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● *Original Contribution*

A NEW METHOD FOR EVALUATION OF FRACTURE HEALING BY ECHO TRACKING

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Abstract—Assessment of bone healing on radiographs depends on the volume and radio-opacity of callus at the healing site, but is not necessarily objective, and there are differences of judgment among observers. To overcome this disadvantage, a clinical system was developed to quantify the stiffness of healing fractures of the tibia in patients by the echo tracking (ET) method in a manner similar to a three-point bending test. The purpose of this study was to ensure that the ET system could clinically assess the progress, delay or arrest of healing. The fibular head and the lateral malleolus were supported. A 7.5-MHz ultrasound probe was placed on the proximal and distal fragments and a load of 25 N was applied. Five tracking points were set along the long axis of the ultrasound probe at intervals of 10 mm. With a multiple ET system, two probes measured the displacement of five tracking points on each of the proximal and distal fragments of the tibia, thereby detecting the bending of the two fragments generated by the load. ET angle was defined as the sum of the inclinations of the proximal and distal fragments. Eight tibial fractures in seven patients treated by a cast or internal fixation were measured over time. In patients with radiographically normal healing, the bending angle decreased exponentially over time. However, in patients with nonunion, the angle remained the same over time. It was demonstrated that the ET method could be clinically applicable to evaluate fracture healing as a versatile, quantitative and noninvasive technique. (E-mail: ohnishii-dis@h.u-tokyo.ac.jp) © 2008 World Federation for Ultrasound in Medicine & Biology.

Key Words: **Ultrasound, Echo tracking, Fracture site stiffness, Fracture healing.**

INTRODUCTION

The most important issue in assessment of fracture healing is to obtain information about restoration of the mechanical integrity of the bone. In clinical practice, fracture healing is usually judged from serial radiographs. Assessment of bone healing on radiographs depends on the volume and radio-opacity of callus at the healing site, but is not necessarily objective, and there are differences of judgment among observers. In addition, radiographs cannot evaluate fracture site strength. In these respects, assessment of fracture healing by using radiographs is far from ideal.

The stated disadvantages of radiography for assessment of fracture healing have been pointed out in recent years, and various other methods of assessment have been developed. Jernberger (1970) devised an invasive method for measuring the bending stiffness of healing fractures of the tibia. With his method, the proximal and distal bone fragments were fixed by screws that were connected to a specially designed beam, and a load was applied through a screw at the center of the fixing screws. The method was based on the principle governing the bending of two beams connected at the ends and subjected to a bending force applied at the midpoint. Burny et al. (1984) developed a method that used a strain gauge attached to a fixator shaft. With their method, the strain gauge readings were monitored over time during weight bearing, and the pattern of fracture healing was classified into seven categories (such as normal, delayed, arrested, *etc.*). Assessment using acoustic emission (AE) was developed by Nicholls and Berg (1981), who detected acoustic pulses generated by microscopic failure of the bone under loading. The investigation by Watanabe et al. (2001) revealed that AE signals occurred with the yielding of callus. However, the strain gauge method and the AE method have the disadvantage that both are limited to patients with external fixation, and both require the in-

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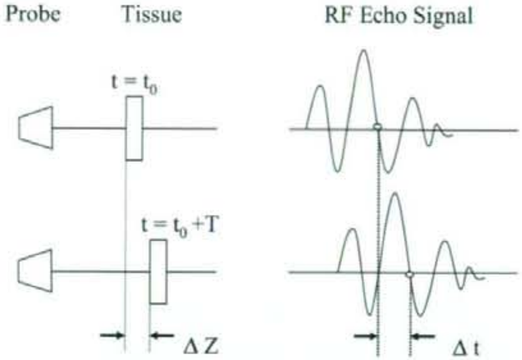

Fig. 1. The target tissue may move closer to or away from an ultrasonic probe over the distance ΔZ during a pulse repetition time of ultrasonic waves (T), causing phase delay of the RF echo signal (Δt). The ET method measures the extent of this displacement by tracking the initialized phase pattern of the echo signal.

sertion of screw pins or wires. For these reasons, such methods have not been widely used and a new method is needed that is both noninvasive and widely applicable.

To overcome such limitations, we developed a new method for the noninvasive and quantitative assessment of fracture healing. Bone always undergoes deformation in response to an applied load. By quantitatively measuring this deformation, it is possible to assess the mechanical properties of bone and thereby estimate the strength of a fracture site. In this study, we attempted to noninvasively assess the bending stiffness of the healing fracture sites after applying a load. To measure bending stiffness, we focused on ultrasound because it is noninvasive. Precise measurement of the displacement of a specific point can be done by the echo tracking (ET) method. This method is a technique for measuring minute displacement of a certain point on a tissue by detecting a wave pattern in the radiofrequency (RF) echo signal reflected from the target tissue (Fig. 1) (Hokanson et al. 1972). To apply this technique for detection of bone deformation, we improved it so that displacement could be measured with an accuracy of 2.6 μm (Matsuyama et al. 2006). We also developed a multi-ET system that was able to simultaneously track dynamic movement at multiple points on the bone surface. In our previous study of the three-point bending test using a porcine tibia, the strain gauge readings and the data from the multi-ET system showed an almost perfect linear correlation with the load ($r = 0.998$). These results indicated the possibility of using the echo tracking method to detect bone surface deformation.

The purpose of this study was to determine whether our newly developed ET system could clinically assess the progress, delay or arrest of healing by detecting the bending stiffness at the fracture healing site. Fracture healing was evaluated in patients with tibia fracture treated by a cast or internal fixation.

METHODS

A clinical system was developed to quantify the stiffness of healing fractures of the tibia in patients by the ET method in a similar manner to a three-point bending test. Five tracking points were set along the long axis of the ultrasound probe at intervals of 10 mm. With a multiple ET system, two probes measured the displacement of five tracking points on each of the proximal and distal fragments of the tibia, thereby detecting the bending of the two fragments generated by the load. ET angle was defined as the sum of the inclinations of the proximal and distal fragments (Fig. 2). When callus was weak in the initial stage of healing, the tracked points were almost in a straight line and the inclination of the two fragments was calculated directly. However, when the callus was more rigid in the late stage of healing, the line connecting the points was curved and the inclination was obtained from the slope of the linear regression equation for the displacement of the points.

Before clinical application of this method, its accuracy was evaluated by measuring the inclination of the metal flat panel.

Measurement of the accuracy of ET angle using an inclined flat metal panel

A flat stainless steel (SUS 420J) panel (length 270 mm, width 60 mm, thickness 5 mm) was used, which had a parallel accuracy and flatness variation of <2 μm. One end of the panel was attached to a magnet stand (DG, Noga Japan Ltd, Saitama, Japan), and the other side was attached to a goniometer (X13–001, Tsukumo Co. Ltd, Saitama, Japan) fixed to another magnet stand. Then, the

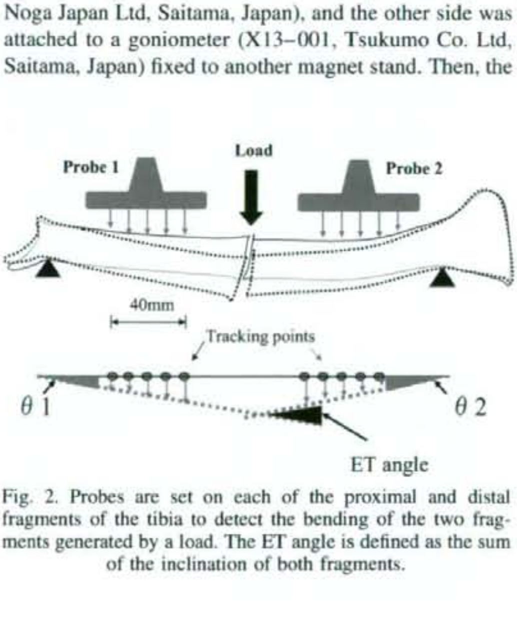

Fig. 2. Probes are set on each of the proximal and distal fragments of the tibia to detect the bending of the two fragments generated by a load. The ET angle is defined as the sum of the inclination of both fragments.

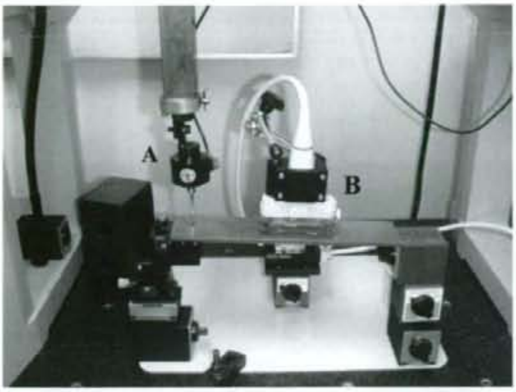

Fig. 3. The accuracy of the ET measurement was evaluated by measuring the inclination of the flat metal panel simultaneously using a 3-D measuring device. (A) 3-D measuring device; (B) 7.5-M Hz linear ultrasound probe.

metal panel was inclined by increasing the height of the goniometer stand. A 7.5-M Hz linear ultrasound probe (UST-5710-7.5, Aloka Co. Ltd., Tokyo) was set at a distance of 20 mm from the panel to measure the changes of displacement of each of five points on the panel (Fig. 3). Using these data, the ET angle of the panel was calculated. At the same time, the inclination of the panel was accurately measured using a 3-D measuring device (AE112, Mitsutoyo, Kanagawa, Japan) with an accuracy of 1 μm. The panel was inclined by elevating the sliding mechanism of the stand by 0.4 mm and the inclination of the panel was measured 5 times, after which the mean and standard deviation were calculated. Accuracy was evaluated by calculating the standard deviation of the difference between the ET angle and the inclination measured by the 3-D measuring device in each of the measurement trials.

Clinical measurement of fracture site bending stiffness

Eight tibial fractures in seven patients with an average age of 37 y (range 24–69 y) were measured (Table 1). Two fractures of two patients were treated conservatively with a cast, and six fractures of five patients were treated by internal fixation (locked intramedullary nailing in 4, plating in 1 and screws in 1). The average measurement period was 40.8 wk (21–60 wk), and the average number of measurements was 7.5 (5–11).

Patients assumed the supine position with both knees extended, and the affected leg was held horizontal with the antero-medial aspect of the tibia upwards. The fibular head and the lateral malleolus were supported and held tight by a Vacufix (Muranaka Medical Instrument Co., Ltd., Osaka, Japan) to avoid rotation of the leg during loading trials. Before measurement, B-mode images of the short axis of the proximal and distal fragments of the tibia were obtained to identify the center in both directions. By connecting both of the centers, the anatomical axis of the tibia was identified. A 7.5-MHz ultrasound probe was placed on the antero-medial aspect of each of the proximal and distal fragments in the long axis. Each probe was equipped with a multi-ET system with five tracking points at 10-mm intervals. The probes were set vertically on the skin of the leg and held tight with an articulated holder (DG61003, Noga Japan Ltd., Saitama, Japan). A load of 25 N was applied at a rate of 5 N/s and then reduced to 0 N at the same rate using a force gauge (DNP, Imada, Osaka, Japan) parallel to the direction of the probe at the most distal part of the proximal fragment adjacent to the fracture site (Fig. 4). For the initial measurement obtained in each patient, the loading point was set right on the long axis near the fracture site using a B-mode image as a guide. With this setup, the tibia was bent in the same way as for a three-point bending test in the direction of the ultrasound beam. In patients with oblique or spiral fractures, the loading point and the tracking points were set so that they did not cover the fracture site. In patients with a bone graft at the fracture site, the loading point was set on the graft, but the probes were placed so as not to cover it. In the patient with a plate, both the proximal and distal probes were set on the plate surface to measure bending of the plate. Using the multi-ET system, the probes

Table 1. Clinical cases of the tibial fracture

Case	Gender	Age	Limb	Treatment fracture healing	Measurement period (Initial-final)	Radiographic finding
1	F	24	L	Casting	4–47 wk	Normal
2	M	29	R	Casting	7–28 wk	Normal
3	M	23	R	Bone grafting	8–27 mo	Normal
4	M	31	R	Nailing	4–39 wk	Normal
5	F	57	R	Nailing	5–10 mo	Normal
6	F	57	L	Nailing	6–10 mo	Normal
7	F	26	R	Nailing	5 y 2 mo–5 y 7 mo	Nonunion
8	M	69	R	Plating	9–45 wk	Delayed

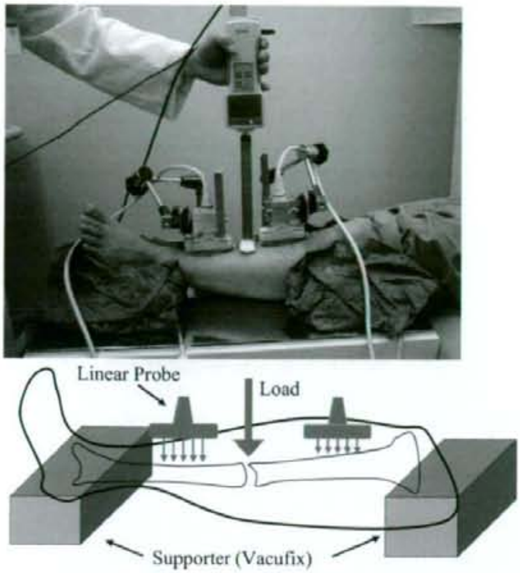

Fig. 4. The affected leg of a patient was held horizontal with the antero-medial aspect of the tibia upwards. The fibular head and the lateral malleolus were supported and held tight by a Vacufix. The probes were set vertically on the skin of the leg and held tight with an articulated arm. A load was applied using a force gauge parallel to the direction of the probe.

detected the angle between the proximal and distal fragments generated by the load. Measurement was repeated five times, and the mean and the standard deviation of the ET angle were calculated.

Fracture healing was assessed at intervals of two or three weeks until radiographic union or arrest of healing occurred. In each patient, the decrease of the ET angle was statistically examined to determine whether it decreased exponentially and whether the decrease was significant. To evaluate the changes of the ET angle over time, exponential regression analysis was performed, and the curve of the ET angle *vs.* time relation was drawn. Differences were considered significant when the p value was less than 0.05.

To investigate the influence of the position of the probes and the patient on the results, the precision of the method was evaluated by repeated measurement of the ET angle in a patient with a diaphyseal fracture of the tibia treated by a cast (case 2). In addition, the linearity of the relation between the load and the ET angle was assessed by incrementally increasing the load from 10 to 30 N. The ultrasound device (SSD 1000, Aloka Co. Ltd.) used in this investigation is used clinically and its safety has been established. The protocol of this investigation was approved by the ethics committee of The University of Tokyo Hospital, and the patients were enrolled after informed consent was obtained.

RESULTS

Accuracy of ET angle measurement for a flat metal panel

Measurement of the inclination of the flat metal panel showed that the average inclination was 0.117° and the standard deviation was 0.002°. The average inclination obtained with the 3-D measuring device was 0.116°, with a standard deviation of 0.003°. The standard deviation of the differences between the data obtained by the ET method and by the 3-D measuring device was 0.002°.

Clinical measurement of fracture site bending stiffness

The average time required for measurement was 17 min (range 15–20 min). At each loading trial, none of the patients complained of pain and there were no complications related to measurement.

The precision of this method was evaluated by repeating measurement of case 2 (treated with a cast), with repositioning of the leg and the ultrasound probes. The mean and standard deviation of the ET angle were 0.316 ± 0.015, and the coefficient of variation was calculated to be 4.6%. The linearity of the relation between the load and the bending angle was very high, with a correlation coefficient of 0.997.

Cases presentation

Case 1: A 24-year-old-woman treated with a cast. The patient sustained a spiral fracture of the proximal diaphysis of the tibia in a traffic accident, and a patella tendon bearing brace cast was applied. Healing was assessed by the ET method, as well as radiographs a total of 11 times from 4 weeks to 47 weeks after fracture. The fracture line became opaque and the callus volume increased from 4 weeks to 19 weeks, but after 26 weeks there was almost no change of the thickness of the callus. On the other hand, measurement showed that the ET angle was about 1° at 4 weeks, and that it decreased exponentially ($y = 1.40e^{-0.105x}$, $r = -0.975$, $p < 0.0001$). The ET angles of both cases 1 and 2 treated with a cast decreased exponentially over time and they reached the level of the intact side by 22 weeks (Fig. 5a, b).

Case 7: A 26-year-old-woman with a fracture of the diaphysis of the tibia treated by a locked intramedullary nailing. ET measurement was performed five times from 5 y 2 mo to 6 y 7 mo after fracture. Her X-ray films showed hypertrophic nonunion, but judgment whether healing was proceeding was extremely difficult. ET measurement showed that there was no significant decrease of the angle over a period of 1 y and 5 mo ($y = 0.264e^{0.002x}$, $r = 0.238$, $p = 0.700$) (Fig. 6a, b).

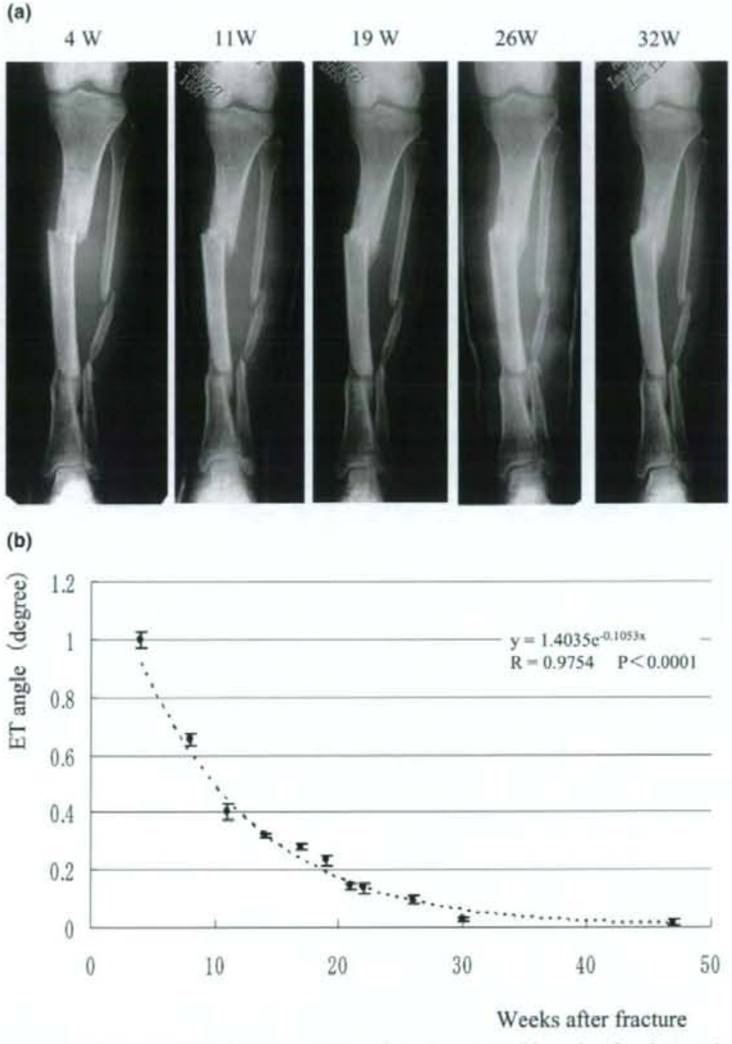

Fig. 5. (a) Time sequential change of the fracture site X-ray from 4 weeks to 32 weeks after fracture in case 1 treated with casting. The fracture site healed normally. (b) In the same patient, the ET angle was plotted. The ET angles decreased exponentially over time.

Case 8: A 69-year-old-man with a long oblique fracture treated with a plate. His X-ray films showed a long oblique fracture line extending for almost 80 mm. Measurement was performed 10 times from 9 weeks to 45 weeks after fracture, during which period almost no change of the fracture site or callus was recognized on X-ray films. The ET method measured the bending angle of the plate. The change was very slow, but the angle decreased significantly from 0.28 to 0.2 degrees, and then finally declined to 0.1 degree. The overall change showed an exponential curve ($y = 0.40e^{-0.030x}$, $r = -0.895$, $p = 0.0005$) (Fig. 7a, b). In patients with radiographically normal healing, the bending angle decreased exponentially over time (Fig. 8). However, in patients with nonunion, the angle remained the same over time.

DISCUSSION

Our method allows noninvasive assessment of bending stiffness at the healing site, so it can be appli-

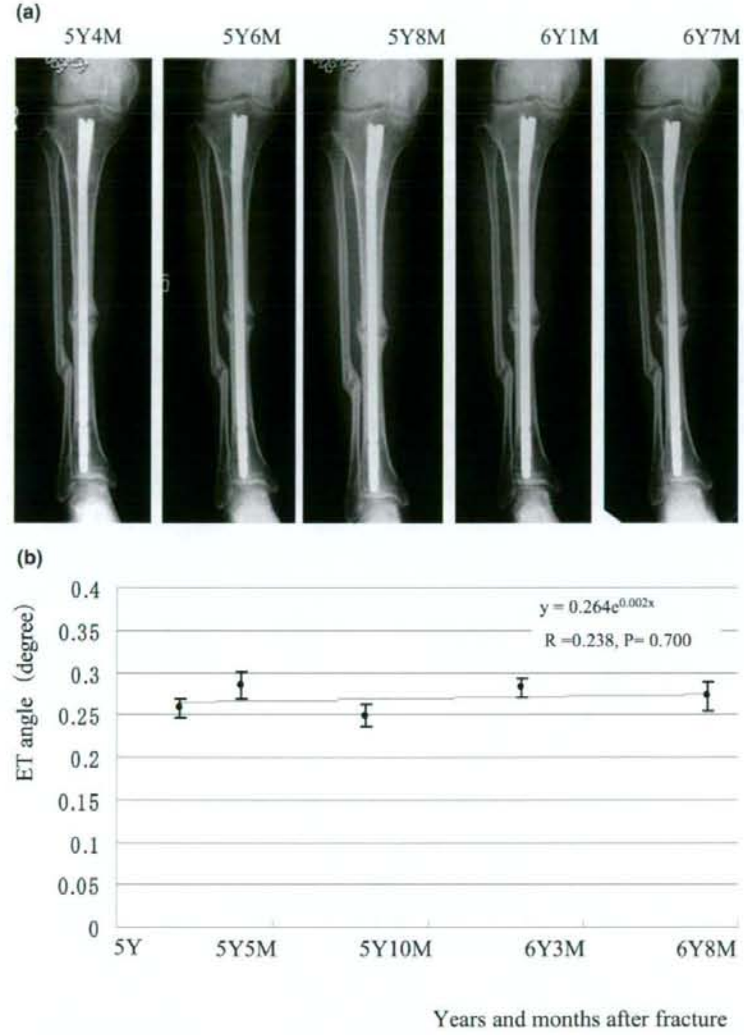

Fig. 6. (a) Time sequential change of the fracture site X-ray from 5 y 4 mo to 6 y 7 mo after fracture in case 7, treated with intramedullary nailing. The X-ray films showed hypertrophic nonunion, but judgment of whether healing was proceeding was extremely difficult. (b) In case 7, the ET angle showed no change over time and the regression lines showed no significant decrease.

cable to patients treated conservatively as well as those managed by surgical intervention with plating or intramedullary nailing.

In this study, the precision and reproducibility of the method were evaluated. The precision of measuring displacement by using the echo tracking system specially designed for bone surface measurement has already been assessed, and a precision of 2.6 μ was demonstrated in our previous study. However, the precision of measuring the bending angle has not been investigated before. We obtained a precision of 0.002°, which was thought to be adequate based on the results of the study by Moorcroft et al. (2001) that evaluated fracture healing. They used the three-point bending test to generate angles of 0.4 to 1.0° in an *in-vivo* measurement trial and connected a goniometer to the bone fragment *via* screw pins fixed to a side bar of the external fixator to detect bending at the fracture site.

When estimation of the linearity of measurement was done in relation to the load, there was excellent

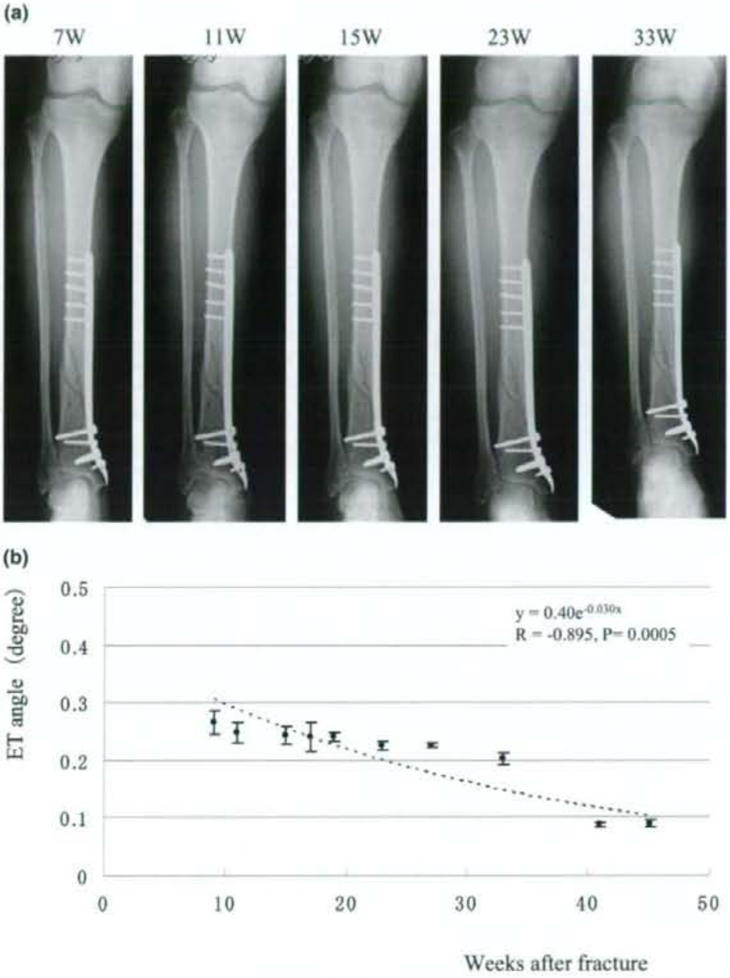

Fig. 7. (a) The X-ray films of case 8, treated with plating. No change of the fracture site or callus was recognized on X-ray films. (b) The ET method measured the bending angle of the plate. The change was very slow, but the angle decreased significantly from 0.28 to 0.2°, and then finally declined to 0.1°.

linearity between magnitude of the load and the ET angle ($r = 0.997$), indicating that elastic deformation of the fracture site had occurred under a load range of 10 to 30 N. Therefore, measurement was shown to be noninvasive as well as safe, without causing any residual deformity.

Reproducibility of the measurement method was estimated to be 0.015°, which was adequate to evaluate fracture healing quantitatively, because the angle ranged from around 1° in the initial stage to about 0.1° in the final stage when it was almost equivalent to that of the intact tibia. However, we have to improve the reproducibility of measurement *in vivo*. The factors affecting reproducibility *in vivo* include the position of the leg, loading direction and positions of the probes. Among these, the positioning or fixation of the leg seems to have the most influence on the reproducibility of measurement.

For clinical evaluation of fracture healing, data obtained by the ET method were compared with X-ray findings over time. In patients with delayed healing or nonunion, judgment of the healing process using X-ray films was difficult because the direction and conditions of obtaining images were not exactly the same every time, so the findings were not reproducible. In contrast, the echo tracking method evaluated fracture stiffness

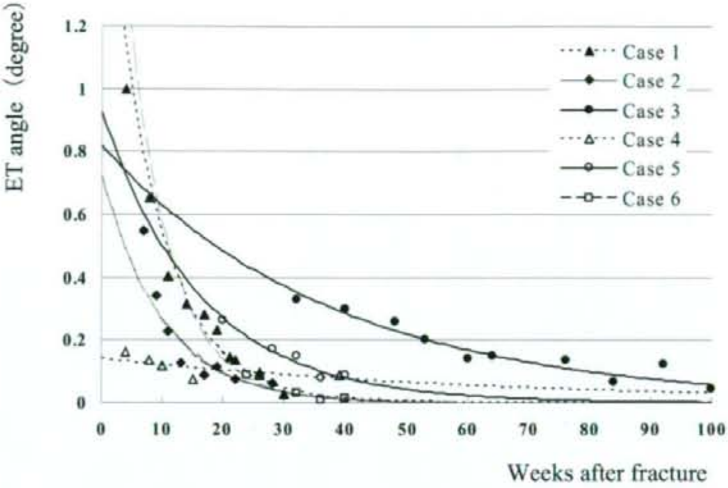

Fig. 8. In cases 1 through 6, the changes of the ET angle showed an exponential pattern. The correlation coefficients obtained by the regression equation for the ET angle and time were very high in these cases.

with considerable accuracy, sensitivity and reproducibility.

In patients with radiographically normal healing, the bending angle decreased exponentially over time. However, in patients with nonunion, the angle remained the same over time. According to the results obtained with previous methods such as the strain gauge method and the invasive method of Jernberger (1970), strain or deformation caused by loading at the healing site has been reported to diminish exponentially over time in patients with normal healing. Among these previous studies, Bourgois and Burny (1972) evaluated fracture healing in hundreds of patients treated with an external fixator that was instrumented with a strain gauge. They not only accumulated considerable clinical data on the strain readings over time, but also theoretically proved by mathematical simulation that the change of the strain over time during normal healing could be expressed as a typical hyperbolic curve. In addition to this, they proved that the time course of the change in strain could also be a hyperbolic curve by developing fracture simulation models with stabilization by intramedullary nailing, plating and external fixation. As a result, their clinical data were compatible with those for the theoretical model of external fixation. They classified the pattern of fracture healing into seven categories depending on the difference in the healing process. Among them, normal healing was defined as healing in which the strain reading *vs.* time curve reaches a plateau at 60 to 90 days after fracture. Slow healing was defined as healing in which the decline of strain was very slow compared with the normal pattern but the healing process was progressive over time. Nonunion was defined as cessation of the progress of healing. In two patients treated with a cast in our study, the ET angle decreased rapidly until 10 weeks after fracture to a level twice that on the intact side, and then it decreased slowly. The exponential regression curve for the echo tracking angle *vs.* time showed a very strong correlation (case 1, $r = -0.975$). Therefore, it can be concluded that the echo tracking method could be used to evaluate normal healing as proposed by Burny et al. (1984). As shown in Fig. 5, the progress of healing in patients treated with intramedullary nailing and bone grafting could be assessed by using the ET method. The ET angle *vs.* time relation in these cases was also expressed by exponential curves. However, the ET angle curve of patient 7 (Fig. 6b) did not show any significant decrease of the angle and there was no correlation between the ET angle and time. From this, the healing process was diagnosed as nonunion. The ET angle of patient 8, treated with plating, showed an extremely slow decrease over time from 9 weeks to 33 weeks, but reduction of the angle was statistically significant until 45 weeks, so the healing process was concluded to be delayed.

Fracture site stiffness was adopted as a parameter for evaluation that was thought to be correlated with strength of bone healing. In various earlier studies of fracture site mechanical properties, stiffness was measured to estimate the strength of the fracture site. However, stiffness is not necessarily correlated with strength. Chehade et al. (1997) investigated this relationship in 24 sheep. The tibia was stabilized with an external fixator and then osteotomy was done. Next, the tibiae were excised at 6, 8 and 10 wk after osteotomy and a 4-point bending test was done. As a result, in the initial stage of healing, stiffness showed a strong correlation with strength ($r = 0.89$), but there was no correlation between them in the remodeling stage. However, as Chehade et al. (1997) stated, because the stiffness of the fracture site is strongly correlated with the strength until remodeling is initiated, it is clinically significant to monitor fracture site stiffness as a substitute for strength to determine the appropriate level of weight bearing so that patients can avoid refracture because of overloading the fracture site during postoperative management. In the remodeling stage, we need to pay special attention to the relationship between stiffness and strength, even if stiffness reached the same value as the intact side.

Fracture healing was evaluated quantitatively by the echo tracking method in patients treated conservatively as well as by internal fixation. All previous methods of assessment could only be applied to patients treated with an external fixator that required the insertion of wires or screw pins, and none of the methods could achieve evaluation in a totally noninvasive manner. The potential problem with evaluating patients treated with internal osteosynthetic devices such as intramedullary nails or plates is that the stiffness at the fracture site is the sum of stiffness for both the healing fracture and the implant. The stiffness of the implant is very high compared with that of the healing fracture because it is made of a metal such as stainless steel or titanium-aluminum-vanadium alloy. Therefore, the combined stiffness at the fracture site is usually very high compared with that in patients receiving conservative treatment by casting. In such patients with internal osteosynthetic devices, comparison of stiffness with the intact side does not have any meaning for evaluation of fracture healing. Therefore, we have to be careful with interpretation of the changes of stiffness over time in such cases. How the implanted material and the configuration of stabilization affect fracture site stiffness should be investigated in the future so that we can assess fracture healing more precisely in patients with internal fixation.

In conclusion, it was demonstrated that the echo tracking method could be clinically applicable to evaluate fracture healing as a versatile, quantitative and noninvasive technique. Further development of this method should be performed so that it can be applied to other anatomical sites by improving accuracy and precision.

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Evaluation of Measurement Precision for Articular Cartilage Ultrasound Speed by Time of Flight Method

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INTRODUCTION:

Ultrasound speed in articular cartilage needs to be determined for morphological evaluation of cartilage using ultrasonography. However, relatively variant values of speed (1658 m/s [1], 1892 m/s [2], ca. 1580 m/s [3]) have been reported in past studies on ultrasound speed in human articular cartilage. Although such variability in speed may originate from error of the measurement method [4] and individual speed differences in samples, no studies have clarified the precision of the measurement method. The purpose of this study was to develop a method of measuring cartilage ultrasound speed and to evaluate the precision of our original measurement method.

MATERIALS AND METHODS:

Cartilage samples

Knee joints of a 6-month-old pig and a 3-year-old pig were obtained from a slaughterhouse (Tokyo Shibaura Zouki, Tokyo, Japan), since we assumed the speed could differ between pigs at different ages. Swine femoral condyle articular cartilage was used in this study, since cartilage size and shape are relatively similar to human cartilage. After slaughter, whole bodies of pigs were kept at 3 °C in a refrigerating room. On the third day, the hind limbs were detached and sent to our facility under the same temperature. In our facility, the limbs with intact knee joints were packed in plastic bags, degassed manually, sealed hermetically and stored at -20 °C. On the day of the experiment, soft tissues including joint capsules and ligaments were removed after the limbs were thawed in normal saline solution (Otsuka Pharmaceutical, Tokyo, Japan) at room temperature. Osteochondral blocks from the medial femoral condyle were acquired by cutting the bone with a band saw (SWD-250; Fuijiwara Sangyo, Miki, Japan), then fixed on a custom-made acryl sample holder (30 x 30 x 13 mm; Murai & Co., Tokyo, Japan) with resin (GC-Ostron; GC Corporation, Tokyo, Japan). During preparation, samples were continuously cooled and moistened using normal saline solution. The osteochondral block was then trimmed using a diamond saw (Minitom; Struers, Westlake, OH) to achieve a sample cartilage surface size of 10 mm x 10 mm.

Acoustic measurement

A radiofrequency (RF) signal-acquiring system equipped with a 10.0-MHz pulse-echo transducer (diameter, 13 mm; radius of curvature, 60 mm; model V311-SU; Olympus NDT, Waltham, MA) connected to a pulser/receiver (NDT-5800; Olympus NDT) was used for measurements. The transducer and sample holder were attached to a custom holding assembly, which has a sample stage with x, y and θxy micrometer adjustment to enable identification of the location of cartilage measurement (Fig. 1A). In the water tank on the stage, osteochondral blocks and the transducer surface were placed in 20 °C water. The distance between transducer surfaces and the sample was kept as the transducer focus distance. RF signals were recorded using an oscilloscope (DPO4034; Tektronix Japan, Tokyo, Japan). Edges of the sample were identified by RF signals, then the center of the sample was identified from those points. RF signals of 9 points at 1-mm intervals at the center of the sample were obtained from both the 6-month-old and 3-year-old pigs (Fig. 1B). Sampling time was 0.2 ns. A bandpass filter (1.0-20.0 MHz) was used to enhance ultrasound signal-to-noise ratio. TOF was defined as the duration (Δt) between peaks of RF signal envelope, corresponding to the travel time of the US pulse back and forth between the cartilage surface and cartilage-bone border of the specimen (Fig. 2).

Optical thickness measurement

The specimen fixed to a custom sample holder was mounted on the diamond saw device (Minitom; Struers), which has an accuracy of 10 μm for adjustment of the cutting plane. Three cut planes were created, each containing 3 RF signal acquisition points. Subsequently, each 1-mm slice sample was mounted on a glass slide, covered with a cover glass after dripping normal saline onto the sample surface to keep the cartilage moistened and inhibit deformation due to drying during measurement. Cartilage thickness was measured using optical measuring microscopy (MM-400; Nikon, Tokyo, Japan). Using this optical measuring microscopy, the points of RF acquisition on the cartilage surface and direction of the US beam were able to be identified from the position and orientation of the acryl sample holder surrounding the cartilage sample.

Thickness of the cartilage (Tc) along the beam direction was measured at each point and ultrasound speed in cartilage (USc) at each point was calculated: $USc = (2 \times Tc)/\Delta t$

Mean and standard deviation (SD) of each sample were calculated. Student's t-test was used to compare ultrasound speed values between the young and adult pigs. Results were considered significant for values of $p<0.05$. In addition, the coefficient of variance (CV) for precision evaluation of this ultrasound speed measurement was calculated for each sample.

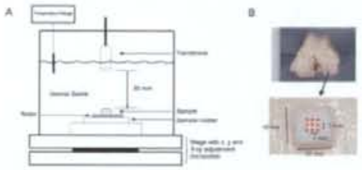

Figure 1A-B. (A) Schematic shows the custom holding assembly. (B) Images show the locations of RF signal acquisition of articular cartilage.

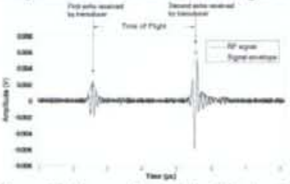

Figure 2. The envelope of the RF signal was calculated and peaks of the envelope were considered as reflection waves of the cartilage surface and cartilage-bone border [3].

RESULTS:

In all RF signals at the 9 points, peaks of reflected ultrasound waves from the cartilage surface and cartilage-bone border were clear enough to be identified. Mean TOF, Tc, USc and CV for both samples are shown in Table 1. With Student's t-test, USc was significantly higher for the 3-year-old pig than for the 6-month-old pig ($p<0.0001$).

	6-month-old pig	3-year-old pig
Time of Flight (us)	3.455	1.355
Thickness (mm)	2.567	1.161
Ultrasound Speed (m/s) *	1488 ± 48	1717 ± 104
Coefficient of variance (%)	3.1	5.5

Table 1. * Values are described as the mean ± standard deviation.

DISCUSSION:

Several factors are likely to influence the precision of ultrasound speed measurement. First, having sharp peaks of RF signals from the cartilage and cartilage-bone border is very important. For this point, transmitter ultrasound waves must hit the sample surface or border as perpendicularly as possible [4]. The cartilage surface must also be as close as possible to the transducer focus. We focused on measuring TOF with these conditions in our study under our original setting. Second, position adjustment of points between RF signal acquisition and optical thickness measurement is important. We developed a customized assembly in a water tank with the adjustment stage for RF signal acquisition and used a cutting device with very accurate plane adjustment. In addition, the customized acryl sample holder that enabled us to detect the direction of the ultrasound beam in microscopic measurement could achieve registration between ultrasound beam direction and microscopic measurement direction. We believe the precision (3.1 % - 5.5 %) of our method is sufficiently high to allow application to measure the ultrasound speed of human cartilage in future studies.

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1-3-PD1-3

3D-CT(multiplanar reconstruction)による骨癒合の診断および経時的変化の分析

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【目的】骨折治療の目的は機能障害を残さず骨癒合を得ることであるが，近年の学会報告症例を見て果たして真の骨癒合が得られているのかはなはだ疑問な症例も散見する．今回われわれはMPR(multiplanar reconstruction)を用いて，大腿骨近位部骨折の経時的変化について分析し，単純X線および臨床評価と対比検討をした．また，当科紹介となって観血的治療を行った癒合不全症例についても同様の検討を行った．

【対象および方法】症例は大腿骨近位部不安定型骨折および，Garden stage 2以上の症例について，術後3週目より3週間ごとにcoronal sectionのMPRと単純X線を撮影し，歩行能力や疼痛などの臨床成績とも対比を行った．MPRは原則として12週目まで行うが，臨床的および単純X線にて明らかに骨癒合が得られていなければ順次追加撮影した．また，他院にて初期治療を受け癒合不全となり当科紹介となった症例について，2方向のMPRを検討した．

【結果】大腿骨近位部骨折症例において，MPRにて内側皮質骨および外側皮質骨の連続性を認めた症例では，telescopingの進行が停止し，局所の疼痛も訴えた症例はなかった．また癒合不全症例も術後12週以降，coronal sectionおよびsagittal section MPRにおいて皮質骨の連続性を認めた症例では全荷重あるいは負荷運動に耐えることが可能であった．

【考察】骨折後骨癒合の判断は苦慮することがしばしばであるがMPRは海綿骨の多い骨幹端部，偽関節部に行った骨移植の判定にも有用であり，骨癒合の判断足りえるものと考える．

国立病院機構岡山医療センター整形外科

1-3-PD1-4

超音波エコートラッキング法を用いた骨癒合評価

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【目的】骨癒合を評価するにあたりX線写真による定性的方法は骨の形状や荷重方向といった力学的情報が欠如しており正確とは言えない．骨癒合においては骨の力学強度の回復が重要であり骨の力学特性を評価することにより骨癒合評価が可能と言える．われわれは体内の骨の歪を非侵襲に計測可能なエコートラッキング(ET)法を用いた新たな診断装置を開発した．ET法は超音波エコー信号の位相変化を測定するもので，荷重負荷に対する動的な骨の微小変形を2.6 μmの精度で測定可能とした．この装置を用い，骨の力学特性である剛性測定を行い骨癒合評価を行うことを目的とし臨床測定を行った．

【方法】脛骨骨折患者(保存療法：2名2肢，手術療法：12名14肢)を対象とし測定を行った．下腿の近位・遠位を固定し，骨折部近傍において25 Nの曲げ荷重を加え，近位・遠位骨片の傾斜角(ET変形角)を測定した．測定は2～6週間隔で実施し，測定期間は平均21.2週で測定回数は平均6.1回であった．ET変形角の経時変化を健側肢と比較し骨癒合を定量評価した．

【結果】保存療法・手術療法のいずれの症例においてもX線上，正常な骨癒合が進行した症例ではET変形角は経時的に指数関数的に減少し，骨癒合を定量評価可能であった．一方，手術症例でX線上，仮骨の形態変化を示さない症例のET計測では，いずれも経時測定で明らかな減少はなく，骨癒合不全であることが診断可能であった．

【結論】ET計測により*in vivo*において非侵襲に骨癒合の進行と遅延が定量診断可能であった．今後，非侵襲に骨強度評価を行う方法として骨折の骨癒合評価だけでなく脆弱性を有する骨に対しても応用可能であると考える．

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1-Pa-7

超音波を用いたヒト関節軟骨音速測定値に軟骨変性度が与える影響についての検討

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飯田 寛治　中村 耕三

【背景・目的】超音波による関節軟骨形態計測を行うためには軟骨音速の高精度測定が必要である。ヒト膝関節軟骨の音速を測定し、軟骨変性の程度が音速に及ぼす影響を検討した。

【方法】本研究における軟骨音速測定法は、第22回本学会で測定精度について報告したtime of flight法を用いた。倫理委員会の承認のもと、人工膝関節全置換術予定の変形性膝関節症患者より術前に同意を得た後、大腿骨顆部の骨軟骨切除片を収集した。患者数4名、検体数8、すべて女性で平均年齢は73.8±5.4歳であった。オリンパス社製の超音波送受信機(MODEL5800)と10 MHzのシングルプローブ(V 311-SU)を用い、脱気水(25℃)内で軟骨表面の3点においてRadiofrequency(RF)信号を検出した。信号はオシロスコープ(DPO4034, Tektronix)を介しコンピューターに記録し、軟骨表面境界、軟骨深層-石灰化軟骨境界(tidemark)に相当する各反射波の包絡線ピークを求め、peak-to-peak法により超音波飛翔時間(TOF: time of flight)を計測した。Minitom(Struers Inc.)を用い、信号検出点の断面を作成し、顕微鏡(MM-400, ニコン)により各点における軟骨表面からtidemarkまでの距離を軟骨厚として測定した。TOFおよび顕微鏡計測の軟骨厚より軟骨音速を算出した。音速測定後Safranin O-Fast Green染色による組織切片を作成、Mankin scoreにより軟骨変性評価を行い、音速測定値とMankin scoreについて回帰解析および相関解析を行った。

【結果】音速値の平均は1762.0±81.1 m/s。Mankinスコアと軟骨音速との一次回帰直線の式および相関係数の二乗はそれぞれ$y = -24.26x + 1877.2$、$R^2 = 0.2257$であった($p = 0.2511$)。Mankin scoreが高いほど軟骨の音速が減少する傾向にあった。

【考察】牛膝関節軟骨を用いた先行研究では、軟骨音速値は変性が進むほど低下すると報告されている(Toyras, et al, 2003)。今回、ヒト膝関節軟骨でも同様な結果が得られ、変形性膝関節症において関節軟骨形態計測を行うに際してこの点に留意する必要があると考える。

東大大学院整形

1-Pa-8

関節軟骨超音波評価法の誤差低減

山田 桂輔¹　山本 浩司¹　服部 耕治²　冨田 直秀

【緒言】近年、生体関節内で軟骨の状態を定量的に、軟骨に損傷を与えずに評価する方法として、超音波反を用いた関節軟骨定量評価法が開発されている。超音価法において軟骨変性の指標となる軟骨表面からの反の振幅は、超音波探査子の軟骨表面に対する照射角がでない場合大きく減少する。しかし、現在探査子の軟面に対する角度を推定する方法はない。臨床における関節の評価では、手作業で測定が行われるため、正確に測するには時間を要する上に多くの誤差を含みうる。究では、関節軟骨超音波評価法の精度向上のため、反射の波形変化を用いた超音波探査子の反射面に対する角度定を試みた。

【試料と方法】ステージに固定した軟骨(豚膝関節軟骨)ステンレス平板に対し超音波を照射し、反射波の振幅が大となるようにステージの角度を調節した。反射波の振が最大となる角度を0とし、そこから0.5°ずつ5°までステージを傾け、各角度における波形を測定した。測定は生理塩水中で行った。測定された反射波の波形の、1つ目のピクが計測されてから自由振動部の最初の負のピークが計されるまでの時間を、本研究ではPeak-to-Peak値と名付た。このPeak-to-Peak値を軟骨からの反射波とステンレからの反射波の各測定波形について計測し、探査子の傾との相関関係を調べた。

【結果と考察】探査子の角度とPeak-to-Peak値は正の相関を示した。このことから、測定波形からPeak-to-Peak値を計測することにより、探査子の傾きを推定できることが示唆された。また、Peak-to-Peak値の変化に対する反射強度の減少割合は、軟骨とステンレスで同じ傾向を示した。このことのから、Peak-to-Peak値を用いて反射波振幅の補正も可能であることが示唆された。

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81-1008 超音波による骨癒合強度定量評価の新しい計測システムの開発

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【はじめに】

骨癒合強度の評価において，現在のところ非侵襲で定量的かつ実用的な評価方法が確立されているとは言えない．我々は，超音波を用いて骨癒合度合いを非侵襲的かつ定量的に評価する計測方法を開発し報告してきた[1),2)]．今回は実用化を目指した新しい計測システムを開発したので，その内容と結果を報告する．

【方法】

超音波によるエコートラッキング（ET）法を用い，骨に荷重を与えたときに発生する骨表面の微小変位を計測することで骨の剛性を評価する．対象骨は脛骨である．被験者へ与える荷重値を低減するため，縦荷重から3点曲げ試験法による横荷重に改良した．その結果，荷重値を従来の約1/4に低減でき，より非侵襲性を高めた[3)]．これにともない評価指標をETS値[1)]から，屈曲角度ET − angle値[3)]に変更した（Fig.1）．

今回は特に，計測システムの実用化と小型化を目指し，新たなシステムを開発した．従来システムとの主な違いは次の点である．

(1) 9素子からなる探触子（Fig2左）を開発し，これを4つ用いた．

(2) 超音波の送受信チャネル数を4つに削減した．

(3) 開発した探触子を荷重点の両側に2つずつ配置し，ET計測点数を4点にした．

(4) パソコンベースにした．

なお，超音波の送信中心周波数は7.5MHzである．変位計測精度の評価は前回と同様に，水中で移動する金属平板の変位を接触式変位計（精度：1 μm）の値と比較した．

【結果】

変位計測精度は，接触式変位計の値に対し標準偏差が2.8 μmで，従来と同等であった．また，送受信チャネル数を減らしパソコンベースにしたことで計測システムを小型化できた（Fig.2右）．一方，Bモード画像の表示機能を省略したため，探触子の設定には慣れが必要であった．

【まとめ】

計測性能を維持したまま計測システムを小型化でき，実用性を高めた．

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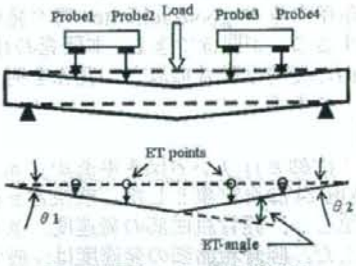

Fig.1 ET-angle 値の説明図

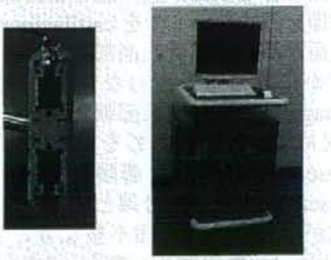

Fig.2 専用探触子(左)と計測システムの概観(右)

Development of a New Measurement System for Ultrasonic Quantitative Assessment of Mechanical Properties of Bone Healing

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A Minute Bone Bending Angle Measurement Method using Echo-Tracking for Assessment of Bone Strength In Vivo

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***Abstract*—The purpose of this study is to develop a new ultrasound diagnostic system for non-invasive and quantitative assessment of mechanical properties of the bone or bone healing. In the previous papers [1] [2], we reported that we had developed a new ultrasound system to measure a minute bone deformation using a multi-point echo-tracking (ET) and that it had a great potential for non-invasive and quantitative diagnosis of bone healing. In this paper, we present a newly developed measurement system with improved accuracy for assessing deformation of intact tibia in vivo. It consists of a dedicated probe, a transmitting/receiving system and analysis software calculating a minute bending angle of the bone surface under a three-point bending (TPB) test. And, we report results of a performance evaluation of the developed system by using test measurements. Furthermore, we evaluated the reproducibility of the in vivo measurement by repeatedly measuring the bending angle of the tibias of 5 healthy volunteers every week for one month. As a result, the evaluation of the accuracy of the measured bending angle using the metallic plate for calibration showed that the standard deviation (SD) of the measurement in range of 0 to 0.1 degrees was 0.004 degrees. Then, we performed an in vivo measurement of normal tibia. The results showed that the mean bending angle of the normal adult tibias under a load of 25N and a supporting span of the tibial length of each subject was 0.058 degrees with a SD of 0.01 degrees. In addition, SD of the data for the measurement repeatability was 0.006 degrees. We developed a bending angle measurement system for the human tibia using a TPB test and obtained an excellent accuracy of the system and also confirmed through the measurement of the tibia of human volunteers that the repeatability was sufficient to quantitatively assess bending property of the intact tibia.**

Keywords:Echo-tracking;Non-invasive;Bone mechanical property

I. INTRODUCTION

In the treatment of fractures, the mechanical properties of the fracture healing site provide useful diagnostic information on the assessment of the degree of healing. Until now, it has been difficult to quantitatively assess the mechanical properties of the bone noninvasively. In clinical practice, the diagnosis of the bone healing has been performed by X-ray images. However, this evaluation is neither quantitative nor noninvasive resulting in re-fracture after union or non-union due to the lack of sufficient accuracy. To solve the problem, we have developed a method to quantitatively assess the mechanical property of the fracture site. The method utilizes ultrasound to measure the amount of a minute deformation of the bone subjected to a small load.

We validated the accuracy and clinical usefulness of the fracture healing assessment system which we developed by applying Echo-Tracking (ET) method [3] by measuring strain of a bone model and by applying the method to fracture patients. The results on the capability of quantitative evaluation of the process of bone healing have already been described [2]. In the bone model experiment, the correlation between the ET-strain (ETS) measurement and the strain measurement of the bone surface was very high. In vivo evaluation of fracture patients, the progress of the bone healing could be quantitatively assessed in all of the patients from the first stage of the consolidation period to the final stage. In the current study, we tried to improve the measurement accuracy and reproducibility to be able to expand the application to non-fractured bones with bone fragility such as osteoporosis. To this end, we enhanced the measurement accuracy of the system.

II. METHODS

We describe the new measurement algorithm that applied the three-point bending (TPB) test method, the newly developed measurement system and its evaluation method.

A. Measurement algorithm

To apply the TPB test method, we change the load direction from axial compression to bending. The measured item is the bending angle of the bone under the load. We can obtain sufficient deformation of the bone surface even under a smaller bending than that of axial compression. Moreover, as the load direction can be controlled, the direction of the deformation can be specified. Fig.1 shows the diagrams of the measurement method. In order to further improve the measurement accuracy, the bone surface displacement of the proximal and distal sides of the loading point is measured by using two probes. The spacing of probes is 110mm. A water bag is put on the probe surface to eliminate the influence of the bone surface shape and to provide an acoustic coupling. Each probe is equipped with two transducers. The spacing of transducers is 40mm. These four transducers acquire the RF signals from each of the four points on the object surface by ultrasound transmitting and receiving. The total of four displacements of the object generated by the load are measured by analyzing the RF signals using the ET method. Thereafter, the two inclination angles of the proximal and distal bone surface are calculated from the four displacements, and finally the bending angle (ET-angle) of the object bone is obtained by adding these two inclination angles.

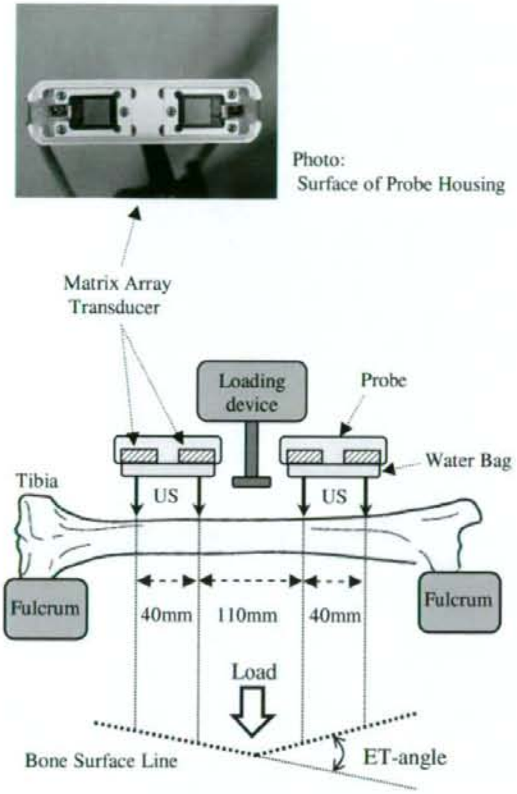

Fig.1 The principle of measurement method using TPB test method

The measured item is the bending angle of the bone under the load. The bone surface inclination on both sides of the load point is measured by using two probes. The ET-angle is calculated by adding each inclination angles obtained by two probes.

B. Measurement system

The measurement system consists of two ultrasound probes, transmitter and receiver, a computer controlled loading device to load the target bone, a leg-holder and a system control/data analysis software.

We developed a new dedicated ultrasound transducer of the matrix array format (3*3, pitch 3mm, 7.5MHz). The transducer is small and lightweight to be able to improve the positioning accuracy for the ET measurement, and to make the handling easier. The purpose of introducing a matrix array format is to identify measurement points easily for ET on the bone surface with various curvature. In addition, we also developed a dedicated ultrasound transmitter and receiver to enable the simultaneous four-point measurement with four matrix array transducers.

Previously, loading on the object bone had been performed with a human hand. To reduce the measurement error factor, we developed a computer controlled loading device. This device applies initial load of 5N to the object bone and, after a few seconds, increases the load up to 30N (maximum load). The reason to have a few seconds pause is to avoid the influence of the visco-elasticity of the soft tissue that might affect the results of the measurement. The loading rate can be arbitrarily specified. In this study, we set it at a speed of 4N/s that does not give uncomfortable feeling to volunteers.

The software of this system controls simultaneously the loading device and the ultrasound transmitter/receiver. The initial load of 5N is automatically applied when an examiner pushes the measurement start button, and then the ultrasound transmitter/receiver starts to operate automatically, and after a few seconds, the loading device starts to increase the load up to 30N. By off-line processing, the displacement of the bone is measured from acquired RF signals by the ET measurement method, and the ET-angle is obtained from the difference of displacements between the 5N and 30N loading. As the object bone is being covered with soft tissue, there is some overall sinking of the bone surface along the loading direction. However, the effect of this translation on the calculating angle can be removed by using differential measurement on the elements of array transducers.

For the measurement in vivo, we developed a U-shaped leg holder to support and stabilize the lower leg.

C. Evaluation of measurement accuracy

Fig.2 shows the diagram of the measurement setup. We measure an inclination angle of the surface polished metallic plate (SUS420J2, 270*60*5t mm, flatness variation 2μm less) tilted by a micrometer using our measurement system simultaneously with an optical displacement meter with an accuracy of 0.5μm (LK-G150, Keyence, Japan). Each inclination angle was calculated by the individually measured displacements and the spacing of the measured points using arctangent. The spacing of transducers is 40mm. The one of optical displacement is 100mm.

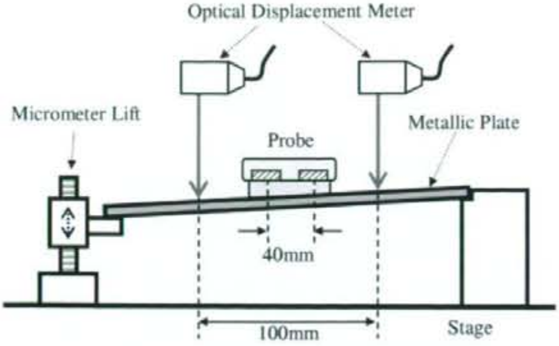

Fig.2 Evaluation method of inclination angle
The inclination of metallic plate measured with optical displacement meter and this system simultaneously. The inclination angle is calculated by each differential displacement and spacing of the measured points using arctangent. The spacing of transducers is 40mm. The one of optical displacement is 100mm. Each inclination angle is compared.

We evaluate the accuracy of the inclination angle measurement of our system by comparing with those of the optical displacement meter.

Next, we perform the ET-angle measurement by using the TPB test of a tibia bone model (SAWBONES 3^{rd}Generation Composite Tibia, Pacific Research Laboratories, Inc., USA) which simulated the elasticity of the human tibia. Because there is no soft tissues, due to the differential algorithm, the angle is estimated to be close to that measured in vivo. Fig.3 shows the photograph of measurement configuration.

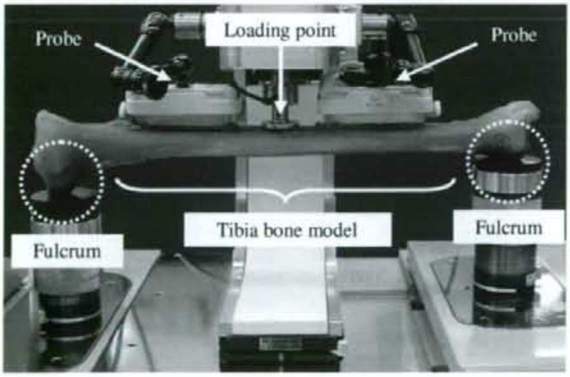

Fig.3 TPB measurements of tibiae bone model
Each end of the bone model is placed on a fulcrum (lower side of the figure). Loading point and two probes are arranged on the midline of the medial surface of tibia (upper side of the figure). The loading device applies the load and the angle is measured using the ET method.

D. Evaluation in vivo

For in vivo evaluation, the measurement area by ET is selected to be the medial surface of the tibia which is suitable for the ultrasound assessment. The proximal fulcrum is positioned at the head of the fibula, and the distal one at the lateral malleolus. These positions are selected because a) they can be easily found by palpation, b) they provide easy access through a thin layer of the soft tissue and c) they offer good balance and a comfortable position for volunteers. The U-shaped leg holder (width of the proximal: 60mm, width of the distal: 30mm) is developed in order to support the lower leg. A silicon sponge is attached to the surface of the leg holder, and the stability of the support was ensured. Loading point is adjusted and placed on the appropriate position on the medial side of the tibia, projected from the midpoint between the head of the fibula and the tip of the lateral malleolus measured on the opposite side. The direction of the load is vertically set to the measurement side. Fig.4 shows the photograph of measurement configuration.

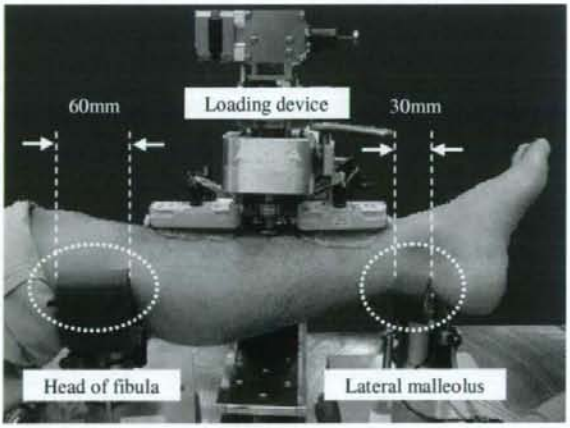

Fig.4 TPB measurements of human tibia
The lower leg is placed on the leg-holder. The proximal fulcrum is set at the level of the head of fibula. The distal one is at the lateral malleolus. The loading device and the probe are arranged on the midline on the medial surface of tibia side. The ultrasound signals from the tibial surface during loading are acquired.

E. Assessment of reproducibility in vivo

The reproducibility of the ET-angle measurement by this system is evaluated by in vivo evaluation method as previously mentioned. Each of the left tibia of five healthy volunteers (from ages 24 to 57) is evaluated four times every week. In each experiment, the measurement is repeated three times and the means and the standard deviations are calculated.

III. RESULTS

The accuracy of the inclination angle measurement by this system was 0.004 degrees. Because the theoretical accuracy of the angle/displacement measurement with the ET method is 0.004 degrees ($\tan^{-1}[3\mu m/40mm]$), it could be confirmed that the accuracy of our system was extremely high almost equivalent to the theoretical value.

As the result of TPB measurement by using tibia bone model, the ET-angle of 0.073 degrees (0.003SD) was obtained under the load of 25N. These values are the mean and standard deviation of five times measurement results. Because the bone model has the elasticity equal with a human bone [4], we were able to estimate the order of ET-angle of the human tibia.

The result of TPB measurement and the reproducibility of the measurement of the human tibia are shown in Table 1 and Fig.5. The variation of each trial in ET-angle showed the reproducibility by assuming that the tibial property would not change during the measurement period. The mean of the standard deviation of the ET-angle measurement was 0.006 degrees in the whole persons. Considering the accuracy of the inclination measurement of this system was 0.004 degrees, this result showed high reproducibility.

Table 1 The reproducibility of the system in vivo every week

Subject	Sex	Age	Tibial length [mm]	Tibial width [mm]	ET-angle [degrees]	First week	Second week	Third week	Fourth week	Ave. /4weeks	SD /4weeks
E.M.	Male	57	330	32.0	Ave.	0.039	0.050	0.040	0.057	0.047	0.008
					SD	0.003	0.003	0.005	0.010		
R.S.	Male	35	320	28.9	Ave.	0.075	0.076	0.073	0.069	0.073	0.003
					SD	0.010	0.013	0.005	0.014		
K.H.	Male	36	330	38.3	Ave.	0.068	0.059	0.051	0.049	0.057	0.009
					SD	0.012	0.004	0.005	0.004		
N.I.	Male	24	340	40.4	Ave.	0.067	0.053	0.053	0.058	0.058	0.007
					SD	0.005	0.000	0.004	0.005		
H.S.	Male	42	334	36.0	Ave.	0.058	0.056	0.049	0.050	0.053	0.004
					SD	0.003	0.006	0.009	0.003		
									Ave.	0.058	0.006
									SD	0.010	

TPB test for the tibia are measured by load of 25N (5N→30N). The subjects are five volunteers (Age: 24-57). The evaluation method is to measure same person four times every week. In each experiment, the measurement is repeated three times and means and standard deviations are calculated.

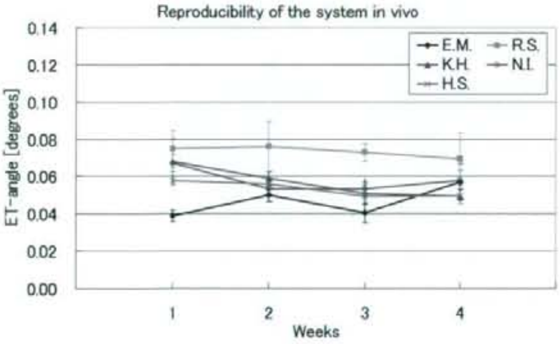

Fig.5 The reproducibility of the system in vivo every week
The mean and the standard deviation of ET-angle in each volunteer were plotted every week.

IV. DISCUSSIONS AND CONCLUSION

We developed a new measurement algorithm and system in order to evaluate the mechanical properties of human tibia with high accuracy and reproducibility. As a result, the possibility of evaluation for not only the fractured bone but also non-fractured bone with bone diseases such as osteoporosis was obtained.

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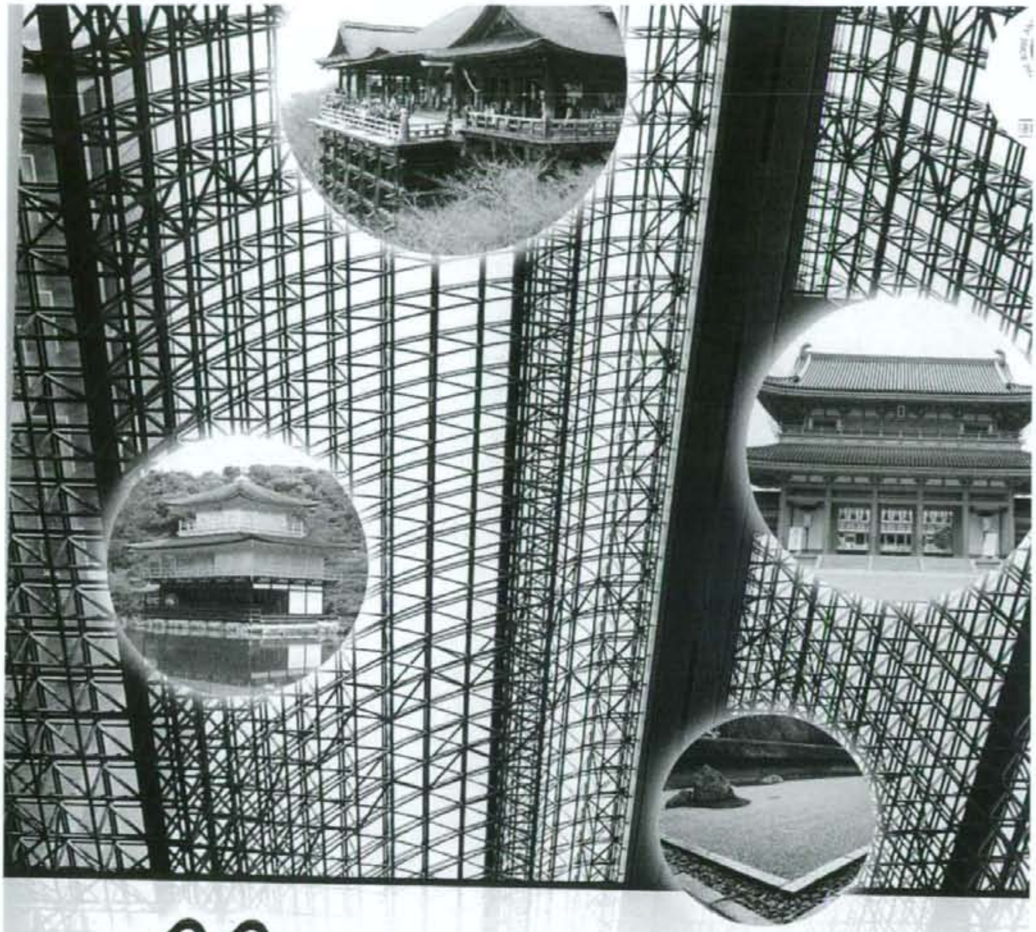

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