Acoustic Assessment of Fracture Healing

Capabilities and Limitations of "A Lost Art"

Robert S. Siffert, MD, and Jonathan J. Kaufman, PhD

ABSTRACT

The ability of bone to conduct sound was applied clinically over 50 years ago to identify the presence of fresh fractures, although the technique has become a relatively "lost art" as more sophisticated X-ray and other imaging techniques have been developed. The objective of this report is to challenge clinical orthopaedic surgeons unfamiliar with the technique to explore this simple bedside method in the clinical management of fractures. A portable computer-based vibrational analysis device was employed and experiments conducted to objectively evaluate the capabilities of auscultatory percussion techniques. Auscultatory percussion can, with certain limitations, detect the presence of fractures, assess qualitatively the progress of healing, detect delayed or nonunions, and indicate when sufficiently firm continuity has occurred to permit early mobilization or loadbearing. Vibrational assessment is, however, subject to systematic and random errors, and thus cannot always discriminate between the stages of healing in a fractured bone; in addition, various artifacts can lead to significant uncertainty in the diagnosis. Nevertheless, auscultatory percussion is a useful tool in clinical fracture management, and particularly where roentgenographic facilities are inadequate or not available. Computerized vibrational analysis can be used in place of classical percussion/stethoscope methods by those with poor tonal capabilities, or when more objective record keeping is desired.

The individual stages of fracture repair, as well as criteria for their recognition, have been well described.[1] Final healing, defined as complete radiological and histological restoration of the former anatomy, is a prolonged process. Clinical management, therefore, demands practical criteria for bone continuity of sufficient strength to withstand mechanical forces of early controlled mobilization or weightbearing in order to encourage early rehabilitation and return to normal activity; to decrease morbidity; and to avoid atrophy, stiffness, and limited motion. These criteria include physical findings of swelling, pain, tenderness, fracture motion, radiological appearance, and accepted experiences as to length of time a particular fracture generally takes to heal.

The more information a clinician has at his disposal, the better may be his judgement. None of these classical findings provide sufficient information regarding actual fracture stiffness and strength. The image of calcified tissue on the radiograph appears relatively late in the healing process after earlier preosseous osteoid, cartilage, and fibrous tissue have bridged the fracture gap to attain continuity and provide some degree of strength.

Auscultatory percussion, long utilized in the diagnosis of pulmonary diseases, was applied to fracture healing by Lippmann in 1932.[2] A historical review of the method was provided by Peltier.[3] The technique, based on observations of the ability of bone to conduct sound, consists simply of tapping a bony prominence distal to the suspected or known fracture and listening with a stethoscope over the opposite end of that or an articulating bone. Sound passes easily through joints. Decrease in volume and pitch indicates discontinuity at a fracture site or an established nonunion. Since most fractures once bridged generally go on to full healing, sequential evaluation compared to the normal side provides a helpful guide that the fracture is beginning to heal. Metal plates and intramedullary devices alter sound transmission sufficiently to decrease the value of this technique in internally fixed fractures.

The most common areas to detect specific fractures are the medial malleolus to subcutaneous medial tibia (tibia), the lateral malleolus to fibula

Dr. Siffert is Distinguished Service Professor, and Dr. Kaufman is Assistant Professor, Department of Orthopaedics, The Mount Sinai Medical Center, New York, New York.
This work was supported in part by NSF grant # BCS-891121, and by charitable donors.

head (fibula), the patella to pubic symphysis (femur or pelvis), the acromium to medial clavicle or sternum (clavicle), the olecranon to acromium (humerus), and the ulna styloid to olecranon (ulna). Note that decreased patella to pubic symphysis transmission is indicative of discontinuity between the two sites, ie, at the hip or the superior and inferior rami of the pelvis. Note too, that an impacted fracture of the neck of the femur will conduct sound normally.

In addition to bedside and office use of this economic and practical method of diagnosis and monitoring fracture healing, its most dramatic value is when an X-ray is not readily available, as in a developing country or when avoidance of exposure is important (Figure 1).

Since employed only occasionally in today's practice, auscultatory percussion is essentially a "lost art." It is rare to see an orthopedic surgeon or resident listen to determine whether there is a fracture or nonunion or to monitor the sequential stages of healing as a guide to whether progress is satisfactory. Early callus, in creating continuity across a fracture site, may often be detected earlier by auscultatory percussion than by X-ray which becomes visible only when more mature callus becomes well calcified.

This paper describes the capabilities and limitations of auscultatory percussion for assessing bone fracture healing. A noninvasive computerized vibrational analysis technique is utilized in the evaluation of both in vitro and clinical data. The in vitro data includes results on healing fractured rabbit tibiae and a human femur undergoing simulated healing with polymethylmethacrylate. The clinical data includes various fractures vibrationally monitored over the course of the healing process.

Figure 1. In 1970 at a rehabilitation facility distant from Jakarta, a 2-year-old child fell and guarded the right lower extremity. In the absence of X-ray and stethoscope, Professor Soelarto Reksopodjo, DJC, then one of the Indonesian CARE trainees, was able to diagnose a femur fracture by tapping the patella and listening over the pubic symphysis using an improvised trumpet made from rolled up paper.

METHODS AND OBSERVATIONS

Computerized Vibrational Analysis

The vibrational test consists of exciting one end of a bone with an electromagnetic vibration shaker (Ling Dynamic Systems V102, Yalesville, Connecticut) instrumented with an impedance force and acceleration transducer (PCB Piezotronics 288A11, Depew, New York), while placing an accelerometer (PCB Piezotronics 308B02) at the opposite end of the bone (Figure 2). The shaker is energized with a periodic signal containing energy in the frequency range 40-1,000 Hz, and the input force, input acceleration, and output acceleration were digitally acquired at a 10 kHz sampling rate and downloaded to a microcomputer for storage and off-line analysis. The data was processed to produce estimates of the overall vibrational response of the bone under test. In particular, the amount of high frequency energy present in the vibrational response of the limb or bone under test relative to that of an intact control limb or bone was quantified, and termed the vibrational index (VI).[4] The vibrational index emphasizes high frequency energy changes because it is these vibrational spectral components that are most dramatically affected by the presence of a fracture.[2,3] The vibrational index is typically small when a fractured limb is compared to a contralateral intact limb, because the fractured limb transmits relatively less high frequency sound energy than the intact limb. When an intact limb under evaluation is compared to a contralateral intact limb, the vibrational index should ideally be close to 1, since their sound transmission characteristics, ie, they are both intact, are similar.

In Vitro Human Femur Data

Vibrational measurements were acquired from an intact human femur from which all soft tissue had been removed. The femur was subsequently cut in half at the mid diaphysis and polymethylmethacrylate (PMMA) applied across the "fracture" gap. Measurements of the vibrational index, computed relative to the vibrational response of the initially intact bone, were acquired for a period of 11 minutes during which time the PMMA transformed from a soft gel to a solid mass, simulating the process of fracture healing (Figure 3). The VI begins at time zero at about 0.0001, increases slow-

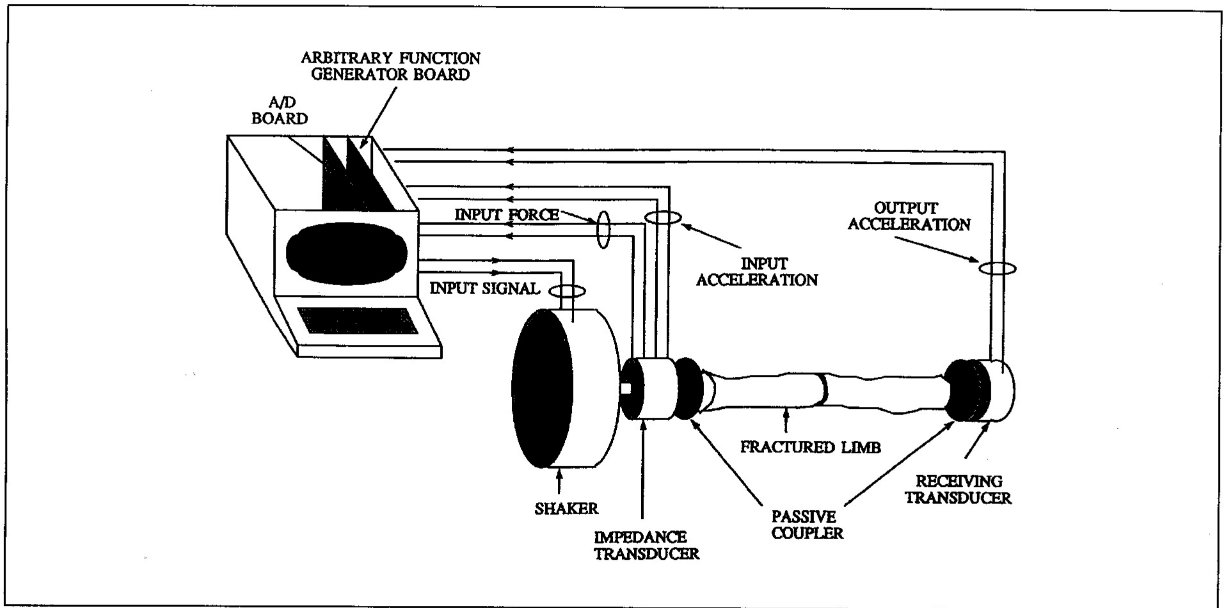

Figure 2. Schematic diagram of the computerized vibrational analysis system.

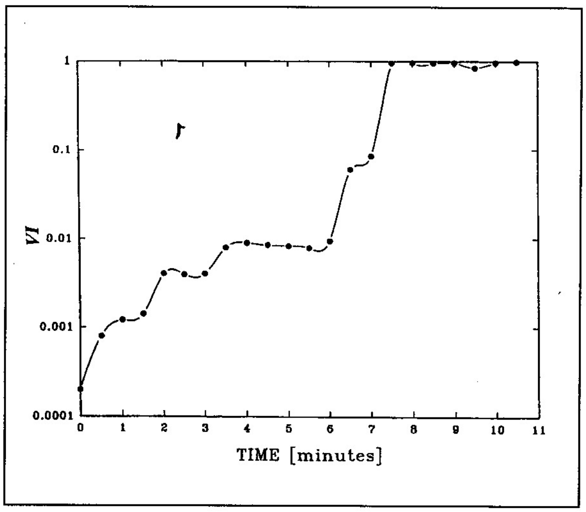

Figure 3. The vibrational index (VI) of the vibrational response of a human tibia in vitro as a function of polymethylmethacrylate (PMMA) curing time. The graph displays the VI which is computed relative to the vibrational response of the initially intact bone. The changes in time of the VI associated with the femur vibrational response correspond to hardening (ie, stiffening) of the PMMA. The VI begins at time zero at about 0.0001, increases slowly past 0.001, and then rises rapidly at about 7 minutes to almost 1.0, where it stays for the remainder of the experiment.

ly past 0.001, and then rises rapidly at about 7 minutes to almost 1.0, where it stays for the remainder of the experiment.

In Vitro Animal Data

Uniform unilateral closed tibial fractures were performed on 20 New Zealand White rabbits. A Kirschner wire was inserted into the medullary cavity and a guillotine was dropped on the limb to produce a fracture.[5] The limb was placed in a fiberglass

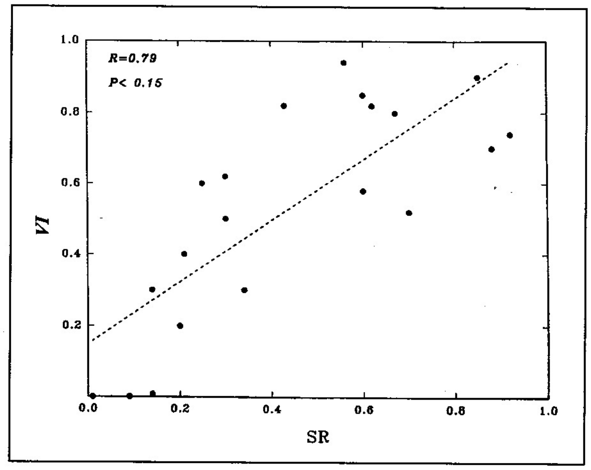

Figure 4. The vibrational index (VI) compared to the ratio of torsional stiffness of the healing fractured bone to contralateral intact bone (SR) for 20 rabbits. There is a significant linear correlation ($r = 0.79$, $P < 0.15$) between relative stiffness (SR) and the relative vibrational index (VI).

cast and the 20 animals sacrificed between the period comprising 5 to 28 days post fracture. The left and right tibiae of each rabbit were dissected, the rod in the fractured limb removed, and then both tibia were radiographed and vibrationally tested. Finally, all tibiae were biomechanically tested to obtain torsional stiffness, utilizing a biomechanical testing machine.[6] The ratio of fractured limb to contralateral intact limb stiffness, ie, the stiffness ratio (SR) was recorded and plotted versus VI for the 20 rabbits (Figure 4). There was a significant linear correlation ($r = 0.79$, $P < 0.15$) between SR and the VI, although there were substantial variations between the fresh fracture and firm healing states.

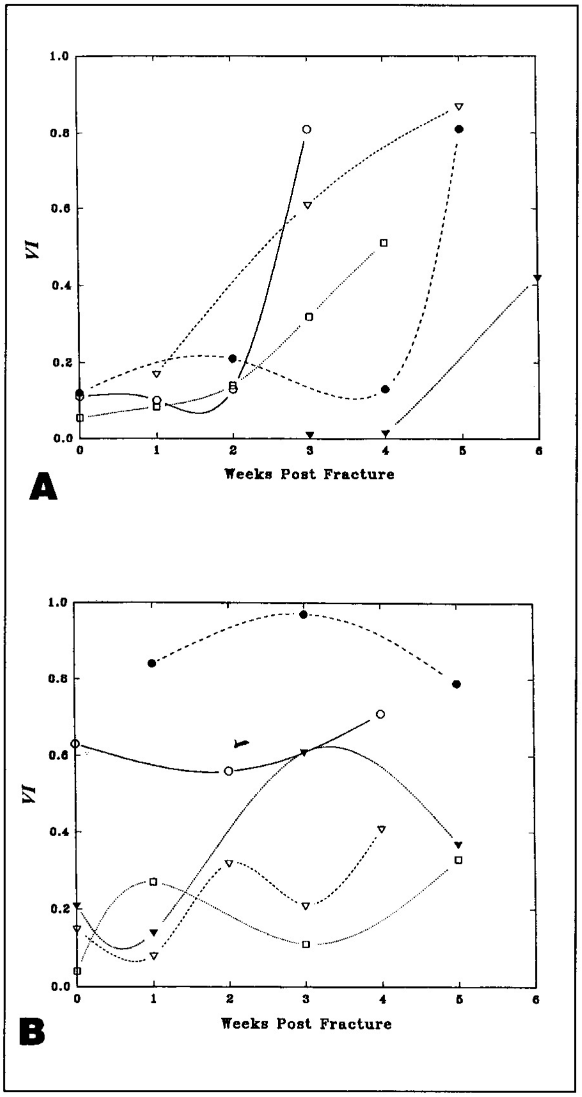

Figure 5. (A) The vibrational index (VI) as a function of days post fracture for 5 fracture patients whose VI values are monotonically increasing as a function of time post fracture. (B) The vibrational index (VI) as a function of days post fracture for 5 fracture patients whose VI values were either initially high and remained at that level or exhibited more inconsistent behavior.

Clinical Data

Vibrational measurements were also acquired from human subjects, both intact controls and fracture patients. Ten healthy controls were analyzed vibrationally. Measurements from each control subject consisted of paired data from the left and right humerus, ulna, and tibia. The data was collected in both "normal" mode, ie, with the subject normally relaxed, and in "tension" mode, ie, with the subject consciously tensing his or her muscles of the limb being tested.

Ten patients with humerus and clavicle fractures were also tested vibrationally in a similar manner to that used for the controls above. Contralateral intact and fractured limb data were recorded at time of fracture and at weekly or biweekly intervals until clinical union occurred. The vibrational response for each patient at each time point was recorded for subsequent computation of the VI. In addition, 3 patients referred because of suspected nonunion were vibrationally tested.

The mean vibrational indices (standard errors of the mean) for the 10 control subjects were 0.73 (0.2), 0.82 (0.2), and 1.1 (0.2) for the humerus, ulna, and tibia, respectively. There was a 25% average decrease in the mean vibrational index when the muscles were tensed, relative to when they were normally uncontracted (P<0.01).

Figure 5 presents the vibrational response data for the 10 fracture patients. In 5 of the cases (Figure 5A), the vibrational response begins with a low value (approximately 0.1) and increases almost monotonically toward 1.0. The remaining 5 cases are shown in Figure 5B. In 2 of the cases the vibrational response starts at a relatively high value, and remains there throughout the monitoring period. In the last 3 cases, there is a non-monotonic variation in the VI, although there is an overall increasing trend in VI. The diagnosis of tibial nonunion was made and bone grafting was recommended in 2 patients whose X-ray demonstrated lucency, eburnation, and hypertrophic changes at the fracture site. Good conduction was identified with the tapping-stethoscope technique and with the computer-based vibrational testing device (VI = 0.63 and 0.84, respectively), indicating preosseous continuity across the fracture site. Further immobilization permitted full healing and surgery was avoided. One patient demonstrated similar X-ray findings and poor conduction indicating a fibrous nonunion (VI = 0.13).

DISCUSSION

No reliable quantitative vibrational assessment method of fracture healing has yet been established, although many studies have addressed this problem.[4,7-17] There are several reasons why this is so. First, analytic results previously reported demonstrate that the main changes in the vibrational response of a healing fractured bone occur during the earliest part of fracture consolidation.[4] Thus vibrational or auscultatory response can be relatively sensitive to initial changes occuring in a healing fractured bone, and in fact are what makes such techniques so potentially useful. Conversely, changes occuring later in the healing process may not be as easy to distinguish.[4]

The degree of change induced by a fracture represents only one aspect of the diagnostic capabilities of the vibrational test. The other fundamental aspect relates to the relative degree of variability that may be reliably obtained in such testing. This was assessed in normal control subjects in several anatomical locations. We observed a nominal variability of about ±30%. This is due to the random aspects of the experiment itself, which included differences in repositioning of the transducers and vibration shaker, differences in repositioning of the limb itself, different boundary conditions (eg, how firmly the transducers are placed on the skin), and normal electronic noise. Better reproducibilties have been reported in the literature, for example by Benirschke et al.[15] This difference may be due to the fact that our results were obtained for a variety of limbs, whereas other studies have concentrated mostly on the tibia.[15] In addition, we observed a systematic bias obtained from muscle contractions of almost 25%. Other bias effects which were not measured in the controls were effects of soft tissue edema, degree of comminution, and anatomical alignment. It can be expected that such effects would contribute some additional errors.[13]

By combining the above observations, that is, the smaller changes in the vibrational response which occur subsequent to initial consolidation of the fracture, the confounding nature associated with impacted and internally fixed fractures, and soft tissue edema, with the random variations introduced into the measurement process, it is clear that vibrational assessment techniques must be used with appropriate care. In particular, vibrational methods can be used for determining (1) if a fresh fracture or a nonunion is present; (2) if there is no fracture present or a fracture has healed or is impacted; and (3) if the fracture site has begun to consolidate between freshly fractured and completely healed. Attempts to infer the quantitative degree of mechanical strength of a healing fracture may be subject to error. Benirschke et al,[15] by use of a similar computerized vibrational system, has been able to obtain a relatively high correlation between vibrational response and time to healing (R^2 = 0.58), although healing time was defined based on the vibrational response itself.

CONCLUSION

This report is presented as a challenge to clinical orthopedists unfamiliar with the art of auscultatory percussion, to explore this simple, noninvasive, inexpensive method as a guide in evaluating the process of healing of noninternally fixed fractures. Classical auscultatory percussion utilizing a finger tap and stethoscope has proven to be a useful clinical tool for identifying the presence of fresh, ununited and healed fractures, as well as gross assessment of changes that are occurring during the healing process. Similarly, computerized vibrational analysis can be used to more objectively distinguish the state of a healing fracture. The potential for errors in such techniques is still significant, making careful interpretations important. Future studies may improve the accuracy of vibrational techniques, for example by identifying and controlling for edema, placement of the transducers, and other factors. For the present, however, vibrational techniques, whether manual or computerized, can provide significant information on the state of an injured limb in the context of the limitations and capabilities described.

REFERENCES

1. Dee R, Mango E, Hurst LC. *Principles of Orthopaedic Practice.* New York: McGraw Hill; 1989:68-73.
2. Lippmann RK. The use of auscultatory percussion for the examination of fractures. *J Bone Jt Surg.* 1932;14:118.
3. Peltier LF. The diagnosis of fractures of the hip and femur by auscultatory percussion. *Clin Orth Rel Res.* 1977;123:9-11.
4. Kaufman JJ, Chiabrera AE, Hatem M, et al. A neural network approach for bone fracture healing assessment. *IEEE Eng Med Biol Magazine.* 1990;9(3):23-30.
5. Bonnarens F, Einhorn TA. Production of a standard closed fracture in laboratory animal bone. *J Orthop Res.* 1984;2:97-101.
6. Pilla AA, Mont M, Nasser PR, et al. Non-invasive low intensity pulsed ultrasound accelerates bone healing in the rabbit. *J Orthop Trauma.* 1990;4:246-253.
7. Markey EL, Jurist JM. Tibial resonant frequency measurements as an index of strength of fracture union. *Wis Med J.* 1974;73:62-65.
8. Lewis JL. A dynamic model of a healing fractured long bone. *J Biomech.* 1975;8:17-25.
9. Wong ATC, Goldsmith W, Sackman JL. Flexural wave propagation in discontinuous model and in vitro tibiae. *J Biomech.* 1976;9:813-825.
10. Sonstegard DA, Matthews LS. Sonic diagnosis of bone fracture healing: a preliminary study. *J Biomech.* 1976;9:689-698.
11. Pelker RR, Saha S. Wave propagation across a bone discontinuity simulating a healing fracture. *J Biomech.* 1985;18:745-753.
12. Doemland H, Jacobs RR, Spence J, Roberts FG. Assessment of fracture healing by spectral analysis. *J Med Eng Technology.* 1986;10:180-187.
13. Nokes LDM, Thorne GC. Vibrations in orthopaedics. *CRC Crit Rev Biomed Eng.* 1987;15:309-349.
14. Hirayama T, Sekiguchi T. Assessment of fracture healing by vibration. *Acta Ortho Scand.* 1989;50:391-398.
15. Benirschke SK, Mirels H, Jones D, Tencer AF. The use of resonant frequency measurements for the noninvasive assessment of mechanical stiffness of the healing tibia. *J Orthop Trauma.* 1993;7:64-71.
16. Tower SS, Beals RK, Duwelius PJ. Resonant frequency analysis of the tibia as a measure of fracture healing. *J Ortho Trauma.* 1993;7:552-557.
17. Nokes LDM, Thorne GC. Vibrations in orthopaedics. *CRC Crit Rev Biomed Eng.* 1987;15:309-349.