A Mechanical Vibration Method Used to Investigate the Evolution of Fractures Fixed with Biocompatible Materials

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Difficulty to objectively determine the moment of bone fracture consolidation by classical imaging methods makes necessary the development of a method that will allow establishing, by objective criteria, the moment in which biomechanical loading of the injured bone segment may be permitted. We propose a method based on the approximation between bone diaphysis and a beam, analysing its behaviour under frequency excitation at one end and measuring the vibrations at the other end. Variation of parameters measured in the structurally sound structures compared to the fractured ones, as well as the possibility to analyse their evolution in the presence of osteosynthesis materials used for the surgical treatment of fractures is ascertained. The existence of composite plastic materials of which the used anatomical bone mould for this experiment is made simulates the real pathological situation, which allows extending the determinations to clinical cases.

Key words: bone, fracture, mould, polyurethane, osteosynthesis material, composite material

It is often difficult to objectively establish the fracture diagnosis, as well as to follow up the healing process (1).

Radiographic methods are routinely used to diagnose these situations, the investigation being made by X-ray examination. The radiographic analysis is sometimes combined with the CT scan to assess the fracture healing process. These methods do not provide comprehensive information regarding the healing process stage (2). Thus there are cases in which fracture treatment did not led to the restoration of bone mechanical resistance and to consolidation, respectively, which caused an iterative fracture, although the radiological investigation showed bone union, leading to the conclusion that the fracture was healed at the time when functional load of the limb was allowed (3).

Other techniques for assessing the fracture healing process are also needed to solve this problem.

In medical practice it is also necessary to acquire information regarding the mechanical properties of the bone. Radiographic methods allow evidencing the bone structure, but do not analyse its mechanical properties, mainly those related to stiffness and breaking resistance (4). The fact is that all the investigation methods aim also to determine the mechanical properties of the bones and to follow up the fracture healing process, depending on their monitoring.

The proposed method is based on the impulse excitation (shock) because of its simplicity and low implementation costs, using a computer to process the signal and to determine signal range. This solution for the analysis of physical properties of the bone (fractured and fixed by the aid of biocompatible material) was not implemented yet in the current medical practice (5).

Assessment of mechanical properties involves passing through a cycle with the following stages:

- excitation
- electrical signal measurement with an transducer
- electrical signal processing
- analysis of electrical signal parameters
- interpretation of results

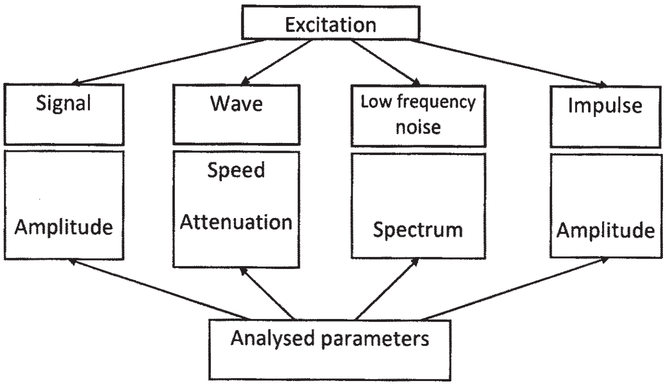

Fig. 1. Various excitation modes and corresponding parameters analysed

A scheme summarising the different options is given in figure 1.

Excitation can be achieved by sinusoidal signal, elastic wave, low frequency noise or impulse (shock) (6).

The electrical signal is measured by the means of a vibration transducer. This may be a motion (stethoscope, microphone), speed or acceleration (accelerometer) transducer.

Signal processing can be done by humans by the aid of ear (when using a stethoscope) or electronically (7,8). There are two options in the case of electronic processing, namely analogical and numerical. Computer technology development makes the numerical processing more attractive (9).

Considering the above facts, it can be noticed that the use of alternative techniques to investigate the osseous tissue is still at an early stage.

We propose an inexpensive, precise and non-invasive method to investigate the bone tissue which will allow the specialist physician to assess the healing process evolution.

The method is based on the approximation between bone diaphysis and a beam. Analysis of beam behaviour in

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frequency domain is made by excitation at one end and measuring the vibrations at the other end or somewhere on its length (10,11). Considering this procedure, the method is developed and its applicability in clinical practice is analysed. Moreover, its applicability will be extended for other types of fractures.

Experimental part

Experimental setup shown in figure 2 has been built to verify the above mentioned theoretical considerations.

A and B ring shape holders of 8 cm diameter were made of 2 mm stainless steel wire (22NiCr130). Elastic features of the holders were symbolised by springs with elastic constants α_{sA} and α_{sB}, respectively, and buffers with buffer coefficients β_A and β_B, respectively. A beam was placed on A and B elastic holders. The bar was then subject to vibrations at one end through a vibration device (VD) controlled by a generator (G). The generator provides an sinusoidal output signal of variable amplitude and frequency, so that both frequency and amplitude of vibration were adjusted by the aid of the generator. The vibration device can also be controlled by impulses or singular impulses.

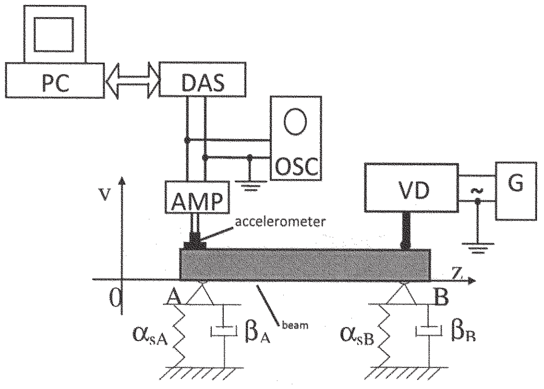


Fig. 2. Experimental installation for vibration measurement G - generator, VD – vibration device, OSC-oscilloscope,AMP - amplifier, A,B – elastic holders,DAS – data acquisition system, PC – IBM computer

The amplifier output signal is applied to the oscilloscope input and to a data acquisition system built around a digital signal processor (11).

By analysing the behaviour of the beam in figure 2 in frequency domain, it has been found that a great number of measurements are needed to evidence spectral components defining its vibration modes. Consequently, in order to increase the 10÷4000 Hz frequency range by a 10 Hz exploration step, 400 measurements are needed. If a basic frequency is not a multiple of 10, which is usual, successive measurements around that frequency are necessary, which significantly increases the number of measurements. To remove this drawback we used the impulse excitation method that allows the increase of frequency range by a single measurement. In order to get close to the ideal, a brief duration and great amplitude impulse was required. The impulse device was used in the beginning. The device was hard to handle, needing a system of positioning towards the intended point of impulse application. It was also difficult to adjust the distance between the striker and the surface of the object subject to excitation so that the acquired impulse to fulfil the above conditions and to ensure measurements reproducibility.

Considering the above, we have decided to achieve excitation by the means of a metallic body gravitationally driven by a constant length tube. We have chosen for this a 12 mm diameter sphere, weighing 15 g. The guiding tube was built, measuring 15 mm in diameter and 300 mm in length. A kinetic energy of the ball at strike point of 50 mJ was obtained under these conditions, which is perfectly tolerable in view of *in vivo* use.

The data acquisition system (DAS) allows for the measurement of samples from the signal acquired at the amplifier (AMP) output. The system performs the acquisition function by computer command (11-13). After the command has been launched, the acquisition is done in real time, independent of computer, thus allowing great acquisition speed. Moreover, the process will not be interrupted by the potential interrupt routines or other tasks ran by the computer. The samples will be memorised in the DAS internal memory. Once the acquisition is finished, sample values will be transferred into computer memory for processing and result display.

Three programmes were used to acquire and process the signal from the vibration transducer:

-achiz.tms – programme written in assembly language for the signal processor that ensures signal acquisition,

-acqp.c - – programme written in C, which commands DAS, ensuring its initialisation and download of samples taken from the useful signal;

-spec_med.m - – programme written in Matlab that processes the acquired data, allowing the display of time variation of the acquired signal and the display of its spectrum.

The programme spec_med.m calls the acqp.c programme. In order to make it possible, the acqp.c programme is made interpretable by Matlab. This is done by compiling the programme in C and then by creating a.mex format interpretable by Matlab programme. As a result of running the needed stages, the acqp.mex programme is obtained.

The acqp.c programme carries out the communication between host computer and DAS, using as input/output circuit a communication registry inside the data acquisition system. By the means of this registry, the achiz.tms programme is loaded in the DAS programme memory and the samples obtained from the useful signal are acquired.

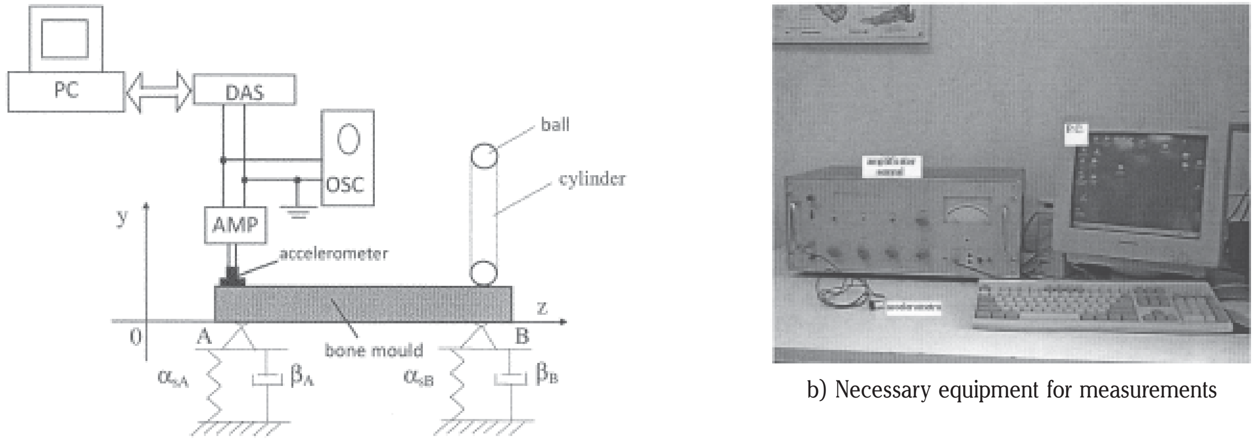
Sample acquisition is performed in the subroutine treating the interrupts generated by a counter circuit located in DAS.

Results and discussions

Based on the experience gained during previous measurements, we proceeded to verify the method on bone moulds, which are made in strict compliance with the anatomical shape. They are also similar to the structural aspect of the bone tissue, being made of a mixture of short glass fibres on the outside and an epoxy resin that stimulates cortical bone tissue. This mixture is injected around a rigid polyurethane core, which reproduces the spongy structure of the bone and delimits, in the case of diaphyseal bones, an intramedullary channel (14). This composition leads to a 1.64 g/cc density structure, exhibiting also mechanic features similar to the corresponding bones, 106 Mpa resistance to longitudinal tension, 157 Mpa to compression and 93 to Mpa transverse tension.

The design of the experimental device is shown in figure 3a, and the PC, the signal amplifier and the accelerometer used for measurements are shown in figure 3b.

The accelerometer is firmly attached to the bone mould surface at one end so that to absorb its vibrations (15). The output signal was amplified by 19.2 dB and then applied to DAS input. A 16 kHz sampling speed and a total number of 5,000 samples acquired in a measuring cycle were chosen



b) Necessary equipment for measurements

a) Experimental setup diagram

Fig. 3 Experimental design to measure the vibrations on the bone mould OSC-oscilloscope, AMP - amplifier, A,B - elastic holders, DAS – data acquisition system, PC – IBM computer

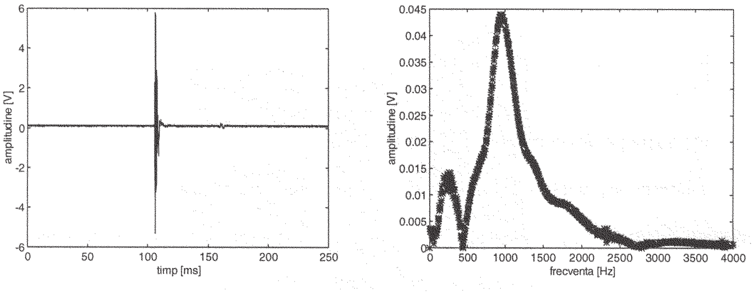


Fig. 4. Time variation of the accelerometer output signal and its range when placing the unfractured bone mould inside of a polyurethane layer

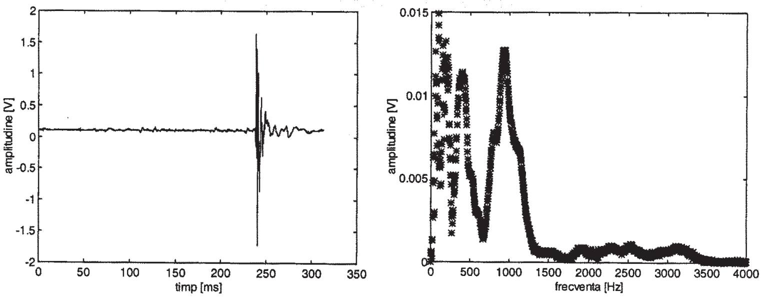


Fig. 5. Time variation of the accelerometer output signal and its spectrum when placing the fractured bone mould inside of a polyurethane layer

in the acquisition programme. The recording time of a measuring cycle is 312.5 ms.

In order to be close to the natural conditions (in the body the bone is surrounded by muscles, cellular subcutaneous tissue and skin, which are vibration attenuating structures) we have stimulated their presence by placing the bone mould inside an elastic polyurethane layer (13,16,17). The results obtained following vibration recording are shown in figure 4 and 5.

We proceeded with a series of measurements on the fractured bone mould and then fixed with different osteosynthesis materials. We tested bone mould in frequency response in two situations: when using an intramedullary rod to assemble the two segments and when using screws and plate (18,19).

The obtained results are shown in figure 6.

Figure 6 shows time variation and spectrum of the accelerometer output signal when using an intramedullary rod. It can be noticed that the 196 Hz main frequency is evidenced in spectrum, having greater amplitude than in the previously presented cases. Similarly, the period of attenuated free oscillations of the bone-rod assembly has been determined, obtaining a value of 5.1 ms corresponding to 196.07 Hz frequency.

It can also be identified the second, the sixth, the eighth, the ninth and the eleventh harmonic corresponding to basic frequency. Other spectral components (such as 714 Hz, 842 Hz, 1028 Hz, 1285 Hz and 1471 Hz) are present in spectrum, which are different from those evidenced in figure 4 and 5. These are characteristic components of the bone-intramedullary rod system.

Figure 7 shows the case in which plate and screws are used to restore the bone mould continuity. The spectrum has a main frequency of 196 Hz, as well as the following harmonics: second, third, sixth, ninth and twelfth. We notice the emergence of a small number of spectral components (815 Hz and 1640 Hz components), which is explained by the increase of bone-plate assembly rigidity.

By analysing the spectra obtained in the case of fractured bone mould under following circumstances: fragments in contact, fragments fixed with a rod and a plate with screws, respectively, we can see that the bone mould own frequency does not differ from case to case, being thus possible to monitor the healing process evolution when the osteosynthesis material is present. By analysing the frequencies of higher values than the basic frequency, we can observe the presence of its harmonics, as well as other frequencies, more numerous in the case of intramedullary rod. The harmonics existence is due to the nonlinear nature of the analysed system. As the three tested systems are different, some different harmonics will be obtained. Likewise, the presence of other spectral components depends on the studied case, with the remark that their number is smaller when using the plate with screws. If we take into account the determinations made in the presence of the polyurethane layer of the bone mould, we can conclude that the 1250 Hz higher frequencies will be attenuated and so the differences between spectral determinations will decrease, leading to the conclusion

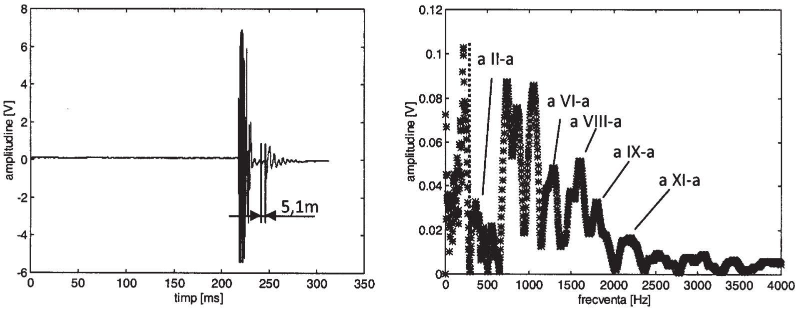


Fig. 6. Time variation and spectrum of the accelerometer output signal for the bone segments coupled with an intramedullary rod

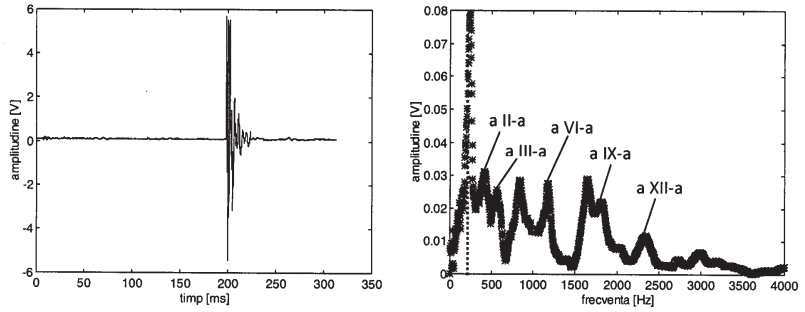


Fig. 7.Time variation and spectrum of the accelerometer output signal for the bone segments coupled with plate and screws

that the way of surgical restoring of the bone continuity does not alter the monitoring of fracture site evolution by the means of vibrations.

Conclusions

The experimental device built and endowed with an excitation device for the fractured and fixed bone system, as well as with a system for measuring and processing the signal from the vibration transducer significantly shortens the length of measuring process and allows evidencing the whole frequency spectrum characteristic to the analysed element.

Analysis of experimental determinations led to the identification of impulse excitation solution.

It has been shown that the cheapest and repeatable solution is the use of a steel sphere that, through free fall guided by a cylinder, performs the percussion of the elected area with the same energy due to the constant height of the cylinder.

Determinations performed on the bone structure restored by the means of osteosynthesis materials (intramedullary rod and plate and screws), have shown that their presence does not modify basic frequency value, experimentally evidencing the possibility to use this method in the case of surgically treated fractures as well. Comparison of the two osteosynthesis techniques shows that in the case of plate and screws both the harmonics and the additional frequencies number is lower than in the case of intramedullary rod, because a more rigid system is ensured.

The use of anatomical bone moulds, due to the composite structure of the plastic materials used, provides the preliminary conditions needed for procedure validations in view of „in vivo" determniations.

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