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Acoustic emission diagnosis for human joint cartilage diseases

KRZYSZTOF WIERZCHOLSKI*

Koszalin University of Technology, Institute of Technology and Education, Koszalin, Poland.

Purpose: The topic of the presented paper concerns the diagnosis of the wear and diseases of human joint cartilage performed by the acoustic waves emission. The aim of this paper is the determining of the necessary parameters for the diagnosis about the wear and diseases of human joint cartilage. Material And Method: To the research methods used in this paper belong the evaluation of measurement results of the cartilage surface samples obtained by means of laser and mechanical sensor and acoustic emission wave might or voltage gained from the AE apparatus during the treatments performed for normal and pathological used and not used human knee and hip joints. Results: The results concern with the corollaries which are implied from reading values gained by virtue of the acoustic emission Apparatus, and from observations from cartilage surface pictures obtained from laser and mechanical sensors. The diagnose of concrete cartilage illness depends on the proper relative values of obtained strongest of generated AE wave as well as the shapes and amplitudes of acoustic waves and wave frequencies. Conclusions: The main conclusions obtained in this paper are as follows: connections between synovial fluid dynamic viscosity or friction forces and intensity of acoustic emission values, the determination of the type of lesions and deformations of the human joint cartilage surface by means of the shapes architecture of the acoustic emission waves. Moreover are indicated the necessary conditions for the diagnosis of the such dieses as: pathological cartilage with arthritic or osteoporosis or rheumatology changes.

Key words: *Acoustic Emission Diagnosis, AE devices, viscosity and cartilage surface identification*

1. Introduction

The acoustic emission diagnosis is a new treatment by means of the acoustic waves administration. The diagnose of cartilage surface identifies the destruction of cartilage degeneration. Such diagnosis enables treatment of osteoporosis, rheumatologic joint inflammation arthritis and other diseases of cartilage in human joints. The treatment with acoustic waves provides the topography and ultrasonic diagnosis of cartilage surface occurring in human joint.

For example, using the acoustic wave device of a new generation we cannot only identify the disease process by means of the waves emission but also we can indicate the way of remodeling the human joint cartilage [4], [13]–[15]. For acoustic emission treatment we can establish and explain the processes of preventing the loss of dynamic viscosity of synovial fluid during the lubrication of cartilage surfaces throughout the disease duration [7], [9]–[11].

The Acoustic Emission (AE) denotes the formation and propagation of elastic waves usually generated in the substance as a result of the liberation of intermolecular bond energy in the cartilage body considered caused by [3], [6], [12], [16]:

(a) The plastic deformations of tissue and sliding processes,
(b) The vehement transformations of volumetric and non dilatation strain in friction regions occurring on the human joint surfaces,
(c) The decreases and increases of cartilage cells during the various diseases symptoms occurring in joints of human limbs,
(d) The friction processes occurring between the cartilage joint surfaces during the motion.

The above-mentioned phenomena and causes are occurring at macro, micro or even at nano-level.

* Corresponding author: Krzysztof Wierzcholski, Koszalin University of Technology, Institute of Technology and Education, ul. Śniadeckich 2, 75-453 Koszalin, Poland. Tel: +48 94 3478344, fax: +48 94 3426753, e-mail: krzysztof.wierzcholski@wp.pl

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Applying the acoustic emission we cannot only recognize diseases of joint cartilage but also we can diagnose the progress of such diseases as osteoporosis or rheumatoid inflammation of joint cartilage.

2. Material and methods

In the research performed, the following materials are used: patients with normal and pathological hip and knee joints, the used and not used samples from for normal and pathological human knee and hip cartilage surfaces.

The research methods used in this paper comprise the evaluation of measurement results of the cartilage surface samples obtained by means of laser and mechanical sensor and acoustic emission wave might be acquired from the AE apparatus during the treatments performed for normal and pathological human knee and hip joints. The research methods and evaluation of measurement results are performed using the following devices: Rank Taylor Hobson-Talyscan 150 Apparatus, laser and mechanical sensors, AE BoneDias Apparatus, acoustic sensor, preamplifier, signal conditioner, upper and lower filter, data conditioner.

On the grounds of the knowledge gained from the European Grant MTKD–CT-2004-51-7226 directed by the author, cooperative partner B. Ziegler from the Technical High-School Mittelhessen in Germany constructs various devices for acoustic wave generation, among others, BoneDias Apparatus for the diagnosis of the joint cartilage disease by means of the acoustic emission [6], [12], [15]. This apparatus is illustrated in Fig. 1. The sequence of the path of measurement devices in typical AE Apparatus is presented in Fig. 2.

Now, we show the material and methods of treatment process performed by measurements using acoustic emission waves. The method process for AE-treatment of knee joint cartilage and applicator localization are shown in Fig. 3a, b.

A simple acoustic measuring system is presented in Fig. 4. The AE transducer mounted generates an electrical signal corresponding to the incoming mechanical wave. It is very important to couple the AE transducer on the specimen to permit transmission of ultrasonic energy between them.

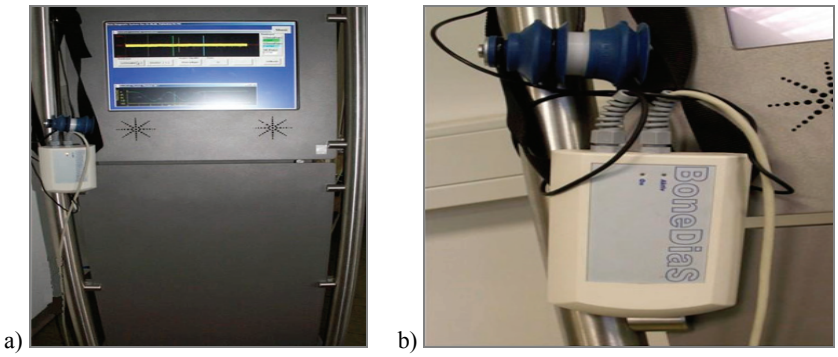


Fig. 1. Apparatus BoneDias for acoustic waves emission with respect to the orthopedic diagnostics and ill cartilage treatments: (a) general view, (b) sensor, filter and amplifier AE

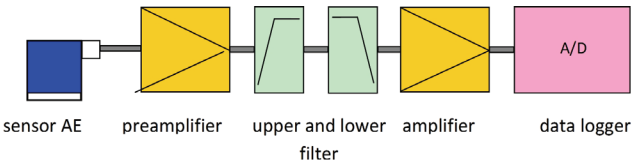


Fig. 2. Path of measurement devices in typical AE apparatus

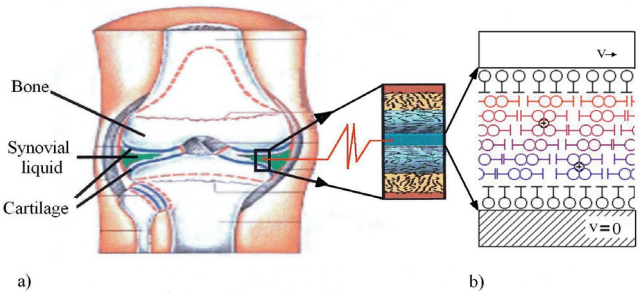


Fig. 3. Acoustic emission measurements: (a) application of an acoustic emission sensor at a human knee joint, (b) molecular substantiation. The ⊕ symbols mark the places in which an elementary acoustic wave provokes the bumping of two molecules and generates the friction effect connected with the dynamic viscosity increments

Using the apparatus for acoustic wave propagation we can present the AE wave spectrum with lower and

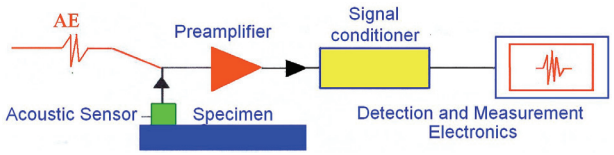


Fig. 4. Scheme of an acoustic emission measuring system

upper peaks in Fig. 5a, b. Such a spectrum of waves corresponds with the sound and pathological damaged knee cartilage deformation in grades versus time in seconds after 4 and 3 crouches, respectively. Figure 6 presents typical AE signals in voltage versus time in seconds after AE measurements [4], [7], [9], [11], [12].

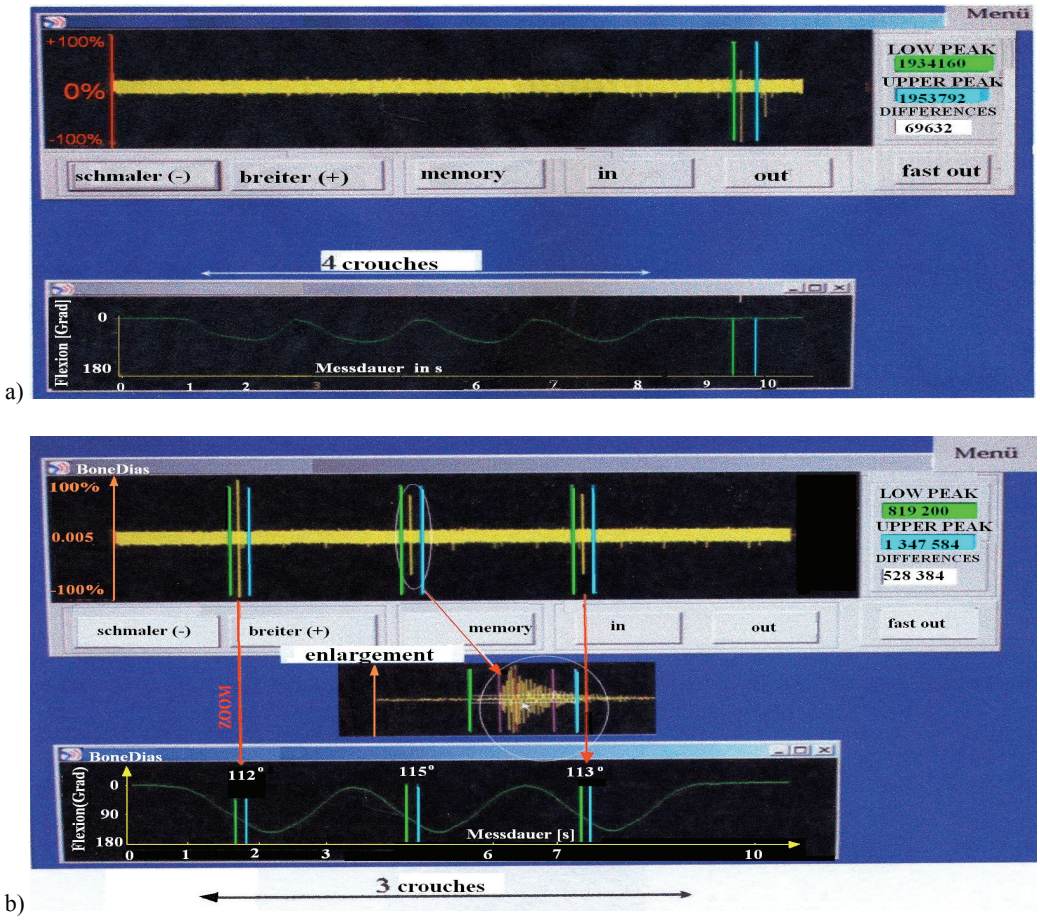


Fig. 5. Acoustic emission diagnosis from BoneDias apparatus:
(a) for cartilage deformation of human normal knee flexion (in grades) versus time (in seconds) after 4 crouches, (b) for cartilage deformation of human pathological knee (in grades) versus time (seconds) after 3 crouches

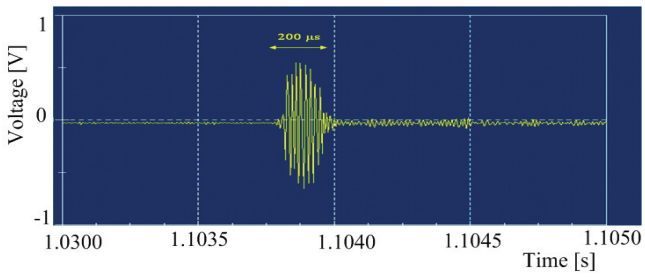


Fig. 6. Acoustic emission signals in cartilage versus time caused by cartilage deformation of a healthy knee joint after a sudden change from a two-leg stand-up position to a one-leg stand-up position [16]

3. Results

By virtue of the above-mentioned material and methods of measurements presented in Section 2 we can show some of the obtained results. First, we show the geometrical shape architecture of performed acoustic signals, frequencies and amplitudes applied for real cartilage diseases in about 20 patients. It is easy to see that AE signal describes the following data and parameters: • number of irregularities of cartilage surfaces, • signal duration (interval between the first

and the last time between threshold exceeding regular line of cartilage surface), • signal peak amplitude (maximum absolute amplitude within the duration of the signal), • signal rise-time (time interval between the first threshold crossing and the maximum peak amplitude of the burst signal), • signal energy (square of signal amplitude).

The acoustic emission signal generated by a known cartilage lesion is shown in Fig. 7 and presents the cartilage lesions and deformation for osteoporosis disease.

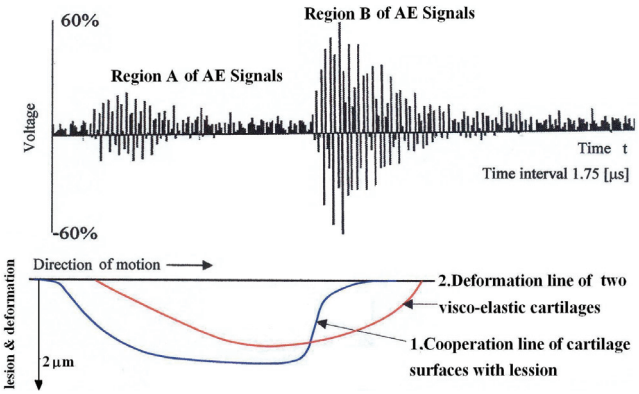


Fig. 7. Acoustic emission signal of a known cartilage lesion: the 1st curve shows the sloping edge of the lesion in region A and its steep edge in region B, the 2nd curve shows small deformations (region A) and large visco-elastic the deformations (region B)

The signal can be split into two regions. Region A of small amplitudes about 2 μm (25%) was caused by sliding two cartilage surfaces onto the slightly sloping edge of the lesion (1st curve) and on the edge with small visco-elastic deformations (2nd curve). Much greater amplitudes 7 μm (60%) of signals appear in region B, caused by sliding out of the lesion from its steep edge (1st curve), and when the lesion has the large visco-elastic deformations (2nd curve). These effects are connected with acoustic emission signals of high rise values, representing both the sequence of motion and the deformation process of the cartilage. The above-mentioned results are not in contradistinction to the results obtained in papers [1], [2], [9], [11], [12].

The acoustic emission activity process caused by large and a few arthritic defects is presented in Fig. 8 and Fig. 9, respectively. In Fig. 8, the first C and second D regions show signals during the entry into the lesion and exit from the lesion on the side of its steep edge in both cases (curve 1). The edge of the lesion for large visco-elastic deformation are shown in curve 2. In this case, we have relatively large amplitudes about 9 μm (64%).

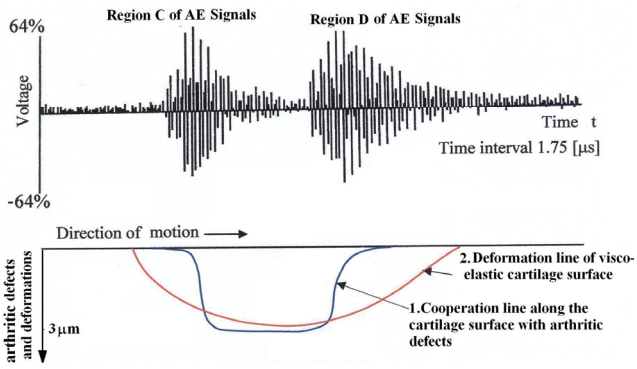


Fig. 8. Acoustic emission signal of an arthritic defect with steep edge at the entry into the lesion and the steep edge at the exit from the lesion, see curve 1, and with accompanying large viscoelastic deformations at the entry and in exit from the lesion, see curve 2

In Fig. 9, the first E region shows no signal because the cartilage has no lesion (curve 1). The entry into the second region F generates large signals with amplitudes 3–4 μm (39%) because we have the steep edge of the lesion, whereas the exit from the second region F occurs on the side of the slightly sloping edge (curve 1). Curve 2 shows the large visco-elastic deformations on the side of the entry into the lesion and the exit from the lesion of cartilage as well [9], [12], [15].

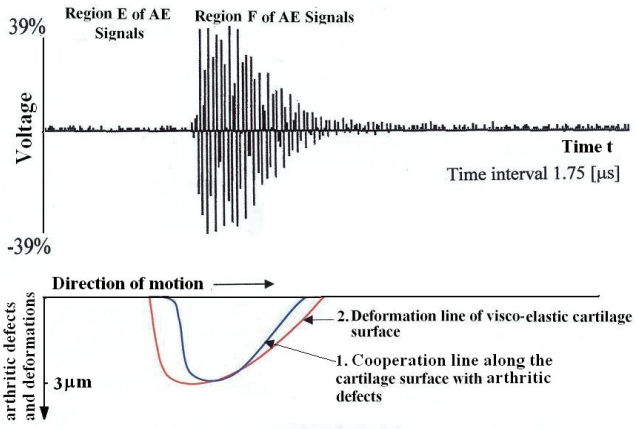
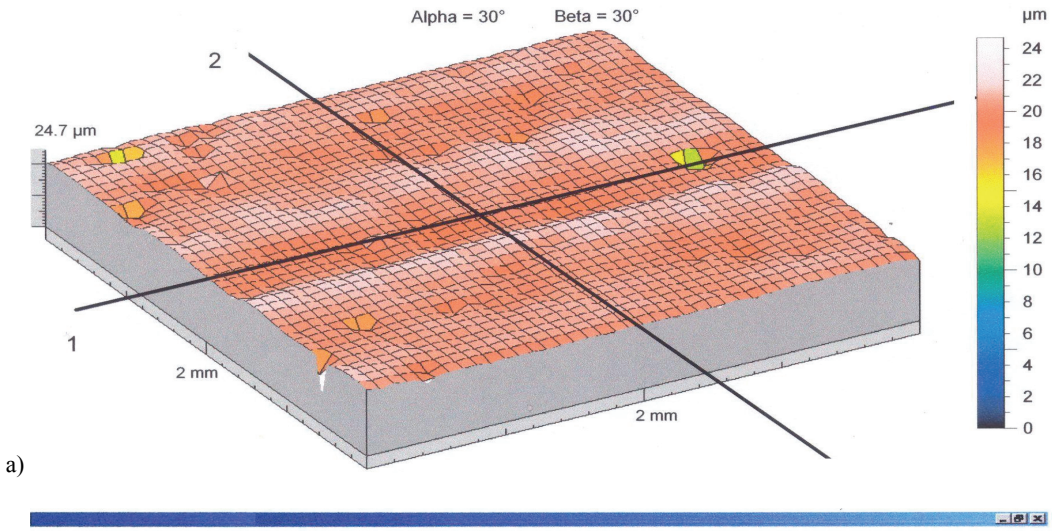
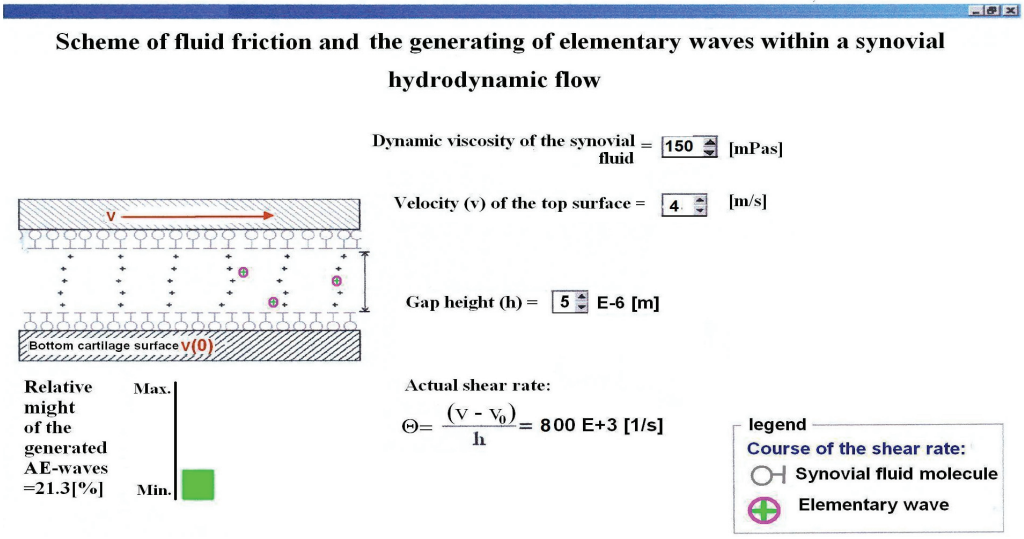


Fig. 9. Acoustic emission signal of a defect at knee joint: curve 1 for the second region F only, with steep edge at the entry into the lesion and the sloping edge at the exit from the lesion; curve 2 shows the large visco-elastic deformations at the entry into the lesion and at the exit from the lesion

Now, we show the results obtained from the measurements performed. In AE Algorithm Apparatus, there are set up the devices which allow us to read the might of AE intensity waves and synovial fluid viscosity on the grounds of the acoustic and hydrodynamic laws. The measurements of the samples of hip joint surfaces presented in Fig. 10a, 11a, 12a are performed by means of a mechanical or laser sensor,



a)



b)

Fig. 10. The measurements of the might of the AE-waves for the normal joint cartilage with very small used surface: (a) surface map of hip joint cartilage measured with the mechanical sensor, (b) reading of the relative might of the AE waves 21.2 % with synovial fluid dynamic viscosity 150 mPa from record-keeper installed in AE Algorithm Apparatus, for the shear rate of the synovial fluid flow equal 800 000 Hz, i.e., for joint gap height about 5 micrometers and for the circumferential velocity 4 m/s of the cartilage surface lying on the bone head and motionless cartilage surface on the acetabulum

where normal (non-used) and pathological (used) cartilage samples are taken into account. During the measurements performed by means of the mechanical sensor the samples of cartilages having dimensions 2 mm × 2 mm are used, and for the measurements by using laser sensor the samples having dimensions of about 10 mm × 10 mm are applied.

The measurements of the bone-head surfaces have been performed by using the micro sensor laser installed in the Rank Taylor Hobson-Talyscan 150 Apparatus. The experimentally obtained data have been elaborated by means of the TALYMAP Expert and Microsoft Excel Computer Program. From 29 measured samples the following parameters have been calculated: **St**, **Sz**, **Sa** of surface roughness expressed in micrometers.

We calculate, for example: **St** – differences between values of rises and deeps of bone head surfaces in human hip joint, **Sz** – arithmetic mean between values of 5 rises and 5 deeps of bone head surface, **Sa** – standard deviation of probability density function of roughness distribution of cartilage surface.

The readings presented in Fig. 10b, Fig. 11b and Fig. 12b illustrate the data performed in the AE Algorithm Apparatus referring to the control simulation results of the intensity increases of the acoustic emission waves. Such remarks are more general in comparison with results presented in papers [9], [11], [13]–[15].

Now, we show and describe the main results which are implied from the comparison of the obtained pictures and readings.

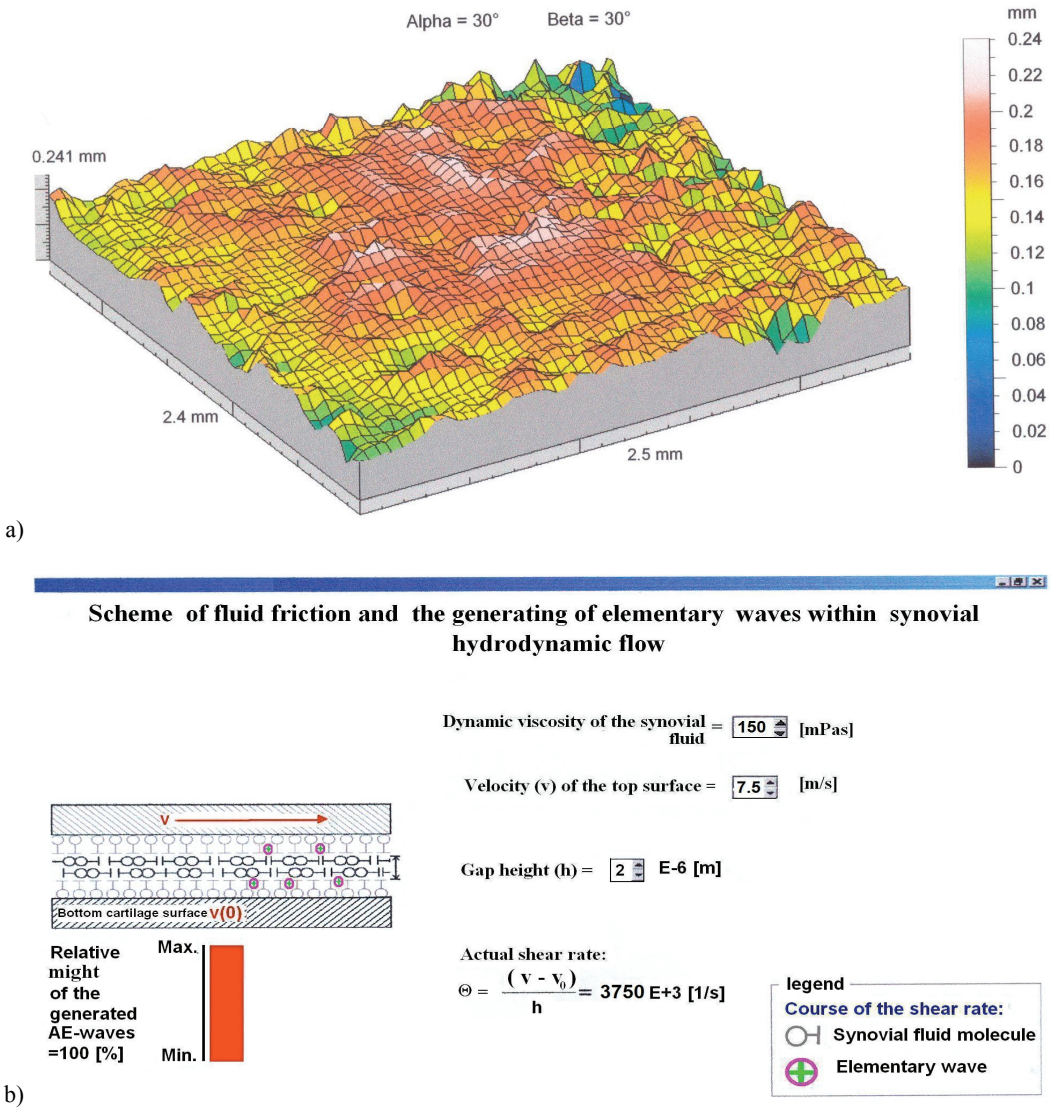


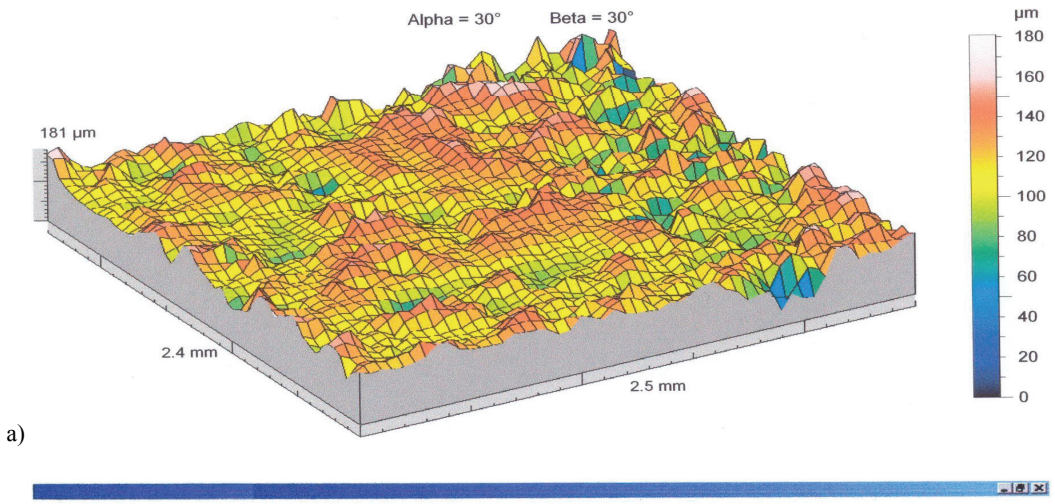
Fig. 11. The measurements of the might of the AE-waves for the pathological joint cartilage with very large defected cartilage: (a) the map of surface hip joint cartilage measured with the mechanical sensor, (b) reading of the relative might of the AE waves 100 % with synovial fluid dynamic viscosity 150 mPa from record-keeper installed in AE Algorithm Apparatus, for the shear rate of the synovial fluid flow equal 3750 000 Hz, i.e., joint gap height about 2 micrometers and for the circumferential velocity 7.5 m/s of the cartilage surface lying on the bone head and motionless cartilage surface on the acetabulum

• At first, we compare calculation results illustrated in Fig. 10a,b and Fig. 11a,b. The computer calculations presented in Fig. 10b show dynamic viscosity 150 mPa, theoretical assumed shear rate of the synovial fluid flow equal 800 000 Hz and 21.3% intensity of AE waves.

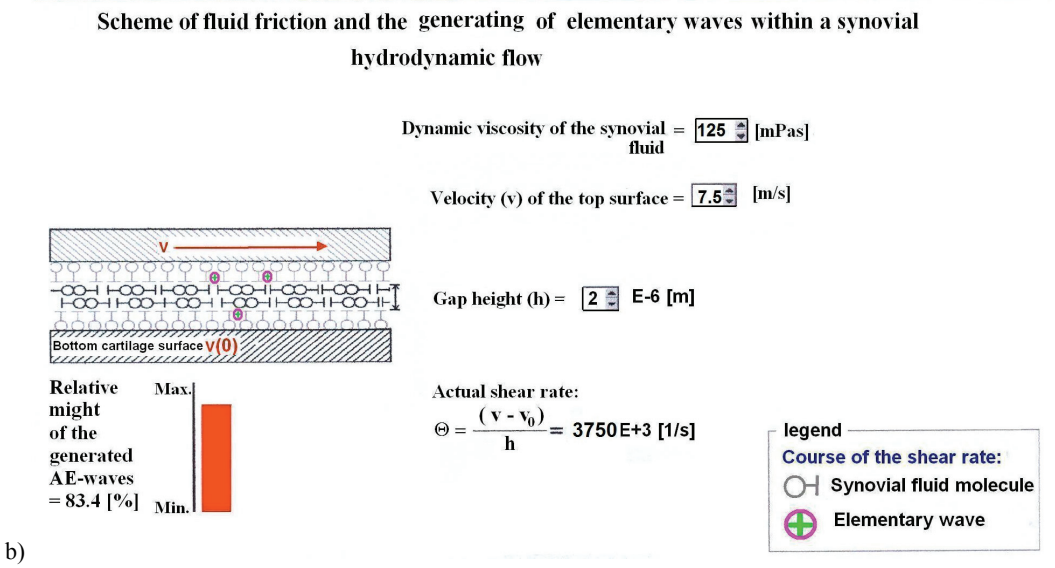
The calculations presented in Fig. 11b show dynamic viscosity 150 mPa, theoretical assumed shear rate of the synovial fluid flow equal 3750 000 Hz and 100% intensity of AE waves.

The above-mentioned data imply the following conclusion. It is well known that the increments of shear rate of the synovial fluid flow decrease the dynamic viscosity. Such decrements are compensated by the increments of intensity of AE waves from 21 to 100 percent. Therefore, in both calculations in Fig. 10b and Fig. 11b we have the same value of dynamic viscosity, i.e., 150 mPas.

• Now, we compare calculation results illustrated in Fig. 11a,b and Fig. 12a,b. The calculations presented in Fig. 11b are already described, i.e., dynamic viscosity 150 mPa, shear rate 3750 000 Hz and 100% intensity of AE waves. The calculations presented in Fig. 12b show dynamic viscosity 125 mPa, theoretical assumed shear rate of the synovial fluid flow equal 3750 000 Hz and 83.4% intensity of AE waves. The recorder registrations presented in Fig. 11b and Fig. 12b, are obtained for the same synovial fluid shear rates 3750 000 Hz with the same joint gap height 2 micrometers and the same theoretical



a)



b)

Fig. 12. The measurements of the might of the AE-waves for the pathological joint cartilage with average large used cartilage: (a) the map of surface hip joint cartilage measured with the mechanical sensor, (b) reading of the relative might of the AE waves 83.4 % with synovial fluid dynamic viscosity 125 mPa from record-keeper installed in AE Algorithm Apparatus, for the shear rate of the synovial fluid flow equal 3750 000 Hz, i.e., joint gap height about 2 micrometers and for the circumferential velocity 7.5 m/s of the cartilage surface lying on the bone head and motionless cartilage surface on the acetabulum

assumed linear velocity 7.5 m/s of the upper cartilage surface. However, in the second registration in Fig. 12b, the acoustic intensity emission decreases to 83.4% in comparison with the intensity 100% existing in previous registration in Fig. 11b. Thus the dynamic viscosity of synovial fluid attains decreases from 150 mPas (see Fig. 11b) to 125 mPas recorded in Fig. 12b. Hence, this implies the thesis that the intensity increases of the acoustic emission correspond with the increases of the friction forces, i.e., synovial fluid dynamic viscosity. This fact completes our thesis.

• The results obtained on the grounds of the above-mentioned research are presented in Table 1.

4. Discussion

The discussion presented contains the justifications of the obtained results in Section 3 on the basis of the molecular structure of the cartilage and protein micro- and nano-particles. Taking into account the dynamic and acoustic phenomena we show the reasons of the statement that the increases of the dynamic viscosity and friction forces of synovial fluid are equivalent with the might increases of the acoustic emission treatments. In the first place we explain the phenomenon of viscosity changes process by virtue of the logical deduction. The phenomenon of the viscos-

Table 1. The matrix of necessary conditions for AE diagnosis problem

Number of patients	Number of samples and the human joint	The average might of AE waves	The average frequency of the AE waves	The average amplitude of the AE waves	Anticipated diagnosis with the necessary data about human joint cartilage surface
10	10 knee or hip	5%	4 kHz	0.5 μm	Normal non-defective cartilage surface
29	29 hip	21%	20 kHz	2 μm	Normal cartilage with the small used places on the surface
10	10 knee and hip	39%	40 kHz	3–4 μm	Pathological cartilage with a few arthritis defects on the external surface
10	10 knee	25–60%	79 kHz	2–7 μm	Pathological cartilage with osteoporosis defects
10	10 knee	64%	80 kHz	9 μm	Pathological cartilage with a large arthritis defects on the external and internal surface layer
29	29 hip	83%	100 kHz	9 μm	Pathological cartilage with average large defects caused by the rheumatologic inflammation
29	29 hip or knee	100%	150 kHz 100%	10 μm	Pathological cartilage with very large defects caused by the rheumatologic inflammation or arthritis defects on the external and internal surface layer

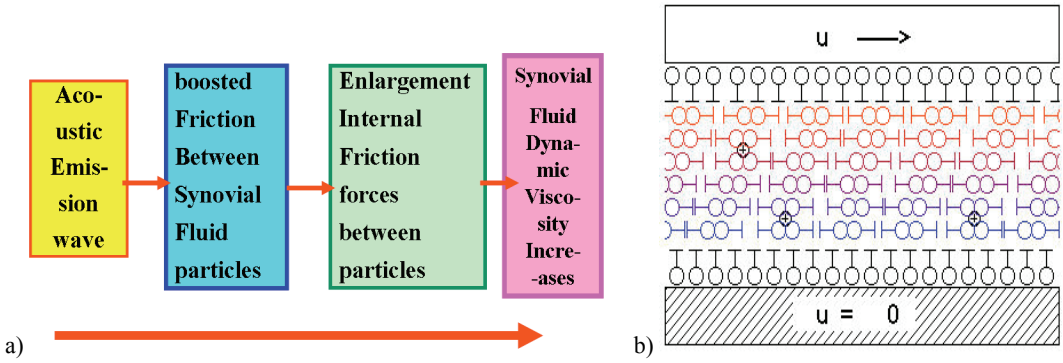


Fig. 13. The reciprocal process with regard to AE diagnosis as the AW therapy phenomenon of dynamic viscosity increases in synovial fluid caused by intensity of acoustic waves increases: (a) logical implications, (b) molecular substantiation

ity increases denotes the increments of internal sum of friction forces between fluid particles which are provoked by the boosted friction effects of mutual fluid particle contacts. The bumps effected by the mutual particle contacts lead to the increases of the intensity of the acoustic emission. Such a process denotes the diagnosis by virtue of acoustic emission, because efficiency of the cartilage depends on the viscosity of synovial fluid and viscosity corresponds with the intensity of acoustic emission [5], [8], [13], [14].

After authors proposal we could consider the reciprocal process, i.e., make an attempt to apply acoustic waves (AW) as therapy. In this case, we must produce the independent acoustic wave source and then we ought to administer an acoustic wave into pathological cartilage. Figure 13 shows the steps of increments process of synovial fluid dynamic viscosity after hypothetical acoustic wave therapy treatment.

Now, using the micro-level and nano-level observations obtained from Atomic Force measurements, we show the reasons of the intensity increases of the acoustic emission waves after increments of the dynamic viscosity of synovial fluid. Acoustic emission identifies the moving of the synovial fluid nano-particles and increments of the mutual contacts with the cartilage nano-particles in the gap joint. Hence, we obtain the increases of nano-friction forces. Such effect denotes the dynamic viscosity increases of synovial fluid.

Figure 14 illustrates the effects of changes of the acoustic wave energy caused by the movement of protein, fluid and cartilage particles. Figure 14 shows the rolling and sliding process between moving cartilage and protein particles in the regions of the fluid and elasto-hydro-dynamic friction. Analogously, the above-mentioned comments show that the nano-friction forces increments, lead to the dynamic vis-

cosity increments during the lubrication occurring in human joints [13].

Moreover we can deduce that acoustic emission (AE or AW), identifies friction forces, wettability, interfacial energy and hydrated phospholipids on the cartilage surface during the lamellar-repulsive lubrication [8].

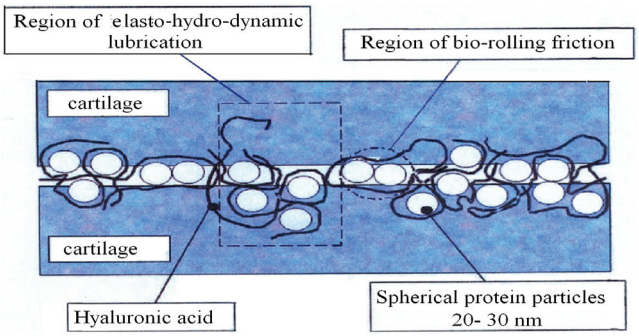


Fig. 14. The acoustic emission waves caused by the nano-level friction between the synovial fluid particles; (a) rolling and sliding effects between moving fluid and cartilage particles presented in nano-level illustration, (b) sliding and rolling effects simulated by the nano-sliding bearing and nano rolling bearing

5. Conclusions

- The determination of necessary conditions for the diagnosis indication of the such dieses as: normal cartilage with a few secular or physiological changes, pathological cartilage with a few arthritic or osteoporosis or rheumatology changes, pathological cartilage with large degenerative changes.
- The intensity of acoustic emission waves is closely connected with the friction forces occurring in human joint gap and with dynamic viscosity of synovial fluid during the treatment of human joint.
- The logger of acoustic waves installed in AE apparatus and pictures of cartilage surfaces obtained from sensors enable us to make a diagnosis of human joint cartilage efficiency corresponding with the value of might of AE intensity waves or amplitudes of AE waves and additionally a diagnosis as to the kind of diseases connected with the cartilage degeneration.
- In this paper, necessary conditions for the human joint cartilage determination are formulated. These include: acoustic intensity value in exactly determined interval, acoustic waves with concrete frequencies and amplitudes, and compliance with the treatment time for acoustic wave administration.
- Acoustic emission diagnosis by virtue of the intensity of AE waves identifies the type of lesions and deformations of joint cartilage surface.
- The advantages of acoustic emission diagnosis compared with those of the established conventional methods (i.e., X ray), are: no pain is caused by the acoustic emission procedure, acoustic emission is non destructive.

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