MASTER**MEASUREMENT OF TIBIAL RESONANT FREQUENCY:****A PRELIMINARY REPORT****John W. Raasoch and John M. Jurist**

Our laboratory is studying bone resonant frequency measurement as an indication of relative skeletal strength [1,2]. To date, we have used the ulna for resonant frequency studies -- driving the ulna at the olecranon process and measuring its response as a function of frequency with an accelerometer at the ulnar head. In hopes of improving the precision and usefulness of the resonant frequency measurement, we are evaluating the tibia. There are two reasons for employing the tibia: First, the tibia is less irregularly shaped than the ulna. Second, the tibia is a weight-bearing bone.

Our first consideration was whether the tibia should be horizontally or vertically oriented during the resonant frequency measurement. The horizontal position was chosen for several reasons. During resonant frequency studies, numerous specific modes of vibration have been detected. These different vibrational modes may be more readily excited by imperfect or inconsistent positioning relative to the irregularly shaped bone, variations in muscle tension, soft tissue edema, and other variable factors [3]. The excitation of inconsistent modes with repeated measurements occurs less frequently and is easier to detect with the tibia in the horizontal position than in the vertical position (Figure 1). In the horizontal position, two modes are often excited during a single recording, thus aiding in identification of these different modes. Another advantage of the horizontal position is the ability of a healthy subject to lay down, while a "cart patient" is not always able to sit up and hold his leg in a vertical position. The horizontal position is also convenient for the technician because of the relative ease of making the resonant frequency recording.

The next consideration was the positioning of driver and accelerometer on the tibia. Eight different combinations of accelerometer and driver position were investigated on eight tibiae (four subjects). The different locations are illustrated in Figure 2. As shown in Table I, position I is more desirable than positions II through VI because of a smaller probability of erroneously identifying inconsistent vibrational modes. A much "cleaner" record is also obtained with position I. It should be

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noted that whenever the driver and the accelerometer are close together (positions III, VII, and VIII), two resonance peaks are commonly found on the same record. With the accelerometer at midshaft (positions VI, VII, and VIII), two peaks are also observed.

The ratio of the frequencies of the two different modes (F_B/F_A) is essentially constant for positions I through VI. The F_B/F_A for positions VII and VIII, however, are markedly different.

An elastic body filled with an incompressible fluid [4] exhibits vibrational modes which are approximately given by $F_N = K_1 (K_2 + N)$, where K_1 and K_2 are constants, and N is an integer. In order to obtain an F_B/F_A ratio of 1.33, it is assumed that $K_2 + N_B = 4$ for mode B and $K_2 + N_A = 3$ for mode A. The F_B/F_A ratio can be increased (as it was for positions VII and VIII), by decreasing the $K_2 + N$ value, for example, to 2 for mode "A". Then, $F_B/F_A = 1.50$. However, if the second or higher mode (B) was suppressed, and the next higher mode was excited instead, the ratio of the two modes would be 1.67 ($K_2 + N_C = 5$, $K_2 + N_A = 3$) which approximates the 1.69 and 1.62 values obtained in positions VII and VIII. This latter possibility is also consistent with the increased difference between modal frequencies found in these positions (roughly twice the $F_B - F_A$ values of positions I through VI). Therefore, it seems that mode B is suppressed or not excited and that a higher mode is excited in positions VII and VIII. In the equation $F_N = K_1 (K_2 + N)$, the value(s) of N can change with the positioning of the accelerometer and driver. K_1 was also found to vary with these positional changes, presumably because of changes in boundary conditions. Positions I through III did not exhibit any significant shift in the value of K_1 , while positions IV and VI exhibited K_1 values about 20% larger than those of positions I through III. Positions V, VII, and VIII exhibited decreased values (10-20% less than the K_1 of position I).

The "best" position for operational measurement of tibial resonant frequency becomes a choice between positions I, VII, and VIII. The lowest probability of erroneously identifying inconsistent vibrational modes was obtained with position VII (Table II). Subjectively, the "cleanest" resonance peak was obtained with

position I, and the largest resonance peak with position VIII. Therefore, no clear-cut choice between these three positions can be made, so position I will be used routinely because of the relative ease of measurement in this position.

Another consideration in measuring the tibia is whether to place the driver on the medio-anterior surface or on the anterior edge. Driving the tibia on the anterior edge is occasionally painful so the medio-anterior surface is used when pain is encountered. The amplitude of response is usually somewhat larger when the tibia is driven on the anterior edge.

Another finding in this study was the rather poor correlation between age and either tibial or ulnar resonant frequency. The ulnar resonant frequencies of children were significantly lower than previously reported [2] (Figures 3, 4, 5, and 6). However, these data were collected in the hospital, so some deviation from the findings for a "normal" population is not unreasonable.

Although we do not have sufficient data to prove this hypothesis, we believe that the resonant frequency versus age data shown in Figures 3 through 6 may represent "families" of curves corresponding to different vibrational modes.

The reproducibility of the tibial resonant frequency measurement ranged from 3% to 13% (RMS about the mean value). For 30 F_A measurements made on one subject during one day, the RMS reproducibility was about 3%. The 13% reproducibility was obtained over several months of measurement (6 tibiae, 36 F_A measurements)

without correction for possible excitation of inconsistent modes. When different modes were identified, the RMS reproducibility about each individual mode was 6%. Without this modal identification, the RMS reproducibility of the ulnar F_A measurement was 10%. The

standard deviation for the repeated ulnar resonant frequency measurement is about 32 Hz as contrasted to that for the tibia (about 42 Hz). However, the difference between adjacent vibrational modes for the tibia is about 37 Hz as compared to about 16 Hz for the ulna. A larger number of different modes can be excited in the ulna than in the tibia (Figure 7). However, the ulna still has a better reproducibility, especially when the measurements are corrected for vibrational mode. The technique of ulnar measurement involves the use of an arm support, while the preliminary tibial measurements were done with a hand-held driver. With some refinement of the tibial measurement technique, the large interval between adjacent resonance peaks in this bone suggests that

resonant frequency studies will improve in reliability by employing the tibia rather than the ulna. The relatively large interval between adjacent tibial resonance peaks will be especially useful during longitudinal studies of skeletal status by allowing identification of different vibrational modes.

In addition to being dependent on positioning, measured resonant frequency is also dependent on frequency sweep rate. It is necessary to use a constant frequency sweep because, at different sweep speeds, different modes may be preferentially excited. For example, our present apparatus has two frequency ranges: A "low" range (about 75 to 550 Hz), and a "high" range (about 150 to 1100 Hz). In the frequency interval in which the two ranges overlap (150 to 550 Hz), different frequency sweep rates are obtained, depending on which range the oscillator is set. We measured both ulnar and tibial resonant frequencies on four subjects (eight ulnae, eight tibiae) with both oscillator ranges. On six of the eight ulnae, the resonant frequencies measured on the two ranges were not equivalent. The resonant frequencies obtained with the oscillator set to the "high" range were higher than those with the oscillator set to the "low" range. On two of the ulnae (three vibrational modes), however, the resonant frequencies matched on both oscillator ranges (Table III). On three of the eight tibiae, resonant frequency values measured on the two ranges were not equivalent. On five of the tibiae (six modes), however, the resonant frequencies matched on both oscillator ranges (Table III). We interpret these findings as showing preferential suppression of lower vibrational modes at high frequency sweep rates such as obtained on the oscillator "high" frequency range. The other phases of this study were performed with the oscillator set on the "low" frequency range only. This problem warrants further investigation.

Age and skeletal condition reportedly affect ulnar resonant frequency [2]. Osteoporotics have been shown to have lower resonant frequencies -- possibly caused by preferential excitation of lower vibrational modes -- than normal subjects matched for age and sex. However, it is also possible that boundary conditions may be different in osteoporotics than in normal subjects because of systematic differences in muscle mass, joint impedance, etc.

Resonant frequency studies are ultimately aimed at distinguishing "osteoporotic" individuals from "normal" subjects. Ulnar resonant frequency studies have shown lower resonant frequencies for osteoporotic subjects [2] and preliminary (unpublished) tibial data support this. However, at present there is too much modal variation

between individuals to allow for an accurate diagnostic test. Positioning must be improved and specific vibrational modes and frequency intervals must be identified. "Good" or consistent positioning is also a function of the cooperation of the subject and thus indirectly of his health. Mode identification and subsequent correction of resonant frequency data increases reproducibility. With such correction, the tibia may prove more useful than the ulna. To this end, we will construct a tibia driver support, analogous to the ulna driver support described previously [1]. Figure 8 shows our design for such a driver.

References

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TABLE I

POSITION	OCCURRENCES		PROBABILITY OF ERRONEOUS MODE IDENTIFICATION	MEAN FREQUENCIES		F_B/F_A	$F_B - F_A$ (Hz)	K_1 (% of K_1 for Position I)
	MODE A	MODE B		F_A (Hz)	F_B (Hz)			
I	1/8	7/8	1/8	178	236	1.33	58	100
II	2/8	6/8	2/8	171	238	1.39	67	96
III	3/8	6/8	3/8	170	245	1.44	75	96
IV	5/8	3/8	3/8	211	260	1.23	49	119
V	6/8	2/8	2/8	158	206	1.30	48	89
VI	3/8	7/8	3/8	208	267	1.28	59	117
VII	8/8	8/8	0/8	147	249	1.69*	102	83
VIII	7/8	7/8	1/8	146	236	1.62*	90	82

*For the first 6 positions, the mean value of F_B/F_A was 1.33 with a standard deviation of 0.08.

TABLE II

<u>POSITION</u>	<u>PROBABILITY OF ERRONEOUS MODE IDENTIFICATION</u>
I	1/8
VII	0/8
VIII	1/8

TABLE III

<u>BONE</u>	<u>RESONANT FREQUENCY VALUES (in Hz) OBTAINED FOR DIFFERENT OSCILLATOR FREQUENCY RANGES</u>			
	<u>LOW RANGE</u>		<u>HIGH RANGE</u>	
Ulna	202	207	201	205
	205	208		
Ulna	252		246	
Ulna	223	226	233	
	223	227		
	224	234		
Tibia	277		264	
Tibia	255		259	
Tibia	260		247	
Tibia	268	285	272	
	271			
Tibia	223	230	236	
	224	231		
	227	243		
	228			
Tibia	260	283	281	
	260	285		
	227	243		
	228

Fig. 1: Distribution of excitation of different vibrational modes in the human tibia as a function of orientation.

Fig. 2: Location of the driver and accelerometer on the leg for the 8 positions studied. The shape of a typical acceleration response vs driving frequency curve is illustrated for each position.

Fig. 3: Tibial resonant frequency vs age for 26 male patients.

Fig. 4: Tibial resonant frequency vs age for 21 female patients.

Fig. 5: Ulnar resonant frequency vs age for 31 male patients.

Fig. 6: Ulnar resonant frequency vs age for 32 female subjects.

Fig. 7: Distribution of excitation of different vibrational modes in the ulna and in the tibia.

Fig. 8: Proposed support for tibial driver unit.