ULTRASONOMETRY EVALUATION OF AXIAL COMPRESSION OSTEOSINTHESIS. AN EXPERIMENTAL STUDY

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ABSTRACT

Objective: To measure the ultrasound propagation velocity (UV) through a tibial transverse osteotomy in sheep, before and after the fixation with a DCP plate. Material and methods: Ten assemblies of a DCP plate with the diaphyseal segment of tibiae, in which a transverse osteotomy was made, were used. Both coronal and sagittal transverse and the axial UV were measured, first with the intact bone assembled with the plate and then with the uncompressed and compressed osteotomy; statistical comparisons were made at the 1% ($p<0.01$) level of significance. Results: Compared with the intact bone assembly, axial UV significantly decreased with the addition of the osteotomy and significantly increased with compression, presenting the same behavior for the other modalities, although not significantly. Discussion and conclusion: In accordance with the literature data on the ultrasonometric evaluation of fracture healing, underwater UV measurement was able to demonstrate the efficiency of DCP plate fixation. The authors conclude that the method has a potential for clinical application in the postoperative follow-up of DCP plate osteosinthesis, with a capability to demonstrate when it becomes ineffective. ***Laboratory investigation.***

Keywords: Acoustic. Ultrasonics. Bone and bones. Bone plates.

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INTRODUCTION

Open reduction and internal fixation (ORIF) has quickly become the preferred method for the treatment of fractures of the shaft of long bones, following the introduction of modern techniques and more reliable implant materials. Among these, the conventional dynamic compression plates (DCP) predominate, particularly for the small long bones (diaphysis of the humerus, radius, ulna and clavicle) of the upper limb, due to their relatively low cost and versatility. Interfragmentary axial compression applied to simple fractures (two fragments) increases the stability of the fixation, thus providing an ideal condition for the so-called direct healing to take place.[1-3] Unfortunately, complications increase at the same proportion as the operated fractures, including early loosening of the plate usually due to inadequate intraoperative reduction and insufficient compression strength, which potentially lead to a healing anomaly and consequent delay in patient recovery. So far, no diagnostic resource can actually provide an intra or postoperative measure of the interfragmentary compression strength, which entirely depends on the surgeon's knowledge and ability in the application of the proper technique for plate fixation.

Ultrasonometry appears to be a real possibility, since it has been extensively demonstrated that the ultrasound propagation velocity (USPV) decreases in a fractured bone and increases as healing takes place, slowly approaching normal values, or remains at levels lower than normal if the fracture does not heal or takes longer to do so.[4-9] Interfragmentary axial compression brings both fragments of a simple fracture so close together that the capacity to propagate the ultrasound waves can hypothetically be restored as early as during the intraoperative period.

Thus, we have decided to test the hypothesis that ultrasonometry can help demonstrate the efficiency of interfragmentary axial compression between two fragments of a simple fractura. A laboratory bench investigation has been designed using fresh-frozen sheep tibiae assembled with 8-hole 3.5 mm DCP plates. A transverse complete osteotomy was made to simulate the fracture.

MATERIAL AND METHODS

The investigation was approved by the Ethics Committee on Experimental Use of Animals of our institution. For economic

All the authors declare that there is no potential conflict of interest referring to this article.

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and ethical reasons, ten (n=10) fresh-frozen intact left tibiae were taken from adult sheeps (10 months of age, 37 kg average body weight) already used in a separate research project, in which the right tibiae had been operated. The tibiae were completely stripped from any soft tissue, including the periosteum, and both proximal and distal epiphyses were resected by an osteotomy at the level of the epiphysis-diaphysis transition, thus leaving the entire shaft of the bone for the plate fixation. The exact epiphysis-diaphysis transition was determined by the application of Heim's square,[10] designed with all sides equal to the width of the corresponding epiphysis, with the proximal side tangential to the joint line and the opposite side marking the transition.

The volumetric density of the bone segments was measured using an electronic densimeter to allow further calculation of the acoustic impedance and reflection coefficient of the water-plate, plate-bone and water-bone interfaces. Acoustic impedance (Z), expressed as kg/m^2/s, is the product of density (ρ, measured in kg/m^3) by ultrasound speed (v, measured in m/s), as follows:

$$(1) \qquad \boxed{Z = \rho \times v}$$

The reflection coefficient corresponds to the amount of ultrasound waves reflected by an interface between two materials for a normal (90^o) ultrasound emission and it is calculated by the quotient:

$$(2) \qquad \boxed{R = [(Z2 - Z1)/(Z2+Z1)]^2,}$$

Where R is the reflection coefficient and Z1 and Z2 are the acoustic impedances for the first and second material crossed by the ultrasound waves, respectively. The reflection coefficient theoretically varies from 0 to 1 and the value obtained with the above mentioned equation multiplied by 100 yields the amount of energy reflected as a percentage of the emitted energy. The remaining value (1 minus R) represents the amount of energy which effectively goes through the interface.

Fixation and osteotomy technique: The bone segments were assembled with 8-hole 3.5 mm AO stainless steel DCP plate (Synthes Brasil®, Rio Claro SP, Brazil), adapted onto the flattest dorsal aspect so that the respective middle points coincided, both lengthwise and sideways. With the DCP plate adapted onto the bone with special forceps, the screws were introduced alternately on each half of the plate (Figure 1). Screw insertion obeyed the recommended technique for a real surgical procedure, as follows: 1) drilling of a 2.5 mm diameter hole through both cortices; 2) tapping the internal screw thread with a 3.5 mm diameter tap; 3) introducing the screws with an hexagonal key.[11] The first two screws were introduced through holes 2 and 7 in the neutral position and tightened until they just touched the plate, with the only purpose of stabilizing the plate and permitting removal of the forceps. The second two screws were eccentrically introduced through holes 4 and 5, with the purpose of obtaining compression after the osteotomy was done; at this stage, both were also tightened until they just touched the plate. The remaining four screws were then eccentrically inserted through holes 1, 3, 6 and 8, since they would migrate to a neutral position after compression applied with screws 4 and 5; all of them were also tightened until they just touched the plate. A complete transverse osteotomy was then performed between the two central screws (holes 4 and 5) with an electric oscillatory saw assembled with a 0.8 mm-thick blade. With the exception of screws 4 and 5, all others were slightly released on each side of the plate to permit the bone fragments to slide under the plate during the application of compression. Screws 4 and 5 were then completely tightened, thus providing firm interfragmentary axial compression, great care being taken to avoid lateral dislocation of the fragments and to ensure total contact between the two osteotomy surfaces. Upon compression, all remaining screws migrated towards the center of the respective holes and were then completely tightened so as to definitively stabilize the assembly.

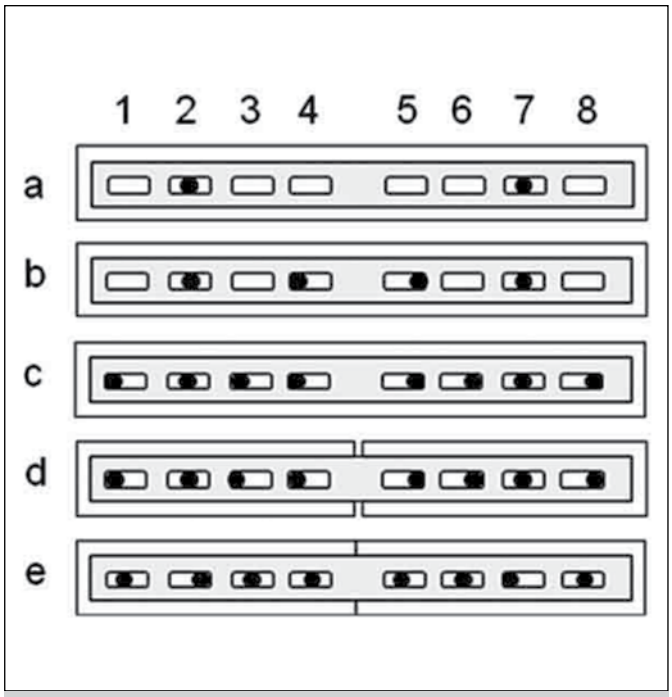

Figure 1. Diagram of plate fixation: the first two screws inserted in holes 2 and 7 (a), followed by the next six screws (b and c); and the uncompressed (d) and compressed osteotomy (e). The excentric insertion of screws 4 and 5 is evident (c and d), becoming central after compression is made (e).

Experimental Groups: Both coronal and sagittal diameters were measured at the exact midpoint of the specimens with a precision pachymeter (Mitutoyo, 0.05 mm error), the sagittal diameter of the assemblies including the plate thickness. Four groups of assemblies were analyzed, as follows:

Group 1:Intact bones;

Group 2:Bone - DCP plate assemblies with no osteotomy;

Group 3:Bone - DCP plate assemblies, with uncompressed osteotomy;

Group 4:Bone - DCP plate assemblies, with compressed osteotomy.

All specimens in all groups were analyzed for transverse USPV on both the coronal (subgroups C, away from the plate) and sagittal (subgroups S, through the plate) planes and for axial USPV on the coronal plane (away from the plate). Five sequential measurements were made for each assembly on each plane, with the greater and the smaller values being discarded and an average value being calculated from the remaining three and used for interpretation and statistical analysis.

Ultrasonometric analysis: USPV was measured with the same research setup used in our previous investigations, consisting of an acoustic tank equipped with two diametrically opposed unfocused ultrasound transducers (2 mm-thick PZT-5 disc, 20 mm in diameter, 1 MHz frequency), one for emission and the other for reception, connected to an ultrasound generator--receiver-amplifier source (Biotecnosis do Brasil Ltda., Model US01, Ribeirão Preto SP Brazil, www.biotecnosis.com) able to generate high power narrow well defined ultrasonic pulses (1 MHz frequency, 1 μs pulse duration, 0.1 ns rise time, 1s repetition). A digital storage oscilloscope (Agilent Technologies, Inc., model DSO3062A, Shangai, China) was linked to the ultrasound source and to a computer loaded with a specific software for automatic calculation of the USPV.

Before starting the measurements, the system was calibrated with a compact 23 mm-thick Teflon® disk of known and constant USPV (1250 m/s, ±0.3%). Water (distilled) temperature was maintained around 35°C.[12] For the transverse USPV measurements, the specimens were positioned lengthwise inside the acoustic tank, onto Teflon® stands, transversely between the transducers, with their central diameter precisely aligned with the longitudinal axis of both transducers. For the coronal USPV measurements the plate was positioned facing upwards, meaning that it remained out of the way of the ultrasound waves (Figure 2), while for the sagittal USPV measurements it was positioned sideways (Figure 3), therefore facing directly the emitting transducer, i.e. in the way of the ultrasound emission. A 4 mm-distance was maintained between the emitting and recipient transducers and the corresponding sides of the specimen.

For the axial USPV measurements, another pair of transducers were assembled onto a Teflon® stand, parallel to each other and at a fixed distance of 50 mm between their centers, and fixed above the specimens so that a 2 mm distance was maintained between them and the lateral surface of the bone. The specimens were placed lengthwise inside the acoustic tank, with the plate facing sideways, therefore out of the way of the emitted ultrasound waves, meaning that the waves would be transmitted along the lateral cortex of the bone, with little or no influence from the plate (Figure 4).

Both emitted ultrasound pulse and first arrived signal (FAS) were identified on the oscilloscope screen, as well as the time elapsed between emission and reception.

Time interval measurements were automatically transferred to the above mentined software, but propagation distance was manually inserted for each individual specimen. USPV was then calculated considering the time required for the ultrasound waves to propagate through the medium alone (water) and through both medium and specimen, as recommend by other authors [13,14] according to the following equation:

$$(3) \qquad V_s = \frac{1}{\frac{1}{V_r} - \frac{(\tau_r - \tau_s)}{d}}$$

Where: V_s is the velocity through the specimen; V_r: velocity through the reference propagation medium (water); τ_r: time for reference propagation medium alone (water); τ_s: time for propagation in the reference medium and specimen; and d: distance (diameter of specimen).

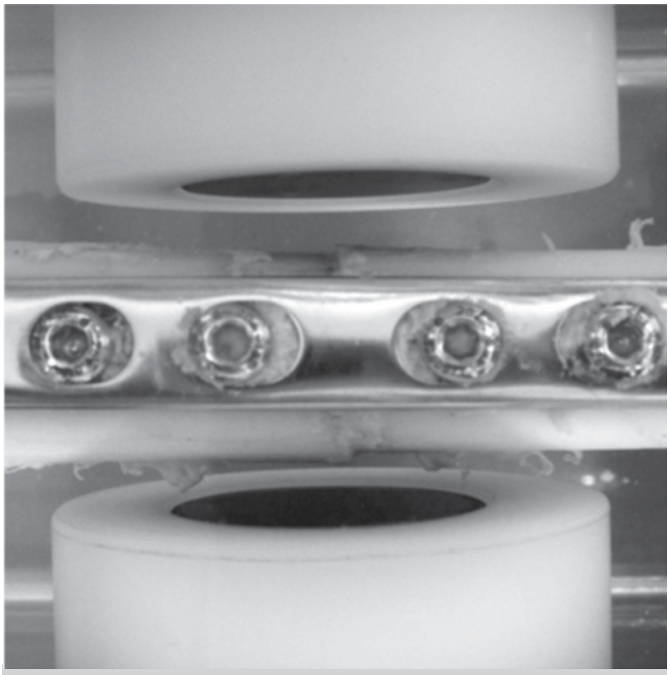

Figure 2. An on-going transverse coronal USPV measurement in the acoustic tank, with the bone-plate assembly between the emitting (below) and recipient (above) transducers and the plate away from the ultrasound wave emission. A 4 mm distance is maintained between the transducers and the assembly.

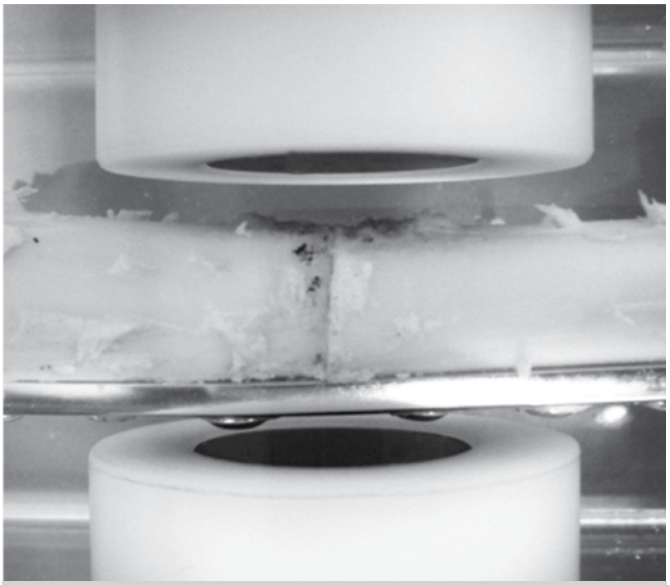

Figure 3. An on-going transverse sagittal USPV measurement in the acoustic tank, with the plate facing directly the emitting transducer, therefore in the way of the ultrasound wave emission.

Statistical analysis: The PRC GLM procedure of the SAS® 9.0 software was used for the statistical analysis at the 1% level of significance ($p<0.01$). Data were first submitted to analysis of variance according to the method proposed by Montgomery,[15] by which the total variance of a given response (dependent variable) is divided into two parts, the first referring to the linear regression between groups, and the second referring to the residues, or errors, within groups. The larger the former in

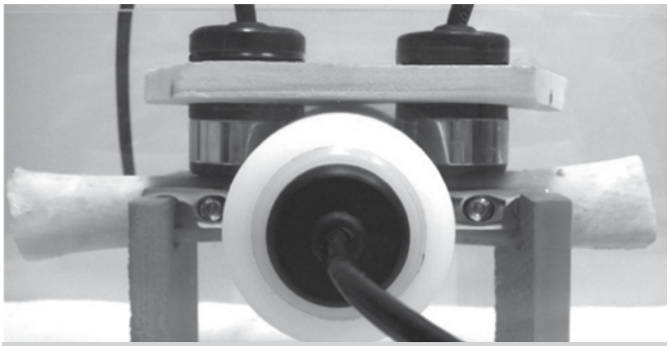

Figure 4. An on-going axial USPV measurement, with two parallel transducers applied onto the lateral cortex, one above and one below the osteotomy, away from the plate.

relation to the latter, the larger the difference between means of the groups compared, assuming that the residues are normally distributed, with 0 (zero) as the mean value; a logarithmic transformation was applied to the variable response whenever this assumption was not met. Comparisons were made using the orthogonal contrasts, based on the Student's *t* distribution.

RESULTS

The mean bone density measured in our bone segments was 1416 kg/m3 (range: 1219.04 – 1626.92 kg/m3), accounting for an acoustic impedance of 3.66 x 10^6 kg/m^2/s, therefore almost twice as high as that of the water (1.4 x10^6 kg/m^2/s), but much lower than that of the steel (46.2 x 10^6 kg/m^2/s). The resulting reflection coefficients were of 0.88, 0.72 and 0.14 for the water--steel, steel-bone and water-bone interfaces, respectively.

Axial USPV was consistently and significantly ($p<0.01$) higher (~2722 m/s) than transverse USPV (~2507 m/s). The mean transverse coronal USPV was consistently but not significantly higher than the mean transverse sagittal USPV. The mean transverse coronal USPV was 2587.50 m/s (range: 2399 - 2876 m/s), 2756.80 m/s (range: 2328 – 3040 m/s), 2569.80 (range: 2265 – 3076 m/s) and 2579.10 m/s (range: 2262 -3065 m/s), with medians of 2550, 2516, 2507 and 2519 m/s, for Groups 1, 2, 3 and 4, respectively. The mean transverse sagittal USPV was 2430.80 m/s (range: 2323 – 2725 m/s), 2429.70 m/s (range: 2302 – 2640 m/s), 2433.40 (range: 2338 – 2652 m/s) and 2448.90 m/s (range: 2338 – 2653 m/s), with medians of 2402.50, 2387.50, 2387.50 and 2398 m/s, for Groups 1, 2, 3 e 4, respectively (Table 1, Figure 5). Differences were not significant for any comparison, with p values ranging from 0.0396 (Group 1 transverse coronal USPV *versus* Group 2 transverse sagittal USPV) to 0.9884 (Group 1 transverse sagittal USPV versus Group 2 transverse sagittal USPV), therefore meaning that the addition of a transverse osteotomy and a compression plate with or without compression does not significantly change transverse transmission ultrasound velocity through the bone, whether measured on the coronal or sagittal planes.

Axial USPV, measured on the coronal plane, was 2727 m/s (range: 2688 – 2783 m/s), 2738 m/s (range: 2669 – 2805 m/s), 2675 m/s (range: 2644 – 2703 m/s) and 2747 m/s (range: 2677 – 2813 m/s), with medians of 2727, 2737, 2681 and 2759 m/s, in Groups 1, 2, 3 and 4, respectively (Table 2, Figure 6). Differences were significant for the comparison between Groups 1 and 3

Table 1. Descriptive statistics of mean values of trasnversal and sagittal USPV (m/s) according to each group.

	Group	n	Mean	St. Dev.	Minimum	Medians	Maximum
Intact	1C	10	2587.5	158.14	2399	2550	2876
	1S	10	2430.8	115.68	2323	2402.5	2725
DCP	2C	10	2576.8	217	2328	2516	3040
	2S	10	2429.7	96.83	2302	2387.5	2640
DCP+ uncomp ost	3C	10	2569.8	236.81	2265	2507	3076
	3S	10	2433.4	97.68	2338	2387.5	2652
DCP + comp ost	4S	10	2579.1	232.67	2262	2519	3065
	4C	10	2448.9	104.91	2338	2398	2653

Legend: St. Dev: Standard Deviation; Ost: osteotomy; comp: compression; C: coronal; S: sagital

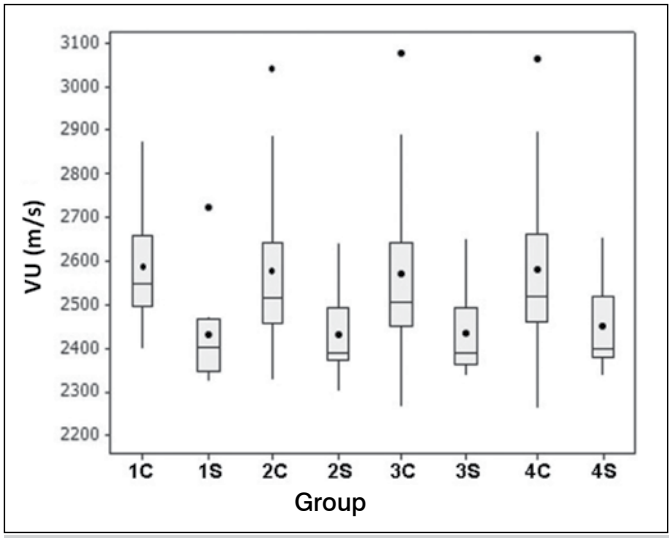

Figure 5. Box plot graph of the transverse coronal (C) and sagittal (S) USPV values, according to each group.

Table 2. Descriptive statistics of mean values of axial coronal USPV (m/s) according to each group.

	Group	n	Mean	St. Dev.	Minimum	Medians	Maximum
Intact	1	10	2727.0	27.06	2688	2727.5	2783
DCP	2	10	2738.9	44.36	2669	2737	2805
DCP+ uncomp ost	3	10	2675.8	21.89	2644	2681	2703
DCP + comp ost	4	10	2747.2	41.03	2677	2759	2813

Legend: St. Dev: Standard Deviation; Ost: osteotomy; comp: compression.

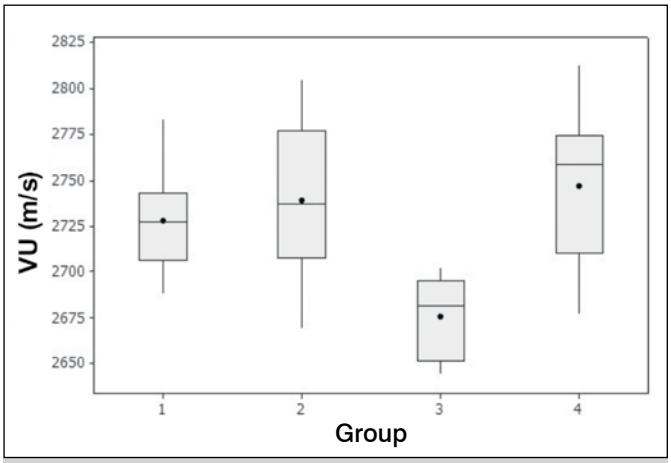

Figure 6. Box plot graph of the axial USPV values, according to each group.

(p=0.002), 2 and 3 (p=0.0003) and 3 and 4 (p<0.0001), but not between Groups 1 and 2 (p=0.4851), 1 and 4 (p=0.2238) and 2 and 4 (p=5978), meaning that the addition of a plate to the intact bone does not change the longitudinal ultrasound transmissivity. However, longitudinal ultrasound transmissivity significantly decreases with the addition of a transverse osteotomy and significantly increases after axial compression by the compression plate (Table 3).

Table 3. Statistical Comparison of mean values of axial coronal USPV (m/s) between groups.

Comparison	Mean	Difference	P	CI (95%)	
1-2	2727.9	-11	0.4851	-42.62	20.62
	2738.9				
1-3	2727.9	52.1	0.002*	20.47	83.72
	2675.8				
1-4	2727.9	-19.3	0.2238	-50.92	12.32
	2747.2				
2-3	2738.9	63.1	0.0003*	31.47	94.72
	2675.8				
2-4	2738.9	-8.3	0.5978	-39.92	23.32
	2747.2				
3-4	2675.8	-71.4	<0.0001*	-103.02	-39.77
	2747.2				

Legend: CI: confidence interval; *significant difference.

DISCUSSION

There seems to be little doubt nowadays that the internal fixation of fractures of the shaft of long bone is much more advantageous than the old-fashioned conservative treatment, since it makes possible a much earlier functional recovery and return to work. The very versatile and easy-to-use DCP plates are among the most used implants, particularly for the diaphyseal fractures of the upper limb bones.[16] However, the final outcome of the fixation largely depends on the surgeon's ability and familiarity with the surgical method and on the strict observation of the recommended intraoperative technique for plate fixation, otherwise inadequate reduction and insufficient compression may result, thus leading to a delayed union or nonunion of the fracture with serious consequences for the patient. Furthermore, the degree of axial compression decreases with time due to bone resorption at the fracture line and plate and screw accommodation, thus reaching about half the amount obtained intraoperatively within the first postoperative month.

Conventional image diagnosis resources, including radiographs, CT scans and MRI, are virtually useless to evaluate the degree of axial compression, over the first postoperative weeks. From a practical standpoint, only conventional radiographs show some details of fracture reduction and fracture line closure, the degree of axial compression being inferred from its appearance. As a complicating factor, the fracture line is only seen on one of the two conventional radiographic views usually obtained, since the metal plate entirely covers one of the surfaces of the bone, therefore obstructing one of the views; depending on the surface of implantation, the plate can obstruct both views. CT scans and MRI images are usually blurred and distorted by artifacts caused by reflection of the x-rays and magnetic energy, respectively, while the latter should ideally be avoided, due to the magnetic attraction upon the steel implant with potentially hazardous effects, particularly during the first six to eight postoperative weeks.[17]

It is here that ultrasonometry probably fits, since it is capable of demonstrating the presence and the healing status of a fracture, including anomalies,[18] represented by the osteotomy in the present investigation. Actually, the amount of new bone formed around and within the fracture line restores biomechanical properties of the bone, thus increasing strength,[19] and ultrasound transmissivity along the bone, thus causing USPV to slowly increase until it eventually reaches normal values.[20] Adequate axial compression through a simple transverse fracture reduces the fracture line to a fraction of a millimeter, which is still filled in with a film of liquid, whether in the water medium of biological tissues or in the acoustic tank. The formulated hypothesis for the present investigation was that the compressed fracture or osteotomy would behave like an intact bone and would transmit ultrasound like the latter.

Ultrasonometry comprises the measurement of both USPV and attenuation, which are fundamental properties of each individual material, including the bone.[21-23] According to our own experience,[24] USPV presents a more consistent behavior than attenuation for evaluating fracture healing and was preferred for the present investigation. In the present investigation, USPV was measured in the intact bone first, and then in the assemblies with the plate only; the transverse osteotomy was then done and USPV was measured again, first without and then with axial compression. For all groups, USPV was measured both in the transverse and axial directions and, in the former, according to the coronal and sagittal planes. The transverse sagittal USPV was always slightly lower than the transverse coronal USPV, with non-significant differences between them for most comparisons. Both slightly decreased with the plate implantation and more so with the transverse osteotomy, but increased with compression, returning to values similar to those of the intact bone, although with non-significant differences between groups.

A possible explanation for such a behavior, at least in part, would be the wave reflection in the water-plate interface, which results in almost 90% of the ultrasound energy returning towards the emitting transducer and only about 10% actually penetrating the plate. The plate-bone interface also reflects about 70% of the ultrasound waves, so that less than 5% of the emitted energy effectively hits the recipient transducer after going through the bone-plate assemblies. As a direct consequence of that, the FAS appears on the oscilloscope screen as a very small positive wave, which sometimes needs amplification to be identified. Ultrasound wave reflection is more pronounced when the plate is directly in the emission way (sagittal plane), but it also occurs when this is not the case (coronal plane). Another reason for such behavior would be that the osteotomy, with or without axial compression, does not hinder transverse ultrasound transmissivity for the simple reason that the osteotomy line is aligned with the direction of wave propagation, which is facilitated by the presence of normal bone above and below and by the water in between. Then, the transverse modality would not be the best option for the purpose of analyzing a fresh fracture submitted to axial compression with a plate, which apparently did not interfere with the transverse ultrasound transmissivity.

Axial USPV, as measured away from the steel plate (coronal plan), presented a somehow different behavior, beginning with the higher values compared to the transverse USPV. It slightly increased with the plate implantation on the intact bone, only to decrease with the osteotomy and to increase again with compression, reaching a level slightly higher than that of the intact bone. Differences were significant for most comparisons, except between the intact bone and the bone and plate assembly groups, indicating that the steel plate on its own did not significantly change axial ultrasound transmissivity, while the osteotomy and subsequent axial compression actually did. Ultrasound wave reflection was not a barrier for axial transmissivity as it was for transverse transmissivity, for at least two reasons: first, the ultrasound energy was directed to the bone away from the plate, and second, axial transmission tends to be more superficial and, therefore, quicker than transverse transmission. However, a fraction of the emitted ultrasound energy certainly hit the plate laterally, perhaps contributing to the higher axial USPV values by at least two mechanisms: first, the plate was a continuous piece of steel along the bone, without an interruption such as the osteotomy, and second, ultrasound transmissivity is much higher for steel than for the bone itself. Whatever the mechanism, the axial USPV measurement modality seems to be more appropriate than the transverse one for the purpose of evaluating the effects of axial compression by a DCP plate through a fracture or osteotomy. Taking into consideration the fact that the transverse modality would be of easier application, particularly for the deeper bones surrounded by a thick muscle layer, the higher reliability of the axial modality brings about the problem of making it clinically applicable by means of a non-invasive method,[25,26] something to be developed in future investigations.

In summary, the uncompressed transverse osteotomy behaved like a fracture by preventing a certain amount of ultrasonic energy from going transversely and axially through the bone. Ultrasound transmissivity returned to normal levels after axial compression somehow restored the bone continuity, therefore confirming the hypothesis of the investigation. Axial transmission appeared more effective for the evaluation of the axial compression degree provided by the DCP plate, but the possibility of also using the transverse transmission modality cannot be ruled out. Actually, non-invasive axial USPV measurement is not yet technically possible at present except for some superficial bones like the tibia, ulna and clavicle, while non-invasive transverse measurement seems more applicable to most of the bones, including the deeper ones like the humerus, femur and radius.

CONCLUSION

With such results, we conclude that ultrasonometry can actually help predict the degree of axial compression with a DCP plate through a bone, with a great potential for clinical application, particularly for evaluation of the evolution within the first postoperative weeks.

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