EXPERIENCES WITH THE USE OF VIBRATIONAL TECHNIQUES FOR THE DETERMINATION OF THE RESONANT FREQUENCY OF BONE IN VIVO

by

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INTRODUCTION

It has been proposed that the resonant frequency of bone in vivo may be empirically useful for the clinical evaluation of bone.¹ While the formulation of a precise mathematical description of a bone vibrating in vivo is difficult, under certain simplifying assumptions concerning the ulna it can be shown that the product of its resonant frequency (F_0) of transverse vibration and length (L) is proportional to the square root of the ratio of Young's Modulus and the linear density of the ulna.² Jurist³ found that the product $F_0 \times L$ of the ulna in osteoporotic women was significantly lower than normal individuals of similar age and physique. An investigation of the relationships between the resonant frequency and various physical parameters of bone such as bone mineral content, density, Young's Modulus, and ultimate strength was planned. A number of experimental conditions such as arm and wrist orientation, etc. affect the measurement of the resonant frequency³ and preliminary measurements in vivo were made to gain familiarity with the technique and to establish suitably controlled experimental procedures. However, difficulties were encountered which prevented the completion of the original investigation. This report describes some of these difficulties and a number of observations on the effects changes in the experimental instrumentation have on the measured frequencies.

METHODS

Two techniques were used for the determination in vivo of the resonant frequency of bone. In the first technique, the vibrational response technique (VRT) of Jurist², an oscillatory force is applied to the ulna at the olecranon process by an electromagnetic driver. The frequency of the force is swept through the range of about 50 to 400 Hz. A small piezo-electric accelerometer strapped to the wrist at the styloid process detects the transverse vibration set up in the bone by the driver. This signal is amplified and rectified to provide a DC voltage which is recorded as a function of the frequency of the driving force on a chart recorder. This record is the vibrational response of the bone and the resonant frequency is taken at the frequency of the maximum amplitude response. In the cases where there are several resonances in the curve, the frequency is taken at the first or lowest frequency. Figure 3 shows a typical ulnar response curve.

In the second technique, the feedback technique (FBT), the bone is the frequency controlling element, a mechanical vibration filter, in a physical

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oscillator.⁴ Figure 1 is a block diagram of the method. A transient vibration which should include the resonant frequency of the ulna is started by either tapping the bone or by random motions of the driver due to circuit noise. This vibration is detected by the accelerometer at the styloid process, and the amplified accelerometer signal powers the driver which is in contact with the olecranon process. The ulna responds preferentially at its resonant frequency, with the relative magnitude of vibration at resonance being greater than at other frequencies. Thus the predominate frequency of the vibration now detected by the accelerometer and hence that of the driving force which is reintroduced into the ulna is the ulna's resonant frequency. As this cycle is repeated a progressively stronger signal at the resonant frequency of the ulna is fed back resulting in steady state oscillations in the circuit with the ulna vibrating at its resonance. A frequency meter is then used to determine the resonant frequency of the ulna.

OBSERVATIONS

In both techniques the frequencies assigned to the resonances found in vivo were dependent upon the orientation of the arm, the position and orientation of the accelerometer and driver, muscle tension, etc. The vibrational response curves obtained using the VRT usually contained several resonant peaks whose frequencies and relative amplitudes could be varied by changing any of the above factors. In a similar fashion the frequencies at which oscillations occurred in the FBT were also dependent upon these factors. However for any particular set of measurement conditions in either technique discrete resonant frequency could be found. The standard deviation was typically 5% and it was slightly better, about 3%, for trained subjects. The reasons for this effect was not known and it was assumed that the discrete resonances obtained were due to preferential excitation of different vibrational modes or non-harmonic overtones of the fundamental. It was believed that comparisons of the resonant frequencies obtained at different times would be possible by rigidly constraining the measurement conditions so that the same mode was always excited.

The resonant frequencies determined by the two techniques were expected to be related due to the similarity in the methods used to excite and detect the vibrations in vivo. However no correlation was found between the resonant frequencies of 131 subjects determined by the two techniques. The driver and accelerometer were positioned to the subject's arm in approximately the same position for both techniques and the two measurements were performed within 10 or 20 minutes of each other. Figure 2 is a scattergram of these measurements. It appeared that one or both of the techniques were not accurately measuring the vibrations of the bone, although the instrumentation seemed to be operating properly. Since the frequencies of oscillation in the FBT seemed to be more sensitive to the contact pressure between the bone and accelerometer than the VRT, the elastic nature of the skin and soft tissue was suspected as modifying the detection of the vibration of the bone. It was thought that the skin might be more important in determining the frequency of oscillation than the elastic properties of the bone. An arm phantom for use with the FBT was constructed to investigate this hypothesis.

MASTER

The phantom consisted of a rod ("bone") supported on a pad of stiff spongy material ("tissue") with small pieces (~ 1 mm thick) of turkey skin ("skin") placed between the "bone" and the accelerometer and driver. Rods of lucite, steel, aluminum, wood, and an excised fibula were used to simulate "bones" of different elastic moduli. The vibrational properties of the phantoms were similar to those of the bone in vivo; the range of frequencies was about the same, i.e. about 300-750 Hz; the frequency was dependent upon contact pressure and/or orientation between the accelerometer, driver and the "bone"; and the coefficients of variation were typically 5-7%. There was no obvious relation between the different "bones" and the frequency at which oscillations were excited and it appeared that transverse vibrations in the "bones" were ineffective in governing the frequencies of oscillation. It could not be determined whether transverse vibrations were occurring and were masked by the effect of the "skin" or whether they were not occurring in the "bone" at all.

Since the manner in which vibrations are excited and detected is the same in both techniques, the question regarding the actual presence of transverse vibration in the bone or whether these are measured is also applicable to the VRT. VRT measurements on the ulna in vivo were performed using different accelerometers, drivers, and oscillators. It was felt that if the measured vibrational response curves and resonant frequencies were relatively independent of different instrumentation, it would at least indicate that a quantity related to the bone's vibrations was being measured. Table 1 contains a list of the various components used, the accelerometers are listed in order of decreasing mass and sensitivity (mv per cm/sec^2). The frequency responses of the accelerometers were uniform in the frequency range of interest, i.e. less than 1000 Hz. The orientation of the limb, position of the accelerometer and driver, and other measurement factors were maintained as constant as possible for the various components used.

Different Accelerometers: Figure 3 shows the ulnar response curves obtained using accelerometers A-1 and A-2 with oscillator 0-1 and driver D-1. While there is fair agreement between the curves above 500 Hz, there is evidence that these peaks are due to variation in the driver output rather than vibrations in the bone.² However, it is frequencies below 500 Hz that are of interest because the technique assumes that the ulnar resonance in vivo occurs in this region. The differences in the recorded responses are apparent; in the case of A-1 the ulnar resonant frequency could be anywhere from 290 Hz to 400 Hz, while for A-2 it would be taken to be about 400 Hz.

Different Oscillators: The ulnar response curve shown in Figure 4 was obtained using accelerometer A-2 with driver D-1 and oscillator 0-2 on the same individual whose responses are shown in Figure 3. The response in Figure 4 should be the same as that labelled A-2 in Figure 3. The only difference in the methods used to obtain these curves is the oscillators used; this is the reason for the different abscissas in the figures. However, there is no correspondence between the curves at those frequencies which overlap. In Figure 3 the resonant frequency would be nearly 400 Hz while if determined from Figure 4 it would be either ~ 125 Hz or ~ 250 Hz. Although the range below 200 Hz is not shown in Figure 3, there was no response corresponding to the one at ~ 125 Hz seen in Figure 4.

Different Bones: Since the anterior surface of the medial tibia is readily accessible and relatively flat it was felt that measurements here might reduce the variations due to changes in orientation of the driver and accelerometer seen with the ulna, and tibial vibrational response curves in vivo were obtained. The position of the leg, points of contact between the accelerometer and driver, and the leg, and contact pressure were maintained constant. Figure 5 shows the response of the tibia obtained using oscillator 0-2 and driver D-1 with accelerometers A1, A2, and A-3. While the apparent resonances at 125 Hz are not greatly shifted in frequency for the different accelerometers, there are slight differences in the shapes of these peaks. There is a shift of about 50 Hz, ~ 200 Hz to ~ 250 Hz, between the frequencies at which the maximum response occurs for accelerometers A-2 and A-3 respectively. Also the corresponding peak is missing in the response obtained using A-1. It is interesting to note that the tibial response obtained using A-2 and the ulnar response (Figure 4) also obtained with A-2 and the same oscillator and driver are remarkably similar for such dissimilar bones.

Different Drivers: Tibial responses were measured using oscillator 0-2 and either accelerometer A-1 or A-2 with drivers D-1 and D-2. These curves are shown in Figure 6. The response curves obtained using A-1 with drivers D-1 and D-2 are similar with resonances at about 125 Hz. However, the curves obtained for the different drivers with A-2 are quite different, there is a shift of about 60 Hz between the frequencies at which the higher resonance appears and the resonance at ~ 100 Hz is not present in the curve obtained using D-2. It could be argued that these differences seen with A-2 are caused by the excitation of different vibrational modes, but it is difficult to see why similar changes are not found in the response curves obtained using accelerometer A-1 with the two drivers.

CONCLUSIONS

The above observations provide a basis for reasonable doubt concerning the validity of the basic premise of the vibrational techniques, i.e. that transverse vibrations are excited in the bone in vivo and that the accelerometer accurately detects this motion. In the phantom studies the resonances appeared to have no dependence on the elastic moduli of the various "bones" used, indicating that transverse vibrations are either not occurring in the "bone" or that the vibrations do not determine the frequency of oscillation. The vibrational response curves which presumably were proportional to the bone's transverse vibrations in vivo change with different excitation and detection instrumentation. The absence or presence of resonant peaks in the response curves or shifts in their frequencies caused by using different accelerometers, drivers, and oscillators make it difficult to believe that the bone's vibration is accurately represented in the response curves. The curves are clearly more complex than first assumed and probably represent motions other than the bone alone. It is doubtful that the true resonant frequency or even a measure of it can be determined by this technique in its present state. Investigators at three other laboratories have also indicated that they have encountered difficulties in the practical use of this technique.⁵ While it is recognized that a complete investigation is necessary to resolve these questions and that the observations presented do not entirely meet this need, they are of value in alerting other investigators to some of the uncertainties not discussed in the initial references concerning the vibrational techniques.

References

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5. Private Communications

Table 1: Instrumentation

	<u>Code Number</u>	<u>Manufacturer</u>	<u>Comments</u>
PIEZOELECTRIC ACCELEROMETERS	A-1	Endevco Corp.	78 gms; Most Sensitive
	A-2	Glenite	20 gms; Intermediate
	A-3		2 gms; Least Sensitive
DRIVERS	D-1	Atlas Electric Device Co.	Atlas PD-4V; Modified with Lucite Driver Piston
	D-2	Reliance Electric Mfg. Co.	Modified Ashworth Sound Reproducer
OSCILLATORS	O-1	Heath Co.	Kit.
	O-2	Home Built	From RCA Design Manual

Figure 1. Block diagram of the feedback technique for determining the ulnar resonant frequency in vivo.

Figure 2. Scattergram of ulnar resonant frequency determined in vivo using the FBT and VRT (Number of subjects = 131).

Figure 3. Ulnar response curves obtained in vivo using oscillator 0-1 and driver D-1 with accelerometers A-1 and A-2.

Figure 4. Ulnar response curve obtained in vivo using oscillator 0-2, driver D-1, and accelerometer A-2.

Figure 5. Tibial response curves obtained in vivo using oscillator 0-2 and driver D-1 with accelerometers A-1, A-2, and A-3.

Figure 6. Tibial response curves obtained in vivo using oscillator 0-2 and accelerometers A-1 and A-2 with drivers D-1 and D-2.