitive transducer, large variations in the total volume of the oncometer and transducer combined have very little effect upon the sensitivity of the instrument. For instance, increasing the volume of the entire system by 400% (5–25 ml) decreases the sensitivity to a 0.010 ml calibration by only 5.4%.

Therefore, minor errors introduced by inaccuracy of measurement of the volume of the system are insignificant.

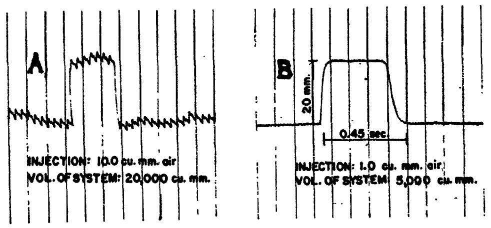

FIG. 4. Volumetric calibrations: *A*, Ten mm^3 air injected with digit in oncometer. Response to volume change is superimposed on digital pulse waves. *B*, One mm^3 air injected into "dummy" oncometer system minus the digit. Amplification at noise level. Note sensitivity and speed of response.

The demodulator is further equipped with a push-button switch which throws a known resistance across one arm of the strain gauge bridge for purposes of calibration. Once the oscillograph response to this signal has been matched with that from the volumetric plunger, this resistance calibrator can be used for conversion of the record to volume changes at any amplification throughout the experiment.

Lack of sensitivity in the instruments generally available has been a limiting factor in plethysmographic studies of the peripheral circulation in man. When reflex vasoconstriction is induced by exposure to an environmental temperature of 20° C, most patients with vasospastic disease, many patients with arteriosclerosis, and some normal individuals fail to show a recordable pulse wave. The sensitivity of the oscillographic plethysmograph is such that it fails to record a digital pulse wave only in far advanced arterial disease or in complete acute arterial occlusion. Under these conditions the digital blood flow may be nonpulsatile or nonexistent.

Fig. 5 illustrates records obtained in studies of the peripheral circulation in man. Section 1 of the figure shows the digital pulse wave in a normal subject.

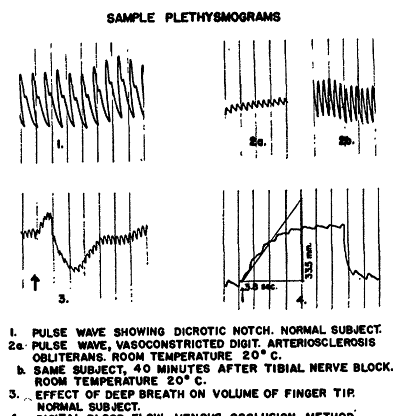

FIG. 5. Sample plethysmograms to illustrate application of the instrument to studies of the digital volume and pulse wave and to studies of the rate of blood flow in the periphery by the venous occlusion method.

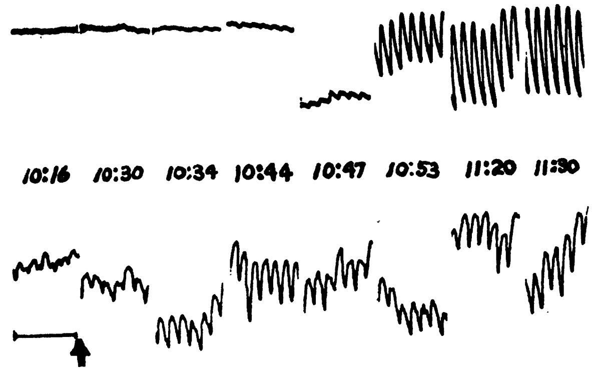

FIG. 6. Digital pulse waves from toes of a patient with severe arteriosclerosis. Environmental temperature: 20° C. At arrow (10:22 A.M.) both arms were immersed in constantly circulated water at 45° C. Upper record, left second toe; lower record, right second toe. Maximum pulse volume recorded represents 7.5×10^{-3} mm^3/10.0 cc of part. Time marker, 6 sec.

Greater detail of the pulse wave contour can be obtained with faster paper speeds. Slow changes in digital volume are accurately recorded (Sect. 3, Fig. 5) with suitable adjustment in the amplifier gain according to the magnitude of the volume change expected. The rate of blood flow in the digit can be measured by the venous occlusion method (Sect. 4, Fig. 5) with negligible artifact. The volume change is expressed in mm^3/10 cc of the part studied. The pulse wave obtainable in a patient with moderately advanced arteriosclerosis is shown in Section 2 of Fig. 5, illustrating a fivefold increase in pulse volume when the digital vessels were released from vasomotor control by blocking the posterior tibial nerve with procaine.

Fig. 6 is a record of digital pulse waves from the left (upper tracing) and the right (lower tracing) second toes in a patient with very severe arteriosclerosis. He had intermittent claudication in the right calf, but not in the left. No arterial pulsations were palpable below the femoral arteries. The nearly absent pulse on the left, with the greater response to reflex vasodilatation (*6*) on this than on the right side, suggests that vasomotor control is more effective in the clinically less advanced of the two sides.

The apparatus can be adapted easily to a variety of purposes. In addition to its use as a plethysmograph, one or more of its channels can be used as an electroencephalograph, an electromyograph, an electrocardiograph, or as an instrument to measure and record pressure and volume changes in physiologic systems. The transducer may be used for measuring differential as well as absolute changes of volume and pressure.

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