Measurement of the body surface physiologic tremor or "microvibration"

ALLAN F. PACELA,¹ BECKMAN INSTRUMENTS, INC.,
APPLIED MEDICAL RESEARCH LABORATORY, 2500 Harbor
Blvd., Fullerton, Calif. 92634

Five sensor techniques were evaluated for the measurement of human body surface vibrations: a noncontacting capacitance sensor, seismic (velocity) and relative electrodynamic types, linear-variable-differential transformer sensors, and the miniature accelerometer type. Of these, only the miniature accelerometer proved to be entirely satisfactory. The electrodynamic transducer utilized by several previous workers was found to be unsatisfactory for use as a physiological vibration sensor, due to resonance problems.

Although this study was primarily concerned with instrumentation techniques, preliminary observations indicated that the resting human microvibration contains a large cardiovascular component, probably obscured in previous observations with the electrodynamic velocity sensor.

Human microvibrations (MV) are normal or physiologic body surface vibrations of micron amplitude, observed at rest. The microvibration has also been termed the normal or minor tremor. Measurement of such vibrations is of significance in study of Parkinsonism and the Intention Tremor (Wachs & Bushes, 1961), and has been used in experimental psychology to distinguish neurotic, schizophrenic and control Ss (Williams, 1964a). Microvibrations may be described in terms of displacement, or its derivatives as: microdisplacement, microvelocity, and microacceleration. Although early research emphasized this response as being neuromuscular and the source of resting muscle tone, more recent work indicates that the source of MV is at least in part cardiovascular (Brunlik, 1962). A lack of suitable instrumentation has obscured both the source and the nature of this phenomenon.

The term, microvibration, was first applied to the minute vibratory movement of the human body surface by Rohrer in 1946, although he first observed the phenomenon in 1943 (1949, 1962b). Other workers studying MV include Denier (1956, 1957), Haider & Lindsley (1964), Heller-Jahnl (1959), Marko (1959), Schrocksnadel et al (1956), Sugano (1957), Sugano & Inanaga (1960), and Williams (1963, 1964a, b). Although Rohrer described the phenomenon as a normal physiological function involved in generation of resting muscle tone and body temperature regulation, Sugano & Inanaga (1960) described it as a kind of minor tremor.

The results of tremor research are closely related to study of the human microvibration; the same instrumentation can be used to study both. Of particular interest in tremor research is the work of Chase et al (1965), Cooper et al (1957), Halliday & Redfearn (1956), Hamoen (1958), Jasper & Andrews (1938), Lansing (1957), Lindsley (1935), Lippold et al (1959), Marshall & Walsh (1956), and Travis (1929). An additional group of workers has studied the "normal or physiologic tremor," which may be an identical phenomenon. This group includes Brumlik (1962), Bushes et al (1960), Wachs et al (1960), and Wachs & Bushes (1961). But little transfer of instrumentation techniques

has occurred between those studying "microvibration" and those studying the "normal tremor."

Significant contributions have been made to instrumentation by: Békésy (1941), Bricout & Boisvert (1950), Driechel & Lange (1956), Hannah et al (1954), Hull (1946), Jackson (1954), Mashima (1956), McAdam & Moreland (1964), Vinycomb (1954), and Zaalberg van Zelst (1947, 1948), although these workers were not specifically concerned with MV or tremor measurements.

Without doubt, Rohrer is the pioneer in the microvibration field (1946, 1949, 1952, 1954, 1955, 1956, 1958a, 1958b, 1959a, 1959b, 1960, 1962a, 1962b, 1964a, 1964b). Since 1943, he has tested over 900 Ss, utilizing a variety of instrumentation techniques, and has reported the following characteristics of human MV: The phenomenon is always present from birth to shortly after death, and is found in all parts of the body. Observed on the left dorsal forearm, MV has an amplitude of .5 to 3.0 microns (1 micron = 39.4 millionths of an in.) with frequency content predominately between 8 and 12 cps. Frequency is not the same at all body sites and is lower for larger but higher for smaller muscles. Smaller animals have a higher MV frequency and severing the medulla oblongata or removal of the heart does not eliminate the phenomenon. Microvibrations increase after exercise, but muscle relaxants reduce the amplitude. Central nervous system stimulants increase MV amplitude, but CNS sedatives reduce it, as do "ganglion blockers." Finally, Rohrer observed that MV frequency is increased in fever, decreased in a hot environment, and increased in the cold.

Based upon these observations, and the supporting work of Heller-Jahnl (1959), Marko (1959), Sugano (1957), and Sugano & Inanaga (1960), Rohrer (1959a, b) concluded that the human microvibration was due to continuously occurring, minute muscle contractions, and he proposed that human MV was the source of the ever present muscle tonus of the striated muscle tissues. Further, Rohrer formulated a hypothesis that the phenomenon was a controlling factor in body temperature regulation (1964b). Observations by Heller-Jahnl (1959), Marko (1959), and Rohrer (1955, 1959a, b, 1964b) on MV frequency confirmed this theory, but data on MV amplitudes did not.

Sugano (1957) and Sugano & Inanaga (1960) viewed the MV as a type of "minor" or "invisible" tremor. Rohrer did not hold a fundamental objection to the minor tremor view, but stated that "microvibration" was a better name for the phenomenon due to its continuous presence in normal Ss. He viewed the MV not as a reaction, but as a biological action of the organism (1949, 1962a, 1962b, 1964a).

Williams (1963, 1964b) contended that human microvibration, as measured by Rohrer, was primarily an instrumentation artifact, and that the mechanical constants (mass, spring constant, and coefficient of damping) of an electrodynamic probe (Rohrer used a Phillips PR9260) could act in combination with the properties of body tissue to modify the probe response. The modified response results in a probe resonance in the 8 to 12 cps region and, thus, generates the apparent MV. Although Williams disagreed with Rohrer's view of the phenomenon, he

tacitly accepted its existence and, in fact, utilized the MV in psychological studies (1964a).

Brumlik (1962) and Wachs et al (1960) studied the "normal tremor" in relationship to Parkinsonism; their accelerometer techniques can be shown to be superior to all previous instrumentation applications in both the MV and normal tremor fields. Brumlik noted that tremor, at rest, appeared similar in amplitude, frequency, and waveform to the ballistocardiogram, and that the normal tremor could not have a muscular origin because of its persistence after complete neuromuscular "blockade" with succinylcholine. Tremor on intention, on the other hand, might include both ballistocardiographic and neuromuscular components.

Finally, Jasper & Andrews (1938) suggested that a relationship might exist between tremor and the EEG waveform, but Lindqvist (1941) studied the problem and concluded that there was none. Later, Kennedy (1959) postulated that the EEG alpha rhythm might be generated by vibrations of the conductive cerebral tissue and might, therefore, be an artifact. But Oswald (1961) and Rosner (1961) appear to have provided evidence in disproof of this hypothesis. Apparently, there is no meaningful relationship between either the EEG and tremor, or between EEG and microvibrations.

INSTRUMENTATION FOR MICROVIBRATION MEASUREMENTS

In the studies described in this report, five different measurement techniques were experimentally evaluated. These included:

- A Non-contacting Capacitance Sensor,
- Phillips Seismic (Electrodynamic) Sensor,
- Absolute Linear-Variable-Differential-Transformer (LVDT) Sensor,
- Relative LVDT Sensor,
- Accelerometer Sensor.

It should be noted that the accelerometer sensor measures the *micro-acceleration* in microns/sec², while the LVDT and the capacitance types measure the *microdisplacement* in microns. The Phillips sensor measures the *microvelocity* in microns/sec.

Non-Contacting Capacitance Sensors

Cremer (1907) proposed a capacitance technique to measure physiological motion. The work was concerned with measurement of gross displacements (e.g., the movement of the heart), but was significant in that it constituted the first description of a non-contacting capacitance sensor in physiological instrumentation. Cremer's technique was elaborated by Atzler & Lehman (1932) and Atzler (1935), who used high frequency signals (100-150 MC) to record thoracic dielectric changes related to cardiac activity. Fenning (1937) used a capacitance technique to record uterine and intrauterine movements, and Bekesy (1941) measured the amplitude of vibration of the auditory ossicles of the middle ear using a shielded capacitance probe.

Capacitive measurement of physiological motion was, thus, well established when Marko used the technique to measure microvibration (Rohracher, 1949, 1959a). Marko placed the entire hand or forearm of S into the air-gap of a large capacitor connected so as to modulate the signal of a 100 kHz oscillator. But Rohracher (1964a), in a reply to Williams, stated that the capacitive method was unsuitable for comparative amplitude measurements because it was impossible to standardize the

distance between S's arm and the condenser plates due to differences between Ss in arm sizes.

In order to measure the MV with a non-contacting sensor, we constructed a simple transistor feedback oscillator with an external capacitance probe connected in parallel with the L-C, frequency determining circuit. The probe consisted of a flat silver plate with an area of 4.15 cm², positioned 1 or 2 mm from the body surface. The micron amplitude changes in spacing between the body surface and the probe had an associated small change in probe-to-S capacitance, which in turn, modulated the oscillator frequency. Some amplitude modulation also occurred, but this was eliminated in an FM receiver, used as a demodulator.

In order to estimate the sensitivity of the probe it was assumed that the probe-to-S capacitance was described by the parallel plate capacitor equation,

$$C = \frac{\epsilon A}{d} \quad (1)$$

Where, A is the plate area, d is the spacing, and ϵ is the dielectric constant of air. Fringing fields were ignored, and ϵ was assumed to be $\epsilon_0 = 8.85 \times 10^{-12}$ farads/meter. Further, it was simply assumed that the frequency of the oscillator was given by,

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

where L and C are the total circuit inductance and capacitance. Using these two equations it is possible to take the partial derivative of C with respect to d, and of f with respect to C. Using these partial derivatives, the system sensitivity may be expressed in terms of total differentials as,

$$\frac{\Delta f}{\Delta d} = \frac{f}{d} \quad (3)$$

Including the sensor initial capacitance in parallel with the oscillator capacitance, this becomes,

$$\frac{\Delta f}{\Delta d} = \frac{f}{2d} \left(\frac{C}{C + C_0} \right), \quad (4)$$

where, C_0 is the oscillator capacitance and C is the probe capacitance. The constructed system was operated at 100 mHz (MC) with $d = 10^{-3}$ m, $C_0 = 19\mu\text{fd}$, and $C = 1\mu\text{fd}$. The predicted sensitivity, $\Delta f/\Delta d$ was then 2.5×10^9 cps/meter, which for $\Delta d = 1$ micron, would indicate an expected frequency change of 2.5 kc/micron. With a typical FM discriminator sensitivity of about 20 kc/volt, an overall measurement sensitivity of 125 mV/micron would result.

In preliminary experiments, a number of MV recordings were obtained from the left dorsal forearm of male Ss. To obtain the measurements with a 1 or 2 mm spacing, it was necessary to shave the area near the probe.

The above derivation of expected probe sensitivity, indicates that overall sensitivities as large as 0.125 V/micron can result. This sensitivity appears to have been achieved, but a great deal of difficulty was experienced due to operation at 100 MC. At this

high frequency, movement of any object within several meters of the probe can be observed as an artifact. A number of grounding and shielding techniques were attempted, with little success. Microvibration recordings were obtained but, due to these artifacts, calibration was not possible. These difficulties do not, however, rule out use of such a probe. The theoretical sensitivity achieved is, in fact, excessive. It is felt that by reducing probe frequency to 10.7 MC/sec (and perhaps to as low as 100 kc), artifacts due to nearby R.F. field effects can be eliminated. Equation (4) indicates that reducing the frequency will proportionally reduce the sensitivity for the same spacing and circuit capacitance.

Figure 1 presents the schematic of the 107.5 MC capacitance sensor. The device is basically an FM modulated oscillator. The tuned resonant circuit, consisting of L_1 , C_2 , and C_3 , establishes the oscillator frequency.

Figure 2 presents arm surface displacement recordings (uncalibrated) obtained with the capacitance probe. To obtain the recordings, the S was prone and the probe was positioned approximately 1 mm from a shaved area of the left dorsal mid-forearm. The S rested upon a padded medical examination table, and the entire arm, abducted 45 deg to the mid-axillary line, was rested upon a pillow. The recordings of Fig. 2 clearly show cardiovascular (A) and respiratory (B) arm surface displacements. The recording was obtained by telemetering the FM oscillator signal approximately 10 to 20 ft to an FM receiver.

Electrodynamic Sensors

Electrodynamic vibration transducers may be organized into two general categories depending upon how the vibration is applied to the transducer. The first category, perhaps the most common, includes all seismic and absolute transducers in which

Fig. 1. Microvibration (MV) capacitance sensor schematic.

Fig. 2. Capacitance probe recordings showing pulse and respiratory arm-surface displacements for the same S (A.P.), left dorsal forearm. Top record is cardiovascular, 5 to 22 cps, 100 mV/cm, 1 cm/sec. Bottom record is respiratory, dc to 22 cps, 200 mV/cm, 1 cm/sec.

(a) Seismic Transducers

(b) Relative Transducers

Fig. 3. Electrodynamic vibration transducers, seismic and relative.

the vibration is applied to the case of the entire unit (Fig. 3a); a moving mass is suspended within the unit. In the case of the Phillips PR9260 sensor used by Rohrer, a voltage coil and a damping coil are rigidly connected and supported by two spring membranes. The coils move within the field of a permanent magnet and generate a voltage proportional to velocity. The second group of transducers may be termed "relative" in that the vibration measurement is made by a probe relative to the case of the unit. The case may either be rigidly clamped to a fixed support or may be stationary due to its own large mass (Fig. 3b).

Figure 3a shows the first group of transducers. The displacement to be measured, x_1 , is applied to the case. The movable mass, m , is attached to the case by a spring with constant, k , and damping, c . If the forces on mass m are summed, we obtain,

$$m\ddot{x}_2 = -k(x_2 - x_1) - c(\dot{x}_2 - \dot{x}_1). \quad (5)$$

If a sinusoidal excitation is assumed, that is,

$$x_1 = X_1 e^{j\omega t}. \quad (6)$$

It can be shown that the response of the mass is also sinusoidal,

$$x_2 = X_2 e^{j\omega t}, \quad (7)$$

and that the relative motion, $(X_2 - X_1)$, due to the excitation, X_1 , is

$$\frac{X_2 - X_1}{X_1} = \frac{-(j\omega)^2}{(j\omega)^2 + j\omega\left(\frac{c}{m}\right) + \frac{k}{m}} \quad (8)$$

Since typical electrical arrangements respond to $(x_2 - x_1)$, Equation (8) will completely describe the frequency response of the system. The "Q" of this mechanical system may be defined in analogy to the Q of a tuned electrical circuit,

$$Q = \frac{m\omega_r}{c} \quad (9)$$

where, ω_r is the resonant frequency,

$$\omega_r^2 = \frac{k}{m}. \quad (10)$$

Using this notation, Equation (8) becomes

$$\frac{X_2 - X_1}{X_1} = \frac{-jQ\left(\frac{\omega}{\omega_r}\right)}{1 - jQ\left(\frac{\omega_r}{\omega} - \frac{\omega}{\omega_r}\right)} \quad (11)$$

Equation (11) is plotted in Fig. (4a) for several values of Q, and clearly shows the resonance of the probe at $\omega = \omega_r$. Equation (11) may be simplified at very high or very low frequencies. At low frequencies, $\omega \ll \omega_r$, or,

$$\frac{\omega}{\omega_r} \ll \frac{\omega_r}{\omega} \quad (12)$$

In this region, Equation (11) becomes,

$$\left| \frac{X_2 - X_1}{X_1} \right| = \left| \frac{-(j\omega)^2}{\omega_r^2} \right| \quad (13)$$

At high frequencies, $\omega \gg \omega_r$, or,

$$\frac{\omega}{\omega_r} \gg \frac{\omega_r}{\omega} \quad (14)$$

In this region, Equation (11) becomes,

$$\frac{X_2 - X_1}{X_1} = -1. \quad (15)$$

Fig. 4. Electrodynamic transducer frequency response for seismic (left) and relative (right) types.

This indicates that X_2 becomes zero above resonance, that is, the mass becomes stationary. The Phillips probe produces an output proportional to the first derivative of $(X_2 - X_1)$, and will, therefore, measure velocity at frequencies above resonance, and the rate-of-change-of-acceleration (rarely used) at low frequencies. Even if critically damped, this probe will be, at best, difficult to use near resonance.

The second group of transducers is best analyzed by solving for the displacement x_2 resulting from an applied force, F . Figure (4b) illustrates this system. Writing the summation of forces, as above, it can be shown that the sensor response is,

$$\frac{F}{X_2} = j \left(\frac{\omega}{\omega_r} \right) \frac{k}{Q} \left(1 + jQ \left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega} \right) \right), \quad (16)$$

which may be simplified at high frequencies, $\omega \gg \omega_r$, to be,

$$\frac{F}{X_2} = \left(j \frac{\omega}{\omega_r} \right)^2 k, \quad (17)$$

and at low frequencies, $\omega \ll \omega_r$, to be,

$$\frac{X_2}{F} = K^{-1} \quad (18)$$

Equation (18) indicates that the transducer appears to be purely a spring at low frequencies. If the transducer produced a voltage proportional to velocity, $\dot{x}_2$, then it would measure velocity at frequencies *below* resonance.

After examination of both groups of transducers, a major difference is obvious. The Phillips PR9260 seismic electrodynamic transducer can measure velocity only *above* resonance. The relative electrodynamic transducer (for example, a variable

reluctance pick-up) can measure velocity only *below* resonance. For comparison, the Gulton accelerometer to be discussed later measures acceleration *below* resonance.

Figure 5 shows a Phillips PR9260 seismic velocity probe presumably identical to that used by Rohrer in the major part of this work. This probe was used to measure the microvibration present on the left dorsal forearm of a male S. In all cases, the S was lying in the prone position. The sensor was supported by a wire harness from a heavy frame, and essentially the entire weight of the probe (600 g) was allowed to rest on S's arm. The voltage output of the probe was directly recorded on either a Beckman Electronic Instruments Division R or RS Dynograph Recorder. The S rested upon a padded medical examination table, and the entire arm (abducted 45 deg to the mid-axillary line) was rested upon a pillow. A simultaneous electrocardiogram was taken using Beckman silver-silver chloride electrodes in lead I, with a sternal ground.

Figure 6 shows resting microvibration measurements obtained with the Phillips seismic probe. Figure 6c shows the probe noise background without S; Fig. 6a and 6b show the effect of restricting amplifier bandwidth to 5 to 32 cps, as was done by Rohrer. Figure 6a was recorded wide-band from dc to 150 cps. The smaller amplitudes in Fig. 6b show that significant frequency components do exist outside the 5 to 32 cps band. To demonstrate the effects of arm muscle tension, a recording was made with S's arm maximally tense, but as stationary as possible. Figure 7 shows the effects of tension and includes a simultaneous ECG: electromyographic artifacts may be seen in the ECG due to the arm tension.

The PR9260 measures velocity in the range 5 cps to 100 cps. The basic probe sensitivity is in mV per cm/sec. To measure the microdisplacement, it is necessary to integrate the probe signal. An accessory, the Phillips PR9252 vibration meter, can perform the necessary integration for sinusoidal vibrations.

Since Rohrer described his apparatus as consisting only of probe, amplifier, and recorder, it must be concluded that MV

Fig. 5. Phillips PR9260 seismic velocity probe.

velocity was measured, and that calibration was in terms of *displacement*. It is true that the integral of a sinusoidal velocity is simply a sinusoidal displacement with shifted phase, but it may not be assumed that the MV is purely sinusoidal. The recordings above clearly show this.

Halliday & Kearearn (1956) have pointed out that it is not sufficient to report tremor as being of one particular frequency unless it is made clear that either displacement or its first or second derivative is being discussed. The authors also point out that electrodynamic systems can measure velocity while optical techniques measure displacement. These comments, although generated in regard to instrumentation for tremor measurement, apply equally well to measurement of the MV. This would tend to explain the differences in amplitude noted by Marko (1959) when using an optical technique, and Rohrer, using an electrodynamic technique. Although the PR9260 is damped for sinusoidal vibrations, the probe exhibits a strong tendency to resonate in the frequency range of interest. Although frequently used, this probe does not appear to be suitable for MV measurements due to its resonance near 10 cps, and its large phase error (approximately 90 deg at 10 cps). Figure 8 presents a graphic demonstration of the resonance problem. The Phillips probe was positioned at (A) a specific blood vessel and (B) at the dorsal mid forearm, without specific attempt to locate a blood vessel. In both cases, however, it was observed that a vibration of vascular origin, at the arm, apparently excited the probe, and generated a burst of 10 cps "false microvibration" signal. The delay time observed between the ECG R wave and the onset of the false microvibration signal is comparable to the pulse-wave-transit time found in pulse-wave-velocity studies.

To further demonstrate the resonance problems associated with the Phillips seismic probe, recordings were obtained after tapping the probe. Such an excitation is, of course, non-quantitative and much larger than microvibration, but nevertheless serves to exhibit the probe resonance. Figure 9 shows recordings obtained with the probe suspended (no S) and tapped in its axial direction. Sustained oscillations may be observed after the excitation.

Linear-Variable-Differential Transformer Sensors (LVDT)

To compare the electrodynamic and noncontacting capacitance measurements with a measurement made by a non-resonant, contacting probe, several sensors employing linear differential transformers were designed and constructed. Sanborn "Linearsyn" LVDT transducers were used with core weights of 18.0 g and .1 g.

An LVDT sensor may be considered to be a type of absolute probe in that it measures with respect to a fixed mechanical reference. The mechanical reference may be independent of S or the sensor may mount on S and measure displacement of one portion of the body relative to another. A simple 2.4 kc/sec carrier system was designed for use with these sensors and the entire system was constructed as a plug-in coupler compatible with a Beckman Electronic Instruments Division type R or RS Dynograph Recorder.

A

B

C

Fig. 6. Resting MV recordings obtained with seismic sensor. (A) MV: dc to 150 cps, 25 mm/sec, 1 mV/cm. ECG: Lead I (sternal ground), .5 mV/cm, A_g/A_{gCl} electrodes. S: M.T., 28 yr. old male, left dorsal forearm. (B) MB: 5 to 32 cps, 25 mm/sec, 1 mV/cm. ECG: lead I (sternal ground), .5 mV/cm, A_g/A_{gCl} electrodes. S: M. T., 28 yr old male, left dorsal forearm. (C) Probe noise without S, 1 mV/cm, 25 mm/sec, 5 to 32 cps.

Fig. 7. Microvibration during arm muscle tension with seismic sensor on 28 yr old male S (M.T.), left dorsal forearm. Upper record shows MV, dc to 150 cps, 20 mV/cm, 25 mm/sec. Lower record indicates simultaneous ECG with electromyographic artifacts, lead I (sternal ground), .5mV/cm.

A

B

Fig. 8. Microvibration in relation to pulse with the seismic sensor used on same S as in Fig. 7. Upper recording (A) shows probe positioned at a specific blood vessel. Lower record: Same probe positioned at dorsal mid-forearm, no specific attempt to locate blood vessel (A) MV: 5 to 32 cps, 1 mV/cm, 25 mm/sec. ECG: Lead I (sternal ground), .5 mV/cm, Ag/AgCl electrodes. S: M.T., 28 yr old male, left dorsal forearm over cubital vein. (B) MV: dc to 22 cps, 5 mV/cm, 25 mm/sec. ECG: Lead I (sternal ground), .5 mV/cm, Ag/AgCl electrodes. S: M.T., 28 yr old male, left dorsal forearm.

Although the sensors were initially constructed with Delrin-Delrin bearings, it was found that lubricated metal bearings had lower friction forces. Calibration of the LVDT microvibration sensors was performed, using precision gauge blocks with

heights known to within $\pm 2, -4\mu$ in., using an optically flat reference block. Sensitivities of $58.4 \mu\text{V}/\mu$ and $66 \mu\text{V}/\mu$ were achieved for two sensors using the small and large core LVDTs, respectively.

Fig. 9. Resonant characteristics of Phillip's seismic probe, suspended, with no S, and tapped in axial direction (dc to 150 cps, 25 mm/sec, 5 mV/cm).

Fig. 10. Relative S-mounted LVDT sensor (top), and absolute frame-mounted LVDT (bottom).

Fig. 11. Accelerometer sensor, Gulton AVR-250-30.

Preliminary S tests with the arm-mounted "relative" LVDT sensor, shown in Fig. 10, revealed an absence of MV signals. Microvibration signals were observed, however, with the same LVDT sensor and S, when the measurement was obtained with respect to a fixed frame. It was concluded that the human MV displacement is not a local phenomenon. It was possible to obtain measurements with the frame mounted LVDT sensor, but this approach was not considered useful because of an obvious limitation. Use of an absolute frame-mounted LVDT sensor

Fig. 12. MV accelerometer carrier system, schematic diagram. All transistors 2N3565; L_1 is TRIAD EM-202, 20 mh; T_1 is TRIAD SP-4.

Fig. 13. Microvibration recordings with accelerometer sensor on same S(H). MV: 5 mV/cm, ECG: .5 mV/cm, 25 mm/sec.

requires the S to maintain the body-to-sensor distance within a few thousandths of an inch, so as not to exceed the sensor dynamic displacement range.

Accelerometer Sensors

The accelerometer shown in Fig. 11 (Gulton AVR-250-30) is basically a variable reluctance device and includes two active inductive elements. The sensor was first reported applied in tremor research by Brumlik (1962), Wachs et al (1960), Wachs & Bushes (1961), and Bushes et al (1960). A seismically suspended magnetic armature varies the air gap of each inductive arm in proportion to acceleration. Since the magnetic armature will remain displaced in response to a fixed acceleration, the sensor will respond to acceleration frequencies as low as zero cps. By rotating the sensor 90 deg, the acceleration of gravity may be used as a convenient calibration.

This sensor responds only to accelerations perpendicular to the plane of the case. Since the sensor resonance is at 250 cps, the useful frequency range extends from zero to over 100 cps. The total weight is only 2.5 g and overall dimensions 7/8 x 17/32 x 3/16 in.

The schematic for the associated carrier system is shown in Fig. 12. The accelerometer carrier system is similar to the LVDT system mentioned earlier except that the sensor is operated in an electrical bridge and a carrier amplifier is provided. The sensor driving signal is obtained at the 2 KC oscillator (Q_1). Transistors Q_2 and Q_3 form an isolation or buffer amplifier. The sensor bridge includes resistive and inductive balance controls so that a true bridge null may be obtained. The operational amplifier provides a gain of 200 to amplify the bridge unbalance signals. The carrier demodulator is a standard voltage doubler. A filter is provided at the output to reduce the carrier frequencies. The

Fig. 14. Simultaneous phonocardiogram and MV (microacceleration) recording from chest of 26 yr old male (D.R.). MV: (Upper recording) 20 mV/cm, noise 2-3 mV, 2.5 cm/sec. Phonocardiogram: (Lower recording) 5 mV/cm, noise 2 mV.

overall system sensitivity was 1.1 V/g of acceleration. Figure 13 illustrates typical experimental records obtained with this sensor. The simultaneous ECG was transthoracic with Ag/AgCl electrodes and a sternal ground. Prominent cardiovascular components are obvious in both records.

With regard to the cardiovascular components in the human microvibration, simultaneous accelerometer-MV and phonocardiograph measurements were made on the chest (Precordium). The phonocardiograph designed for the NASA Gemini program was used. Very strong accelerations were observed on the chest surface, bearing a direct correlation to the phonocardiogram and electrocardiogram. Figure 14 shows a simultaneous microacceleration (upper) and phonocardiogram (lower). The first and second heart sounds visible in the phonocardiogram are clearly seen in the MV recording. These preliminary observations tend to confirm the existence of a large cardiovascular component in the human microacceleration.

CONCLUSIONS

The existence of human body surface microvibrations was verified; some previously used instrumentation techniques were found inadequate. In preliminary experiments, it was observed that the body surface microacceleration apparently contains significant cardiovascular components. This result is in opposition to the muscular and temperature regulation theory of Rohrer (1946-1964).

Accelerometer sensors proved to be most satisfactory for measurement of the microacceleration; several types of commercial units are available. Due to small size and mass, such sensors can be mounted by means of doublefaced adhesive tape to almost any portion of the body, yet allow relative S freedom. Measurement of acceleration is experimentally superior, as a fixed sensor reference is not needed. The capacitance sensor, although offering the advantage of not contacting the body, was extremely sensitive to artifacts from gross motions.

The Phillips seismic probe was much too large and massive, and although critically damped, exhibited resonance in the microacceleration spectrum at 10 cps. When excited, this transducer produced a 10 cps signal not unlike the microvibration itself. Near 10 cps, phase errors also presented a difficult problem. Seismic probes can be shown to have a low frequency resonance that severely limits their usefulness in measurement of the MV.

The LVDT sensors experienced bearing friction problems. A small frame-mounted (absolute) LVDT sensor was attempted but required the S to maintain body-to-sensor distance within a few thousandths of an inch, an obviously impractical requirement.

REFERENCES

- ATZLER, E. Dielektrographie. In: *Handbuch der Biologischen Arbeitsmethoden*. Berlin-Wien: Urban and Schwarzenberg, 1935. Vol. 5. Pp. 1073-1084.
- ATZLER, E., & LEHMAN, G. Über ein neues Verfahren zur Darstellung der Herztaetigkeit. *Arbeitsphysiologie*, 1932, 5, 636-680.
- BÉKÉSY, G. von. Über die Messung der Schwingungsamplitude der Gehörknochen mittels einer kapazitiven Sonde. *Akustische Zeitschrift*, 1941, Jan., 1-16.
- BRICOUT, P. A., & BOISVERT, M. Measurement and amplification of minute displacements by frequency modulation. *Rev. Sci. Instr.*, 1950, 21, 98-99.
- BRUMLIK, J. On the nature of normal tremor. *Neurology*, 1962, 12, 159-179.
- BUSHES, B., WACHS, H., BRUMLIK, J., MIER, M., & PETROVICK, M. Studies of tone, tremor, and speech in normal persons and Parkinsonian patients. *Neurology*, 1960, 10, 805.
- CHASE, R. A., CULLEN, J. K., & SULLIVAN, S. A. Modification of intention tremor in man. *Nature*, 1965, 206, 485-487.
- COOPER, J. D., HALLIDAY, A. M., & REDFERN, J. W. T. Apparatus for the study of human tremor and stretch reflexes. *EEG clin. Neurophysiol.*, 1957, 9, 546-550.
- CREMER, M. The recording of mechanical processes by electrical means, particularly with the aid of the string galvanometer and string electrometer. (in German). *Muenchener Medizinische Wochenschrift*, 1907, 33, 1629-1630.
- DENIER, A. Les microvibrations du corps, tremains du tonus physiologique. *Revue Neurologique*, 1956, 95, 503-506.
- DENIER, A. The microvibrations of the body as an expression of physiological tonus. *EEG clin. Neurophysiol.*, 1957, 9, 362-363.
- DRISCHEL, H., & LANGE, C. Über unwillkürliche Augapfelbewegungen bei einäugigem Fixieren. *Pflugers Archiv.*, 1956, 262, 307-333.
- FENNING, C. A new method of recording physiological activities, I and II. *J. lab. clin. Med.*, 1937, 22, 1279-1284.
- HAIDER, M., & LINDSLEY, D. B. Microvibrations in man and dolphin. *Science*, 1964, 146, 1181-1183.
- HALLIDAY, A. M., & REDFERN, J. W. T. An analysis of the frequencies of finger tremor in healthy subjects. *J. Physiol.*, 1956, 134, 600-611.
- HAMOEN, A. M. On the physiology of tremor. *EEG clin. Neurophysiol.*, 1958, 10, 752-753.
- HANNAH, K. W., JONCICH, M. J., & HACKERMAN, N. An automatic system for the study of catalytic reactions involving gases. *Rev. Sci. Instr.*, 1954, 25, 636-639.
- HELLER-JAHLN, I. Die Mikroviibration bei psychischer Spannung und Entspannung. *Zeitschrift Psychother. Med. Psychol.*, 1959, 9, 34-38.
- HULL, G. F. Resonant circuit modulator for broad band acoustic measurements. *J. appl. Physics*, 1946, 17, 1066-1073.
- JACKSON, P. Resistance strain gauges and vibration measurement. *J. British IRE.*, 1954, 14, 106-114.
- JASPER, M. M., & ANDREWS, H. L. Brain potentials and voluntary muscle activity in man. *J. Neurophysiol.*, 1938, 1, 87-100.
- KENNEDY, J. L. A possible artifact in electroencephalography. *Psychol. Rev.*, 1959, 66, 347-352.
- LANSING, R. W. Relation of brain and tremor rhythms to visual reaction time. *EEG clin. Neurophysiol.*, 1957, 9, 497-504.
- LINDQVIST, T. Finger tremor and alpha waves of the electroencephalogram. *Acta Medica Scandinavica*, 1941, 108, 580-585.
- LINDSLEY, D. B. Electrical activity of human motor units during voluntary contraction. *Amer. J. Physiol.*, 1935, 114, 90-99.
- LIPPOLD, O. C. J., REDFERN, J. W. T., & VUCO, J. The influence of afferent and descending pathways on the rhythmical and arrhythmical components of muscular activity in man and the anaesthetized cat. *J. Physiol.*, 1959, 146, 1-9.
- MARKO, A. R. Optisch-mikroskopische Registrierung der Mikroviibration des menschlichen Körpers. *Mikroskopie*, 1959, 14, 102-105.
- MARSHALL, J., & WALSH, E. G. Physiological tremor. *J. Neurol. Neurosurg. Psychiat.*, 1956, 19, 260-267.
- MASHIMA, H. Recording technique of mechanical changes. *Rec. adv. Res. nerv. System*, 1956, 1, 179-191.
- McADAM, W., & MORELAND, G. R. A magnetic null-balance displacement measuring system using radio-frequency modulation. *IEEE Trans. Instr. Meas.*, 1964, IM-13, 94-102.
- OSWALD, I. On the origin of the EEG alpha rhythms. *Psychol. Rev.*, 1961, 68, 360-362.
- ROHRACHER, H. Schwingungen im menschlichen Organismus. *Anz. Phil.-Hist. Ost. Akad. Wiss.*, 1946, 230-245.
- ROHRACHER, H. *Mechanische Mikroschwingungen des menschlichen Körpers*. Wien: Urban und Schwarzenberg, 1949.
- ROHRACHER, H. Neue Untersuchungen über biologische Mikroschwingungen. *Anz. Phil.-Hist. Ost. Akad. Wiss.*, 1952, 153-161.
- ROHRACHER, H. Neue Untersuchungen über biologische Mikroschwingungen II. *Anz. Phil.-Hist. Ost. Akad. Wiss.*, 1954, 229-248.
- ROHRACHER, H. Warmehaushalt und Mikroviibration. *Acta Neurovegetativa*, 1955, 11, 181-200.
- ROHRACHER, H. Über eine ständig vorhandene mechanische Mikroschwingung des menschlichen Körpers. *Ber. ges. Physiol.*, 1956, 180, 119.
- ROHRACHER, H. Neue Untersuchungen über die Mikroviibration des menschlichen Körpers. *Anz. Phil.-Hist. Ost. Akad. Wiss.*, 1958a, 59-78.
- ROHRACHER, H. Muscular micro-activity ("microvibration") as an indicator of physiological tension. *Percept. mot. Skills*, 1958b, 8, 150.
- ROHRACHER, H. Continual muscular activity ("microvibration") tonus and constancy of the body temperature. *Zeitschrift für Biologie*, 1959a, 38-53.
- ROHRACHER, H. Untersuchungen über die Wärmeproduktion zur Konstanthaltung der Körpertemperatur. *Anz. Phil.-Hist. Ost. Akad. Wiss.*, 1959b, 229-240.

- ROHRACHER, H. Methoden zur Registrierung und Auswertung der Mikrovibration. *Psychologische Beiträge*, 1960, 4, 118-126.
- ROHRACHER, H. The biological function of the alpha rhythm. *EEG clin. Neurophysiol.*, 1962a, 14, 791.
- ROHRACHER, H. Permanente rhythmische Mikrobewegungen des Warmblüterorganismus ("mikrovibration"). *Die Naturwissenschaften*, 1962b, XLIX, 145-150.
- ROHRACHER, H. Comments on a resonance theory of microvibrations. *Psychol. Rev.*, 1964a, 71, 524-525.
- ROHRACHER, H. Microvibration, permanent muscle activity and constancy of body temperature. *Percept. mot. Skills*, 1964b, 19, 198.
- ROSNER, B. S. Alpha rhythm of the EEG and mechanical properties of brain. *Psychol. Rev.*, 1961, 68, 359-360.
- SCHROCKSNADL, H., LIENER, A., & SEMENTITZ, E. Zur biologischen Wirkung mikromechanischer Schwingungen von Intraohallfrequenz. *Ber. ges. Physiol.*, 1956, 180, 120.
- SUGANO, H. Studies on the microvibration. *Kurume Medical J.*, 1957, 4, 97-113.
- SUGANO, H., & INANAGA, K. Studies on minor tremor. *Japan J. Physiol.*, 1960, 10, 246-257.
- TRAVIS, L. E. The relation of voluntary movement to tremors. *J. exp. Psychol.*, 1929, 12, 515-524.
- VINYCOMB, R. K. Electronic aids to vibration measurement. *J. British IRE.*, 1954, 14, 115-127.
- WACHS, H., BRUMLIK, J., & BUSHES, B. Studies in Parkinsonism: Relationships between tone and tremor in Parkinsonism and in normals. *J. nerv. ment. Dis.*, 1960, 144.
- WACHS, H., & BUSHES, B. Studies of tremor in normals and in Parkinsonism. *Arch. Neurol.*, 1961, 4, 66.
- WILLIAMS, J. G. L. A resonance theory of "microvibrations." *Psychol. Rev.*, 1963, 70, 547-558.
- WILLIAMS, J. G. L. Use of a resonance technique to measure muscle activity in neurotic and schizophrenic patients. *Psychosom. Med.*, 1964a, 24, 20-28.
- WILLIAMS, J. G. L. A resonance theory of "microvibrations" a reply to Rohracher. *Psychol. Rev.*, 1964b, 71, 526-527.
- ZAALBERG van ZELST, J. J. Circuit for condenser microphones with low noise level. *Philips Tech. Rev.*, 1947/1948, 9, 357-363.

NOTE

1. The author acknowledges the significant contributions of Mr. Merrick Troupin, Miss Joyce Bullis, and Mr. David Reed. This work would have not been possible without the support of Dr. Thomas Weber.

The roots of territorial marking in the Mongolian gerbil: A problem of species-common topography

D. D. THIESSEN, UNIVERSITY OF TEXAS, Austin, Texas 78712

The Mongolian gerbil (*Meriones unguiculatus*) has recently been introduced into behavioral research. Many features make it an ideal laboratory animal. It is docile, highly exploratory, a good learner, virtually odorless and can be maintained without water; other than that it metabolizes from its food. General characteristics of the gerbil are described, and a brief review of behavioral research is given. The gerbil also possesses unique attributes that can only be studied by matching experimental methodology with species-common responses. Territorial marking is used as example. The gerbil regularly marks objects in an open field by skimming the object with a midventral sebaceous scent gland. The marking and gland are dimorphic, with the male marking about twice as frequently as the female and possessing a gland roughly twice the size. The configuration of the field (object quality) modifies the frequency of the response, as does the time of day the animals are exposed to the field. Androgen levels control the level of marking in the male and female, and the correlations between testis weight, size of the sebaceous gland, secretory output and marking frequency are significant. When a gerbil is introduced into an open field recently contaminated by another gerbil, or when objects are smeared with sebum and placed in the field, the male tends to be more hesitant in several types of behavior. The laboratory measures are internally consistent and congruous with the notion that natural selection has acted to reinforce a hormone-behavior relation of social significance to the gerbil.

The Mongolian gerbil (*Meriones unguiculatus*) is rapidly becoming a significant target for biological research. Most of the work is physiological in character (see Schwentker, 1963), but interest is also focusing on behavior. In our laboratory we have concentrated on three species-common components of gerbil behavior—spontaneous epileptiform seizures found in a propor-

tion of the population (Thiessen, Lindzey, & Friend, 1968), apparent lack of depth perception (Thiessen, Lindzey, Blum, Tucker, & Friend, 1968) and territorial marking with a ventral sebaceous gland (Thiessen, Friend, & Lindzey, 1968; Lindzey, Thiessen, & Tucker, 1968).

The first section of this paper describes various features of the Mongolian gerbil that will be of value to those interested in maintaining and breeding the animal in the laboratory.

The second section describes the marking response and illustrates the effects of altering the configuration of the territory and the circadian phase of testing. The third section gives the relations between marking and other variables and demonstrates the hormone control of the behavior. It also presents an easy technique for measuring the pheromone involved in territorial marking. Last is a discussion of the social and evolutionary significance of marking. Attention is focused throughout on how well the instrumentation of laboratory tactics has elicited species-common reactions of importance to the adaptation of the gerbil.

CHARACTERISTICS OF THE MONGOLIAN GERBIL Classification

The Mongolian gerbil, *Meriones unguiculatus*, was first described by Milne-Edwards (1867). It is a native of northeast China, eastern Mongolia and Korea. Dr. Victor Schwentker of the West Foundation introduced the gerbil into the United States in 1954. Of the original eleven pairs, five females and four males were induced to breed. Progeny of these matings served as the historical nucleus for most research colonies now in existence. Victor Schwentker at Tumblebrook Farms in Brant Lake, New York, remains the major supplier of research animals.

According to Schwentker (1963, 1968) gerbils are classified into 10 and possibly 12 genera. The Mongolian species, *unguiculatus*, is in the genera *Meriones*, and is further recognized as part of the subfamily, *Gerbillinae*, the family, *Cricetidae*, the