# *Equilibrium and Walking Changes Observed At 5, 7½, 10 and 12 RPM in the Revolving Space Station Simulator*

BERNARD D. NEWSOM, PH.D., JAMES F. BRADY, B.S., and GUY J. GOBLE, PH.D.

**Rotation tolerance of man in space is difficult to analyze on earth because of the gravity artifact. In the operating space station centrifugal force will be nearly perpendicular to the floor and the velocity will be constant over the entire floor area. The data available in the literature have not considered these factors. The general acceptance of four RPM as a maximum rotation rate and 40 feet as a minimum radius is a severe design restriction for an early space station. Careful examination of all factors used to define these limits must be made in order to be sure the tolerances described are close as possible to those to be found in space. For this reason a Revolving Space Station Simulator was constructed by modifying a 220,000 g pound centrifuge. A room 7 x 8 x 14 feet was suspended at an 18-foot radius by trunnions so the resultant force would be normal to the floor. Preliminary results of the equilibrium and walking tests performed at rotation rates above the presently accepted limits demonstrate a learning process and suggest that post rotational decrement is attributable to the acquired compensatory responses.**

IT IS THE HOPE of engineers and biologists that a way will be found to allow men to exist for prolonged periods at zero g. In the event that degeneration should occur, however, it will be necessary to consider artificial gravity systems. All rotating simulators on earth are subject to the g artifact, thus it is difficult to assess a situation where the resultant force vector will be in the plane of spin.

Despite these difficulties the engineer needs to know the optimum design values today. These are dependent on the maximum rotation rate at which man can adapt and perform with various radii and stabilities.

Available literature suggests that four RPM is the limit for long term tolerance and that the radius must exceed forty feet.[1,2,3] Little if any speculation has been made about the stability requirements. Most design envelopes such as that published by Dole[1] have been formulated from the work of Graybiel and his group.[4,5,6]

Their studies were performed in a room rotating about its center and not meant to simulate a space station. In addition the radius of the facility was very small and though this does not affect the coriolis produced it does amplify the required velocity change when walking on any chord within the room.

Figure 1A depicts the situation of a 15-foot diameter room revolving about its center. The subject must lean toward the axis; the angle of inclination must be continually adjusted. In addition walking past the center of rotation will reverse the direction of force adding further confusion and difficulty in adaptation. A man standing on the periphery of such a room has a linear velocity that is five times what his velocity would be if he were six feet closer to the axis. This means he must decelerate as he approaches such a point or the floor would have a slower linear velocity than his body. A situation would then result where he would fall to the right (in counter clockwise rotation), as though a rug were pulled out from beneath him. To return to the

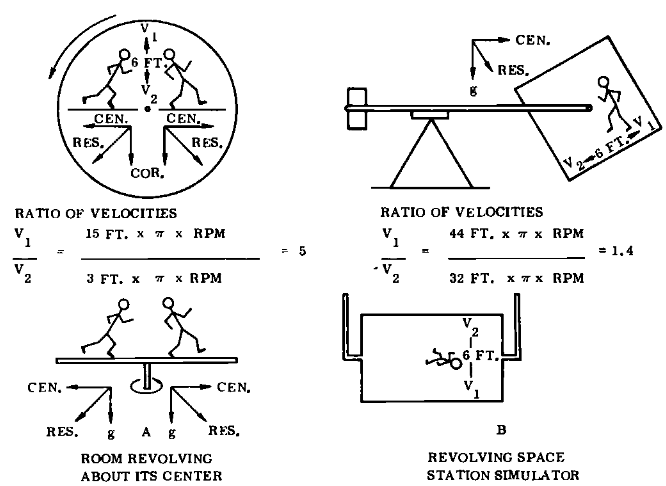


Fig. 1. The Manned Revolving Space Station is one step closer to simulating space conditions than previous facilities. It aligns the resultant force normal to the floor and decreases the velocity change resulting from radial movement within the room toward the axis of rotation.

periphery of the room he would have to accelerate to catch up with the higher velocity or an opposite reaction would occur. Continual acceleration and deceleration add to the bizarre stimuli to which the man is confronted, one in which there is little in the way of a constant force reference.

Tolerable rotation conditions could be defined as those that do not prevent nausea. It would seem more important however to describe the required envelope of RPM, radius and stability in terms of an environment where adequate adaptation can take place to achieve proper performance of duties. Such a study would require a series of physiological and psychomotor tests

From the Aerospace Medicine Group, Life Science Department, General Dynamics/Astronautics, San Diego, California, 92112.

under conditions as close as possible to those in a revolving space station.

The environment of a revolving space system has been described by Loret.[7] The principal point is that men will be in the plane of spin and perpendicular to the floor. Having the men live in the plane of spin is probably not possible to simulate but in a study by Stone and Letko,[8] where subjects lay in the plane of spin, adaptation to a simple task was found to be satisfactory. What now is required are data developed specifically to answer the engineers' needs. This requires simulator facilities resembling a space station in as many aspects as possible. It is possible to create a revolving simulator where the resultant inertial forces are normal to the floor by trunnioning a room at the end of a centrifuge as seen in Figure 1B. This aligns the force vector with the man's spine when he is vertical and provides a constant source of reference for equilibrium. In addition it is possible to greatly reduce the artifact of velocity change by making the room narrow in proportion to its length and providing a twenty-foot working radius.

An 8- by 14-foot room was mounted in a cradle suspended by two I-beams across the boom of the 220,000 g lb. centrifuge at Astronautics. In this room a subject increases his linear velocity by a factor of only 0.4 when he moves six feet radially outward (Figure 1B). The eighteen-foot radius to room center increases to twenty feet or more when the room swings out. This facility is an important step closer to simulating conditions in a revolving space station than others in present operation.[4]

The room is planned for prolonged continuous runs. Fresh water is piped to the cabin and sewage pumped back through rotary couplings. The two lines are separated by the high pressure air line to the room position actuating piston, which prevents possible contamination of the water with sewage. The trunnioned cradle is positioned by the pneumatic piston and is locked by a

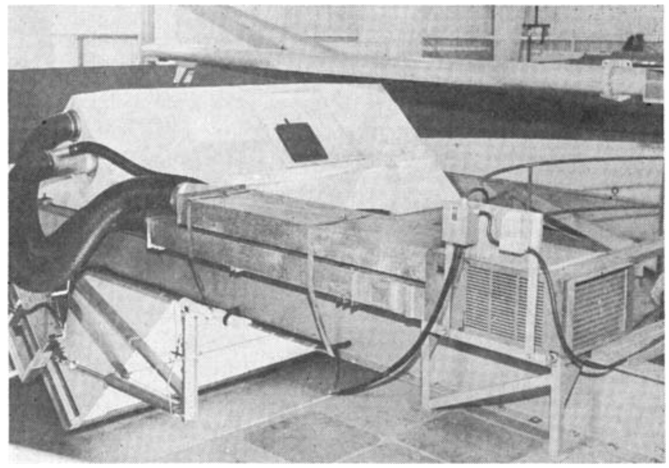

Fig. 3. Simulator suspended from centrifuge.

second hydraulic piston. The driving piston can be used to program instability into the system. Variable radii can be obtained by positioning the cross beams and changing the counterbalance. The facility plan is seen in Figures 2 and 3. Considerable space was devoted to sleeping quarters for anticipated extended runs. Two full-size twin mattresses were used to assure proper sleeping capability. The toilet is mounted on a kitchen disposal so all waste can be removed through the line.

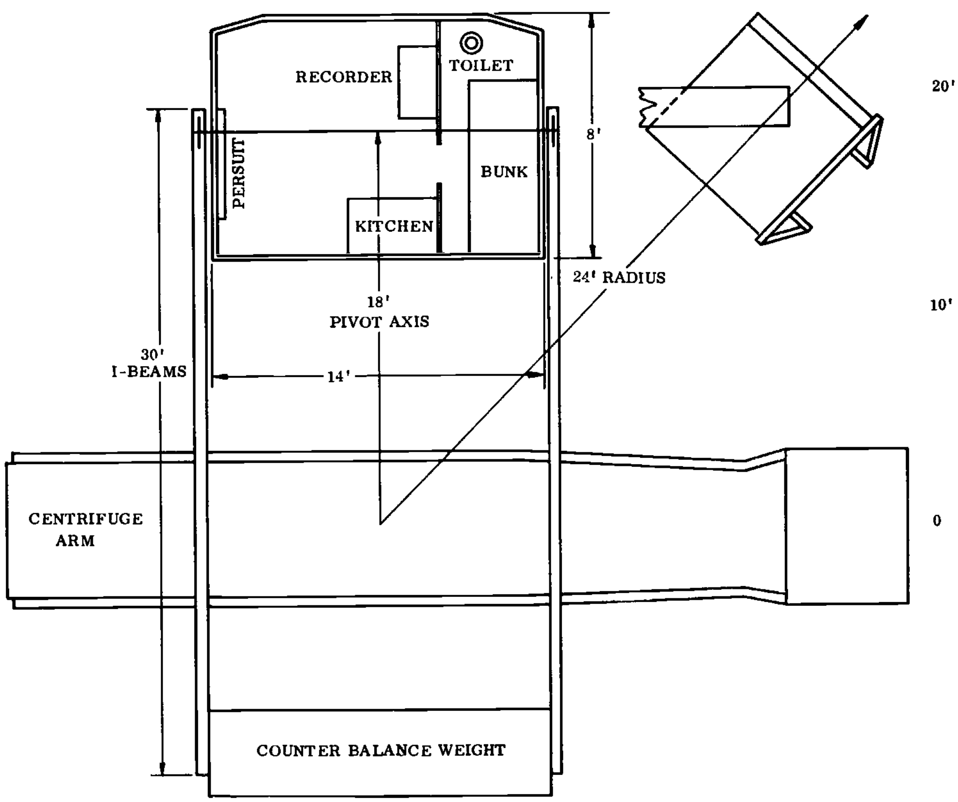


Fig. 2. Arrangement of the Manned Revolving Space Station Simulator.

A small galley with sink and running water is available for cooking and food storage.

## METHOD

To determine artificial g space station design criteria on a performance basis a set of standardized tests are required that can be evaluated objectively. Several of the Astronautics tests investigated for this purpose have been reported.[9,10,11] This paper deals with the balancing and walking aspects as these are most directly related to the velocity change and force alignment discussed previously.

At low RPM's, the Graybiel-Fregley rail[12] was used for walking and standing tests. Above five RPM the tasks of walking on the ¾-inch rail and standing with eyes closed on the 2¼-inch rail were found to be too difficult for the average subject. At these higher RPMs the only rail test used required subjects to balance on the 2¼-inch rail on one foot, first the right and then the left, with arms folded and eyes open. A modified stethoscope was used to distribute all noise symmetrically to the subjects' ears. Sixty seconds was considered a perfect score.

To quantitate the difficulty in walking a straight line a grid placed on the floor was aligned radially so the subject should walk toward the center of rotation. It consisted of a five-foot square marked off in a six-inch grid. Subjects walked toward a goal with eyes closed, arms folded and wearing the stethoscope. The number of steps completed and the point on the grid where the subject lost his balance were recorded.

In both tests the best three out of five scores were averaged for each trial. Subjects were tested once each hour. The testing schedule was two hours pre-rotation, four hours at the designated RPM, followed by two hours post-rotation testing. The subjects were male engineers between 25 and 35 years of age. All passed a Class 2 flight physical. Those who became ill were retired to the bunk area and instructed to lie motionless. Their data was not included in the results.

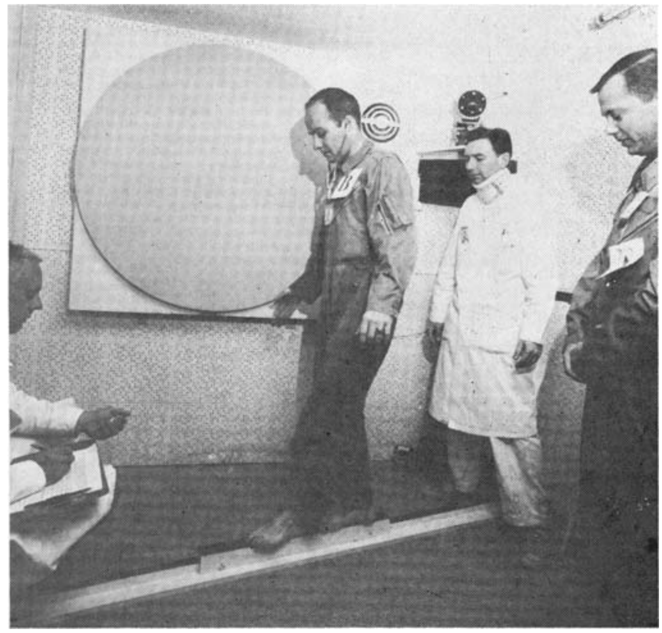

Fig. 4. Modified Graybiel-Fregley Rail on board MRSSS. Myocervical collars used to restrict head movement and decrease vestibular effects.

## RESULTS

Figure 4 depicts the modified rail test. The balancing was done on the 2¼-inch rail. Observers wore myocervical collars to reduce disturbing head movement. Though approximately 50 per cent of 40 subjects tested

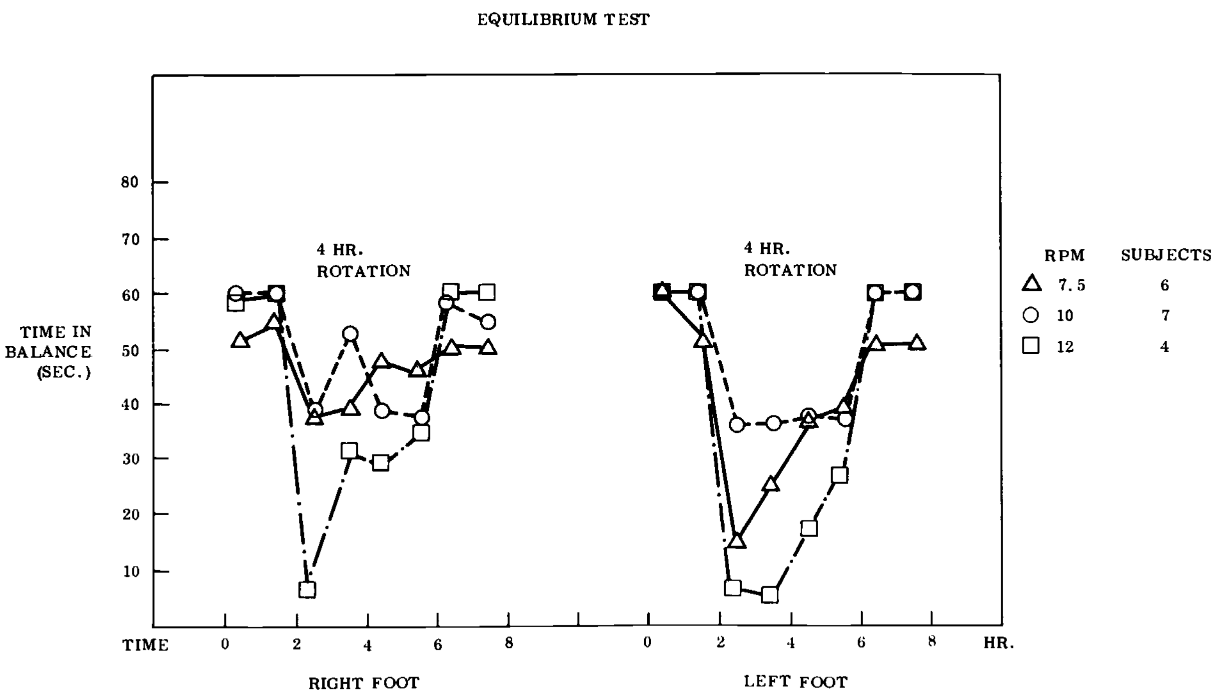


Fig. 5. Time of balance on one foot. Subjects were tested in sequence once each hour.

in previous tests became ill at some time during the test, none of the five observers was ill while wearing the collars.

The time of balance differed from right to left leg. This may be due to a majority of right handedness or to the effects of the gravity gradient acting to the right when facing radially inward. Counterbalance is more difficult under such a situation on the left foot. Figure 5 indicates that considerable adaptation to the initial disorientation can take place within the four-hour time of rotation. Performance was better at 10 RPM than at 12 but not much different from 7.5 RPM considering the pre- and post-rotation scores.

Following the balancing test subjects were asked to walk the grid toward the designated goal with their eyes shut, as seen in Figure 6. Subjects usually lost their balance without becoming alarmed. They frequently would fall into the observers arms without opening their eyes or unfolding their arms. They were seemingly unaware of how to correct their fall. During rotation subjects usually fell to the right; this is consistent with the coriolis effect produced by walking toward the axis in a system rotating counterclockwise.

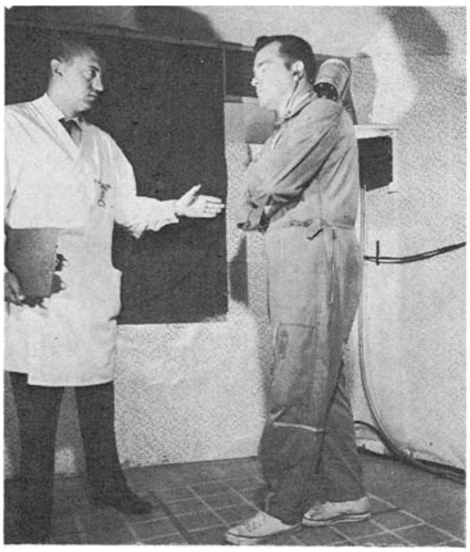

Fig. 6. Subject being tested on grid in MRSSS. Stethoscope used to orient all noise to a constant direction.

Considerable degradation in performance is apparent from Figures 7 and 8. Prior to rotation the task is a simple one to accomplish but during rotation it becomes quite difficult. Other performance tests[9] show a faster adaptation rate. During rotation the path of the unadapted subjects resembled that of a ball rolled over the same grid. A ball assumes an apparent spiral path in a spinning room. This course has been explained by conservation of momentum and coriolis effect.[13] The result is that the subjects take a series of steps in a path of decreasing radius and lose their balance. One mode of adaptation appears to be increased ability to maintain balance. The second part of adaptation is compensating for the deviation from path. Repeated errors result in a learning or adaptation so that subjects show improved performance during the four hours of rotation.

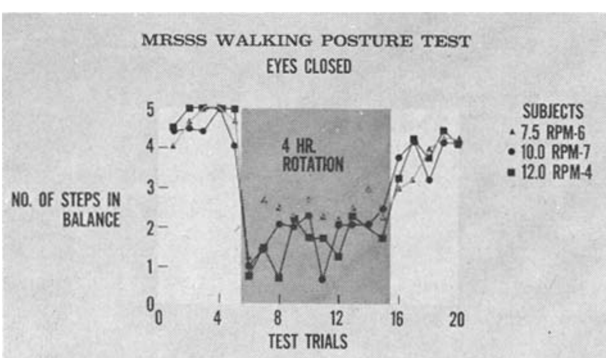


Fig. 7. MRSSS walking posture test. Number of heel-to-toe steps taken in balance with eyes closed.

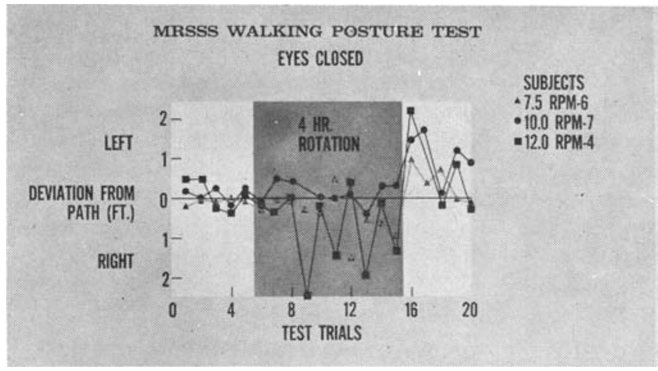


Fig. 8. MRSSS walking posture test. Deviation from path at time of equilibrium loss.

## DISCUSSION

The results indicate that there is a substantial decrease in the ability to balance on one foot in the rotating environment. Performance at 10 RPM had the least decrement but it also exhibited the least indication of adaptation. Both the 7.5 and 12 RPM curves show considerable adjustment. Subjects considered the 10 RPM desirable to either the 7.5 or 12 RPM tests.

Both balancing and walking tests indicate that a learning process can be accomplished in this rotating environment; this is shown most dramatically by data on the deviation from desired path in Figure 8. Subjects had begun to adapt to the rotating system by making the necessary compensations to overcome coriolis forces. They carried this learning process over into the tests during post rotation. Deviations to the right of path suddenly became errors to the left. Readaptation then had to take place for the static environment. No such post rotation effect was evident in the balancing tests, where recovery was immediate when the room stopped spinning.

The subjects who were confined to bunks during rotation did not show any post-rotation disorientation. They were able to proceed directly across the grid just as they had prior to rotation. This indicates that the compensation is a learned response requiring dynamic exposure and correction. A generalized adjustment to the unique environment does not appear to take place in the four-hour exposure.

## SUMMARY

Two important artifacts may exist in the use of data from a small room rotating about its center for defining space station design criterion. First, the small radius requires the crew to undergo considerable acceleration and deceleration for all motions that are not at a constant radius. This will not be the case in the space station and the effect can be considerably reduced by using a simulator with a longer radius.

The second artifact is the alignment of the floor in a turn-table-type room. In space the artificial gravity will be normal to the floor and thus act as a constant reference for balance but in the room revolving about its center, subjects must constantly compensate for a changing angle of force during ambulation.

Two tests were used to assess the adaptation of subjects to high rates of rotation. A simulator with a trunnioned floor revolving at a 20-foot radius was used. The standing test shows that considerable learning takes place in balancing ability within the four hours when the g force is perpendicular to the floor. Walking ability similarly was tested by having subjects walk toward the radius with eyes closed. Again, adaptation was evident during the short period of the test and it can be anticipated that continued improvement would occur with longer testing.

Space station design criteria should be based on physiological and psychological performance limits rather than nausea alone. The tolerance of individuals to rotation differs greatly and it can be assumed that selection of a crew with high rotation tolerances will be possible. In addition studies of the type reported will undoubtedly result in protection methods and training programs to increase rotation tolerance of susceptible individuals.

## REFERENCES

1. Dole, S. H.: Research, Memo 2668, Design Criteria for Rotating Space Vehicles, Rand Corp., Oct. 18, 1960.
2. Landsberg, M. P.: *A Primer of Space Medicine.* Elsevier Press, Amsterdam 1960.
3. Clark, C. C. and Hardy, J.: Gravity Problems in Manned Space Stations, *Proceedings of the Manned Space Stations Symposium.* Inst. of Aeronaut. Sciences, April 22, 1960.
4. Graybiel, A., Clark, B. and Zarrielo, J.: Observations on Human Subjects Living in a "Slow Rotating Room" for Periods of Two Days, *Arch. of Neurology,* 3:77, 1960.
5. Clark, B. and Graybiel, A.: Human Performance During Adaptation to Stress in the Pensacola Slow Rotating Room, *Aerospace Med.*
6. Graybiel, A., Guedry, F. and Johnson, W.: Adaption to Bizarre Stimulation of the Semicircular Canals as Indicated by the Oculogyral Illusion. Rep. No. 464, U. S. Army Medical Res. Lab. (Fort Knox) 23 Feb. 1961.
7. Loret, B. J.: Optimization of Manned Orbital Satellite Vehicle Design with respect to Artificial Gravity. *ASD TR* 61-688.
8. Stone, R. W. and Letko, W.: Effects of Rotation on the Ability of Subjects to perform Simple Tasks. *NASA TN D-1504,* Aug., 1962.
9. Brady, J. F., Urmston, R. E., and Newsom, B. D.: Large Excursion Rotary Tracking of Target and Target Light in a Space Simulator Revolving at 7.5, 10.0 and 12 RPM. *Aerospace Med.,* 35:260, 1964.
10. Lagerwerff, J. M. and Newsom, B. D.: Visual Changes Observed in the Manned Revolving Space Station Simulator at High Rotational Speeds. *Aerospace Med.,* 35:273, 1964.
11. Goble, G. J. and Newsom, B. D.: Urinary Changes in Man Induced by Rotation. *Aerospace Med.,* 35:268, 1964.
12. Fregley, A. R.: Graybiel-Fregley Posture Tests (Personal Communication) U. S. Naval School of Aviation Medicine.
13. McDonald, J. E.: The Coriolis Effect. *Scientific American,* 186:89, 1956.

## ERRATUM

The correct legend for Figure 2 of the paper entitled "Hearing Sensations In Electric Fields" by H. C. Sommer and H. E. vonGierke is shown below. This was published in *Aerospace Medicine,* 35:834, 1964.

Fig. 2. Alternating pressure (p) on the head, or the plate of a condenser, for the frequency $\omega_m$, as a function of the static field strength $E_o$ and the modulation factor $\xi = \frac{E_m}{E_o}$ of an electric field $E = E_o\ (1 + \xi \sin \omega_m t)$. For $E_o = 0$ the pressure is of the frequency $2\,\omega_m$ and follows the line so marked. See text for applying the same curves to an amplitude modulated high frequency field. Approximate pressure ranges for the human auditory thresholds for air and bone conduction at 1000 cps are indicated. The dashed curve (radiation pressure) indicates the radiation pressure on a conducting sphere in a plane progressive electromagnetic wave with a wave length small compared to the diameter of the sphere. "A" represents the range of electric field strength used in this investigation with small electrodes on the skull (Fig. 1b); "B" represents the range with the insert electrode (Fig. 1c); "C" represents the range used by Puharich and Lawrence[12,13] on normal subjects; and "D" indicates the range of the field strength in Frey's[6,7] radar beam.