Acta orthop. scand. *53*, 867–874, 1982

RESONANCE OF THE HUMAN TIBIA

Method, Reproducibility and Effect of Transection

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Driving point impedance technique was used for *in vivo* determination of the lowest frequency of resonance (F_a) in the human tibia. Optimum conditions for measurement were investigated. The precision of the method was 4.7 per cent and the greatest source of variation was the positioning of the leg and muscular tension. F_a was investigated during transection of the human tibia post-mortem and was found to decrease as stiffness was reduced by the transection. Accordingly F_a was decreased in four patients with crural fractures. The experiments indicate that the method can be used for the determination of fracture healing.

Key words: bending rigidity; bone; fracture; mechanical impedance; resonance frequency; tibia

Accepted 20.iii.82

Determination of the mechanical properties of bone *in vivo* has in most cases been based upon invasive techniques (Jernberger 1970, Jørgensen 1975), but during the past decade vibrational methods have been introduced which could prove to be of great importance for the non-invasive evaluation of fracture healing and the detection of osteoporosis. Wave propagation tests by ultrasound or sound transmission have not yet gained clinical application probably due to the difficulty in obtaining the necessary contract between the two transducers and the bone, but Jurist (1970) presented a two-point impedance testing technique for the detection of osteoporosis, and Campbell & Jurist (1971) later introduced the driving point impedance technique for *in vitro* testing of femoral neck fractures.

We have studied the *in vivo* reproducibility of the point impedance technique on the human tibia, using lowest frequency of resonance (F_a) and mobility at F_a as parameters. Optimum conditions for measurement were investigated.

Accurate assessment of fracture healing is frequently difficult and evaluation based on the expected healing time, callus formation as revealed by radiography, and manual testing for stability and pain in the fractured area, may be inconclusive.

To illustrate to what extent the frequency of lowest resonance (F_a) reflects changes in stiffness in the healing fracture, F_a was measured during gradual transection of the human tibia post-mortem. In addition preliminary determinations were performed on patients with crural fractures.

SUBJECTS AND METHODS

The apparatus which was employed is shown in Figure 1. From the sine generator the signal is transmitted through the power amplifier to the shaker on which an impedance head is mounted. Dynamic force (L_F) and

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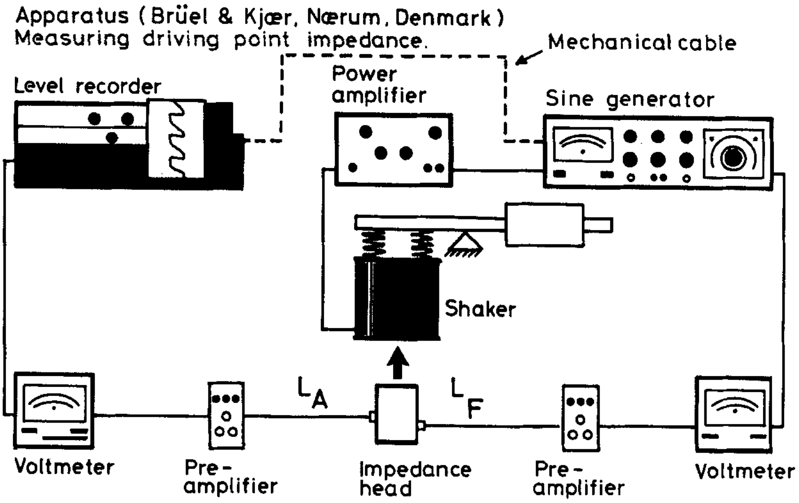

Figure 1. The signal from the sine generator is transmitted through the power amplifier to the impedance head. The force signal L_F from the impedance head is fed to the compressor loop keeping the force constant. The accelerometer signal L_A is integrated and recorded (as mobility) on the level recorder as the frequency is scanned.

acceleration (L_A) are measured and the force signal is used in the compressor loop of the sine generator to maintain a constant dynamic force as the frequency is scanned. The signal from the accelerometer is integrated in the preamplifier and the velocity signal (mobility) is recorded on the level recorder.

The investigations were performed on healthy humans with no previous history of fracture or bone disease. The person lies supine, with the limb on a Braun splint as shown in Figure 2. The splint is made of a steel frame covered with cloth; thus the leg is supported continuously from the knee to the heel on a stretched cloth. The impedance head is placed on the anterior tibial margin 2 cm below the tuberosity in the sagittal plane and the frequency is scanned from 30–1000 Hz. The frequency of lowest resonance is determined by tuning the oscillator to the maximum velocity response. Triple determinations are used in the tests.

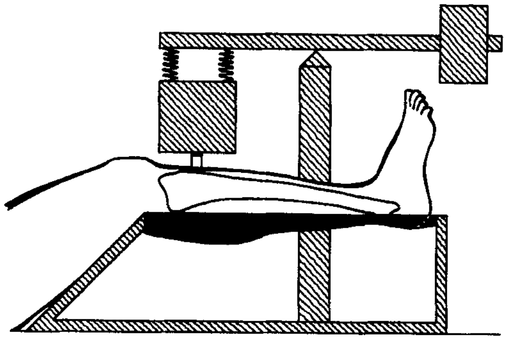

Figure 2. The leg is placed on a Braun splint, and the shaker with the impedance head is placed on the anterior tibial margin in the sagittal plane 2 cm below the tibial tuberosity. The static preload is set to 8 N by the adjustable counterweight.

A cadaver with no history of metabolic bone disease or tibial fracture was used in the transection study. At the time of measurement no rigor mortis was present. After initial measurement the fibula was transected. The admittance and lowest frequency of resonance (F_a) were measured during gradual transection through the middle of the tibia, parallel to its posterior surface. The same procedure was performed on the other leg after initial removal of soft tissues to evaluate the effect of damping.

Four patients with crural shaft fractures were tested by making a small window in the plaster cast over the tibial tuberosity for the positioning of the impedance head. The values were compared to those of the other leg. The effect of the plaster cast on the lowest frequency of resonance was studied by measuring before and after removal of the cast.

RESULTS

Positioning of the transducer

The transducer was placed on the anterior tibial margin at various distances from the knee joint and the lowest frequency of resonance (F_a) and mobility at F_a were measured. Figure 3 shows

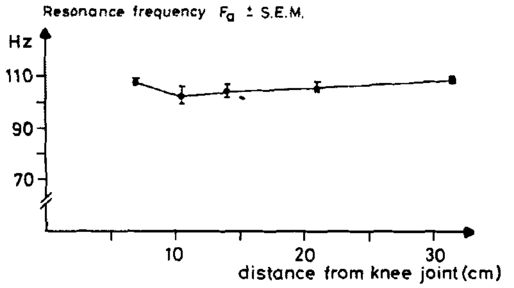

Figure 3. Resonance frequency versus distance from knee joint. Triple determinations.

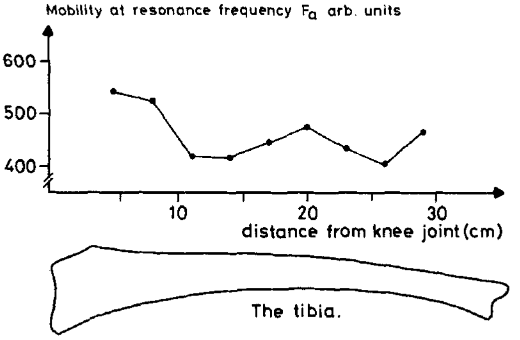

Figure 4. Mobility at resonance frequency versus distance from knee joint.

that F_a was independent of the positioning. In Figure 4 the lowest mobility at resonance was found to be at 12.5 cm and 25 cm from the knee joint, corresponding to the nodes for the lowest mode of transverse vibration. These points should be avoided in measurements, because of the small amplitudes. Based on these results the transducer was placed 2 cm below the tibial tuberosity.

Angle of application

With the transducer placed 2 cm below the tibial tuberosity, transverse to the axis of the tibia, the inclination to the sagittal plane was varied. Figure 5 shows that medial angulation in particular increased the variation in the results. The sagittal plane was chosen for the investigation.

Range of frequency

Above 1kHz no resonances were measured due to damping; below 30Hz instability in the system made it impossible to keep the transducer in position. No well-defined resonances below this value were measured, but mobility was significantly higher, probably because of the resonance of the spring-suspended shaker and of the whole limb supported on the Braun splint. The frequency range chosen was from 30 to 1000Hz.

Dynamic force (L_F)

Signals below 1 N r.m.s. (root mean square) were insufficient to maintain a stable compressor loop and above 4 N r.m.s. (Figure 6) the apparatus was no longer able to maintain constant force through the frequency range. Dynamic forces from 2 to 4 N r.m.s. caused no significant changes in the mo-

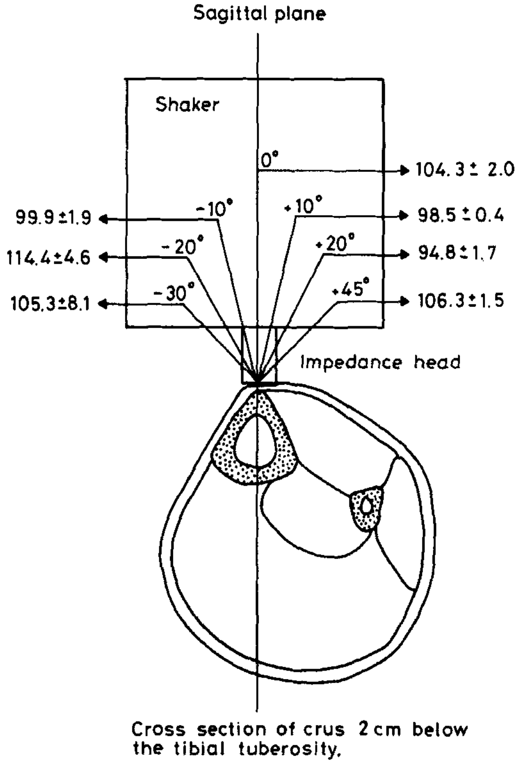

Figure 5. Frequency of resonance (F_a ± SD) versus angle of positioning the impedance head. Triple determinations.

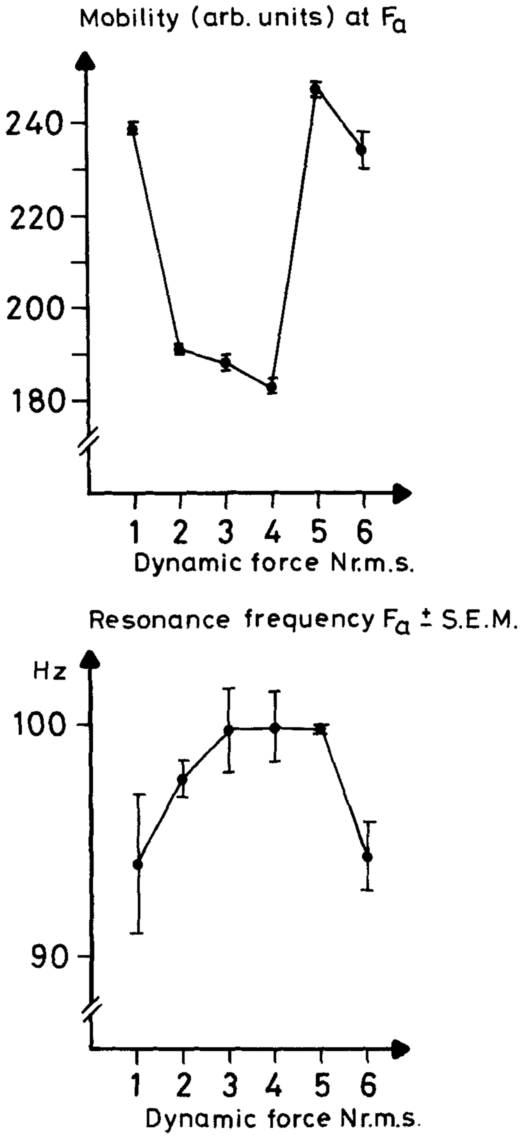

Figure 6. Dynamic force versus mobility and lowest frequency of resonance F_a.

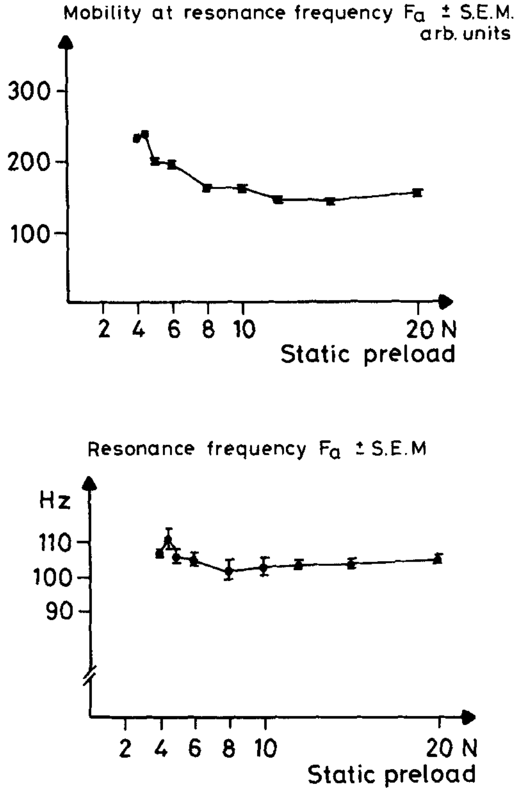

Figure 7. Static preload versus frequency of lowest resonance (F_a). Triple determinations.

bility or the frequency of lowest resonance; 3 N r.m.s. was chosen as a standard procedure.

Static preload

The influence of static preload on the impedance head was investigated (Figure 7). With a dynamic force of 3 N r.m.s. a minimum static force of 4 N was necessary for appropriate bone contact. Above 20 N the pressure caused pain. Mobility decreased with higher preload, but resonance showed no changes from 5 to 20 N. A static load of 8 N was chosen because it gave good bone contact and was tolerated for a longer period without discomfort.

Muscular tension

The influence of muscular tension by flexion-extension in the ankle and knee joints is presented in Table 1. Muscular tension, especially extension of the knee joint, increased F_a, indicating that the muscles must be relaxed during the determinations.

Table 1. Muscular tension versus resonance frequency $(\bar{x} \pm S.D.)$

	Ankle joint	Knee joint
Flexion	115±8.4	115.6±4.7
Extension	112.6±10.9	159.0±2.4

(Relaxed 95.3±4.7)

Table 2. Precision of method in standard position (Triple determinations)

Source of variation	Resonance frequency		Admittance	
	S.D.	C.V.	S.D.	C.V.
Apparatus	1.9	1.6 per cent	4.3	3.7 per cent
Change of position	5.4	4.7 per cent	9.2	8.5 per cent

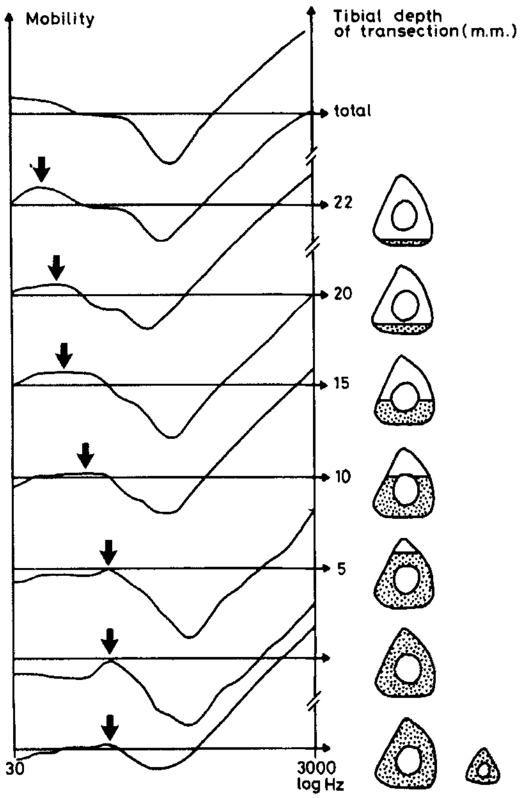

Figure 8. Frequency of resonance (F_a) with soft tissue damping versus fracture of the fibula and increasing transection of the tibia.

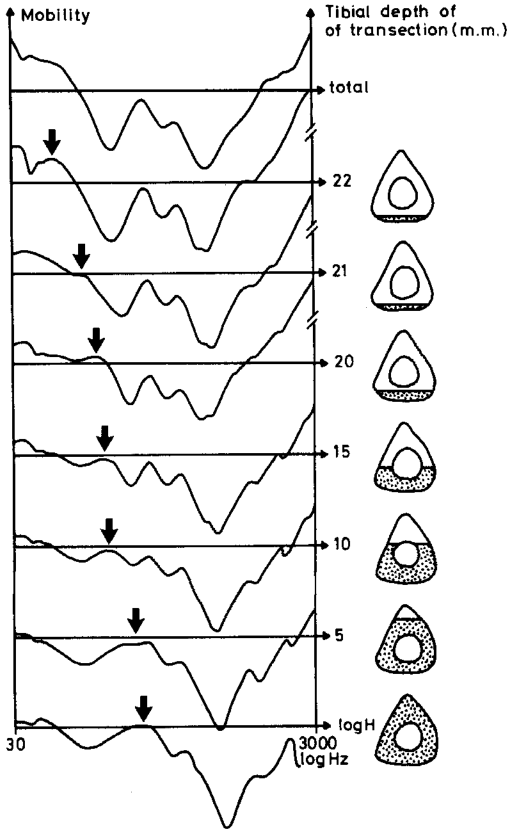

Figure 9. Frequency of resonance (F_a) after removal of soft tissues and the fibula versus increasing transection of the tibia.

Precision of the method in a standard position

The precision of the method was measured both with the subject and the transducer in unchanged positions, and with the position of the subject and of the transducer altered between the tests. Table 2 shows that repositioning the leg and the transducer increased the variation both in F_a and the mobility at resonance, indicating that the triple determinations in the clinic should be performed with repositioning of the leg.

Figure 8 shows the mobility of the tibia during gradual transection. No difference is found after transection of the fibula. F_a decreases as the transection proceeds. The higher resonance F_1 from the proximal fragment with the shorter dynamic length occurs when the tibia is half

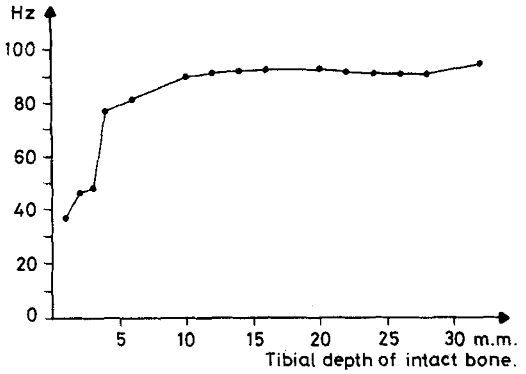

Figure 10. Frequency of resonance versus decreasing transection.

transected. After removal of soft tissues the curves become more detailed (Figure 9), showing higher resonances. The frequency of the lowest resonance was then 18 per cent higher but showed the same decrease during transection as in the first series.

Figure 10 shows the frequency of resonance (F_a) versus the depth of intact bone during the transection.

In the clinical test shown in Figure 11 the F_a was decreased on the fractured side. No changes were found in the F_a before or after the removal of the high circular femur cast.

DISCUSSION

This study demonstrates that F_a of the human tibia can be determined by the point impedance technique, with the same degree of precision as that found by Jurist (1970) in his study of the ulna, using a two-point impedance technique. The point impedance technique is, however, more convenient in the determination of fracture healing, since it requires only a single subcutaneous point for the measurements.

We found that the positioning of the transducer along the anterior tibial margin caused no change in F_a, but did lead to considerable change in mobility at resonance. Determinations will not be sensitive to minor deviations from the sagittal plane. Jurist (1970) found a 22 per cent increase in F_a of the ulna as the angulation varied 20–30 degrees dorsally from the standard position.

A static preload between 5 and 20 N did not change F_a. This is in accordance with Jurist, who reported that changes in the preload only altered F_a by 10 per cent. Thompson et al. (1976) showed that mechanical impedance changed with varied static preload, but the graphs show no variation in F_a.

Muscular tension was obviously an important factor. We found a much greater increase in F_a during muscular tension than that demonstrated

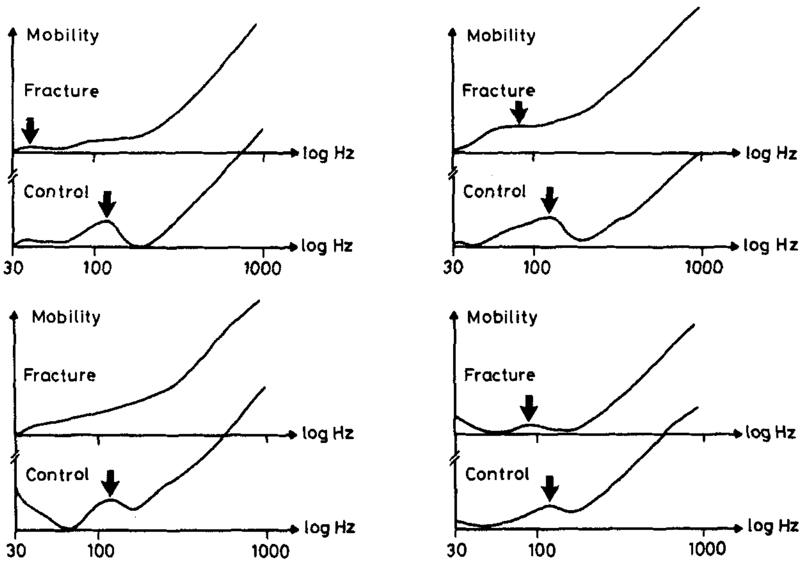

Figure 11. Resonance frequency (F_a) in four cases with crural fractures using the other leg as control.

by Jurist on the ulna. This was probably due to the larger muscular mass of the leg.

Muscular tension could have been the cause of the reduced precision when repositioning the leg, but as the subjects were well relaxed the changes were probably caused by altered boundary conditions as the leg was replaced on the Braun splint. This theory is supported by Doherty (1971), who showed that the measured resonance will depend upon the supporting conditions of the limb and claimed that rigid body motion could predominate over deforming modes of vibration. Spiegl & Jurist (1975) presented four models of the vibrating ulna, where the fourth was the rigid body vibrating on a spring. This model failed to predict the vibrational behaviour of bones in most of the clinical tests, so this mode of vibration was considered less important. Thompson et al. (1976) presented an improved mathematical model for the vibrational behaviour of the tibia, and showed a high correlation with the clinical results found by driving point impedance tests. Hight et al. (1978) presented a computer model for the prediction of natural frequencies of the tibia and found that boundary conditions were clearly the most important factor.

The precision of the results shows that boundary conditions are reproducible to a certain degree, indicating that the method could be a valuable tool in determining tibial resonance frequency during fracture healing.

The results of the study of the tibial transection illustrate the changes in resonance frequency that one could expect in the healing fracture. In the fractured bone the dynamic length is reduced, which initially would raise the lowest frequency of resonance. As healing proceeds a lower frequency of resonance will emerge when the two fragments exert transverse vibrations, with the fibrous tissue in the fractured area serving as a joint for the motion. This lower frequency of resonance will gradually approach the normal values of the non-fractured bone as the stiffness in the fractured area increases with callus formation.

As bone stiffness shows a high correlation with breaking strength (Jurist & Foltz 1977), stiffness evaluated by resonance frequency could be a measure of the breaking strength in the healing fracture, thus improving the detection of delayed healing or allowing early plaster removal and mobilization of the fractured limb.

The results in this study indicate that fractures can be detected and that increasing stiffness in the fracture gap can be monitored by resonance frequency.

The plaster cast caused no variation in the lowest frequency of resonance, probably because only the posterior part of the leg was in contact with the cast, creating conditions similar to the leg on the Braun splint.

Damping by soft tissues makes it more difficult to determine the value of F_a. Removing the soft tissues raised F_a by approximately 18 per cent, which suggests that oedema might change the resonance. Further investigations will show whether changes in F_a can be used to determine the exact amount of time taken for a fracture to heal.

ACKNOWLEDGEMENT

The authors wish to thank Brüel & Kjær A/S, Nærum Hovedgade 18, DK-2850 Nærum, Denmark, for making the apparatus available for the research.

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