16

Phonoarthrography: A New Technique for Recording Joint Sounds

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1. Introduction

In Medicine there are a lot of sounds emerging from the human body. Many of them are used either for diagnosing the condition such as heart murmurs or following up cases of ileus by hearing nascent intestinal borboregmi or even hearing bruits traversing the skull in cases with brain angiomatous malformation and many more. There is one sound of interest to both rheumatologists and orthopedic surgeons which is the one heard and felt when osteoarthritic knees are moved. As knee sounds were regarded as an accompaniment to OA, the idea of recording knee sounds seemed interesting and plausible to many investigators.

The historical background was handsomely written before (Mollan et al, 1982). An early report dates back to 1882, when Heuter reported the first study involving the evaluation of sounds from the locomotory system, as he described hearing and localizing loose bodies within the knee, using a stethoscope. Blodgett reported in 1902 his experiences on auscultation of the knee using a stethoscope fitted with a rubber diaphragm to prevent slipping and skin friction noises. He could classify different joint sounds, graphically linking each to joint position .In 1906, Ludloff claimed a possible diagnosis on spinal arthritis on auscultatory basis .Bircher in 1913 investigated meniscal lesions of the knee and concluded that each type of injury had a specific sound emission .Walters in 1929, reported the auscultation of 1600 joints and suggested that these sounds might be a sign of early arthritis and promoted the use of joint auscultation in early phases of arthritis . Later, microphones have been used to reduce subjectivity; that step was taken by Erb (1933), when he used a contact microphone obtaining the clearest sound, with the exception of cases of meniscal tears, when he placed the sensor over the patella.

Most of the joints recorded were the knees (M H Bassiouni & El-Feki, 1986;M H Bassiouni et al., 1995; Krishnan et al., 2000; Nagata, 1988) and temporomandibular joints (Ciancaglini et al., 1987; Guler et al., 2003). The first reason, they are superficial thus perfect for auscultation and recording and the second reason is that they produce sounds when diseased.

In 1986, a detailed report was published on phonoarthrography, performed using a special sensor, amplifier, special recorder tape, and a memory oscilloscope (M H Bassiouni & El-Feki, 1986). This device, however, had many disadvantages, such as tape noise imposed on the knee signal; the limited memory storage of the oscilloscope, which did not allow storage of the full motion of the knee; and finally, the incapacity of auto-analysis of the obtained signals.

In 1995 a full report was published on a computerized program used to record knee sounds with a sensor; the results were reproducible and were expressed as average amplitude (units/recording) or frequency/second (M H Bassiouni et al., 1995). The average amplitude was calculated per 2 seconds of recording, while the frequency was measured per 1 second.

When sound engineers deal with this specific area of research, they prefer to name it, externally detected vibroarthrographic signals (VAG) .They concentrate basically on the study of sound definitions rather on the medical point of view. In a paper of that kind, the authors concluded that VAG could provide quantitative indices for non-invasive diagnosis of knee osteoarthritis. They also proposed the use of statistical parameters of VAG signals including the form factor involving the variance of the signal and its derivatives, skewness, kurtosis and entropy to classify the VAG signals into normal or abnormal (Krishnan et al.,2000). Unfortunately, this may not serve rheumatologists as it is not clearly related to the pathophysiology of the disease, or to other investigative tools and treatment impacts.

2. Nomenclature

All sounds are vibrations, but not all vibrations are sounds, that is why the nomenclatures given to the technique included the word vibration such as joint vibrational analysis (JVA) and vibroarthrographic signals (VAG) (Krishnan et al.,2000). Phonoarthrography is the most widely accepted term to describe the medical process as it refers to sounds (phono), originating from joints (arthro) and appearing on a graph.

3. Briefing on sounds

3.1 Definition

Sound is a mechanical wave that is an oscillation of pressure transmitted through a solid, liquid, or gas, composed of frequencies within the range of hearing and of a level sufficiently strong to be heard, or the sensation stimulated in organs of hearing by such vibrations (The American Heritage Dictionary, 2008).

3.2 Propagation of sound inside a joint

Sound is a sequence of waves of pressure that propagates through compressible media such as air or water. Inside the joint the tissues will allow propagation of sounds easily even through the thin patella. During propagation, waves can be reflected, refracted, or attenuated by the medium (The propagation of sound).

Sound propagation during phonoarthrography may be affected by the relationship between density and pressure. This relationship, affected by temperature, determines the speed of sound within the medium. For joint recording, the density of structures do not seem to vary between individuals, nevertheless the intra-articular pressure is increased in cases of OA due to effusion (H M Bassiouni et al., 1992). That is why it is recommended to aspirate excess synovial fluid before recording. The propagation of sound may be affected by the motion of the medium which is not applicable to recording of joint sounds since there is no medium to be moving during recording.

3.3 Sound wave properties and characteristics

Sound waves are often simplified to a description in terms of sinusoidal waves, with some characteristics such as:

- Frequency
- Wavelength
- Wave number
- Amplitude

The important ones used by investigators were the frequency/second, and the amplitude. The wavelength and individual wave number carry no importance to researchers recording joint sounds.

3.4 Speed of sound

The speed of sound depends on the medium traversed by the waves . In general, the speed of sound is proportional to the square root of the ratio of the elastic modulus (stiffness) of the medium to its density. And since the velocity of sound in water is approximately 1,482 m/s then it is assumed that the sound originating from the cartilage surface would take a negligible time to reach the sensor (http://library.thinkquest.org/19537/Physics4.html).

3.5 Noise

Noise is a term often used to refer to an unwanted sound. In science and engineering, noise is an undesirable component that obscures a wanted signal. The problem of noise recording during the process of recording the joint sounds has been dealt with properly. The solution to avoiding the noise background level is either to record in an anechoic chamber or recording first the noise then subtracting it from the joint recording.

3.6 Equipment for dealing with sound

Equipment for generating or recording sound includes transducers such as microphones and loudspeakers. The latter may help to listen to the joint recording afterwards.

4. Joint tissues producing sounds

4.1 Cartilage

Cartilage friction is the mostly accused of producing sounds. If it wears out it produces a complex sound known as crepitus (figure 4) but if there is a torn meniscus it produces one sharp sound during flexion and same on extension (figure 5). The cartilage covering the patella and the femur is also incriminated in sound production together with the femoro-tibial articulations in the knee joint. In the temporomandibular joint, the articulating disc is usually the source of sound production in disorders of mastication, while pain and tenderness come from the synovial lining of the joint.

4.2 Muscles

Muscles acting on knee for flexion and extension as well as those for mastication in the temporomandibular joint may produce sounds during contraction. That is why during recording of the knee sounds flexion and extension are done passively by the examiner to annul the muscle noise. Recording the sounds originating from the temporomandibular joint necessitate active opening and closure of the mouth, while the microphone is put directly on the superficial part of the joint far from the 4 muscles causing jaw movements.

4.3 Ligaments

Ligaments do not move hence they are not major sound contributors.

5. Different recording techniques

The use of a special sensor together with a recording tape and a memory oscilloscope was done in 1986 with many disadvantages such as the inability to get rid of the background noise; also the oscilloscope had a small memory insufficient to complete the full recording of knee flexion- extension at one time. The Inability to analyze the waves was also a disappointment (M H Bassiouni & El-Feki, 1986). A couple of years later another work was able to analyze the joint sounds using a narrow-band spectrum analyzer and a computer. The authors could subtract the spectrum of background noise from the linear averaged spectrum to obtain the phopnoarthrograph (Nagata, 1988). Nevertheless; this work carried some disadvantages. First the authors had to divide the sounds into two levels, the (L type) representing the low level less than 2.5 kHz and the high frequency sound (H type) lower than 3.5 kHz. This did not permit enough flexibility for diagnosing the cartilage condition regarding degeneration, and furthermore it did not help to classify the degree of degeneration. The authors concluded that the sounds emerging were due to thickness and hardness of the cartilage surface.

In 1987, a study was conducted to evaluate the dysfunctional temporomandibular joint (TMJ) by recording the joint sounds heard by a microphone during full mouth opening then closure done repeatedly. The main objective of the authors being dentists was to evaluate masticatory disorders attributed to TMJ disorders. They also correlated the phonoarthrographic values with pain in the TMJ area and also the radiological arthropathic index finding a high degree of correlation between the phonoarthrographic values and the arthropathic index (Ciancaglini et al., 1987).

The first report on phonoarthrography using a sensitive microphone and a computer with a special program came in 1995 with me as a co-author (M H Bassiouni et al., 1995). We proposed the following steps for recording the knee joint:

1. The selected and fixed time for the recording was two seconds. One second for flexion and the other for extension. It was done to be similar to what we do in clinical examination of the knee to feel the crepitus.
2. The patient was seated on a chair with the knee bent in order to fix a constant load (that of the lower limb) and to avoid noises coming from the hip joint Figure 1.
3. A recording of the background noise in the room was done. After its analysis, a standard value for the noise is now obtained. If the device is placed in a sound-proof room (anechoic), there will be no need for standardization of the noise.
4. Ultrasound gel was applied over the shaved patellar skin to avoid friction noises.
5. The sensor was put over the center of the patella in a fixed point.
6. The signals now appear on the monitor after flexing and extending the knee in two seconds.
7. Signals are analyzed and printed.

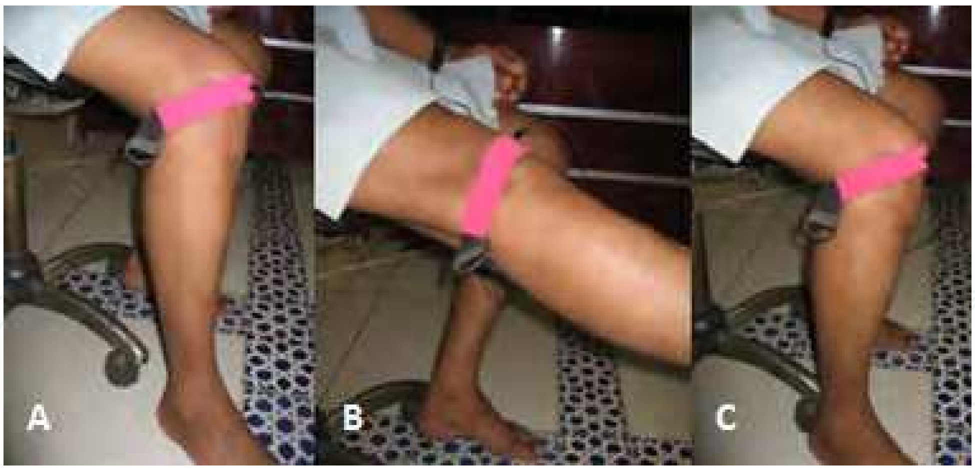

Fig. 1. Showing the microphone attached to a rubber band fixed around the knee so as to be centered on the patella. A –The knee is resting at 90°flexion. B- The knee is fully extended passively. C- Return to resting 90° flexion.

In another work done by some researchers from a department of electronics engineering (Kim et al., 2010), the authors recorded the knee sounds in 2 sec as stated above but they repeated the motion of knee flexion extension during a 20 seconds period. Unfortunately, this method did not add to the outcome of the recording, not to mention muscle fatigue and change in the velocity of movement which renders the test not precisely reproducible. The authors also did the recording using 2 postures the first while the patient is sitting and the second while the patient was standing. The values obtained while on standing were larger than those obtained while sitting; the authors attributed this result to the effect of the patient's weight or stress or both on the knee joint. During knee flexion and extension in standing mode, the different agonist muscles contributed to these movements, such as the hamstrings, biceps femoris, quadriceps femoris, muscles needed a more forceful contraction than in sitting position which increased the sounds recorded. Additionally, during these movements, the exposed area within the patella (which generates the knee sounds due to friction), could become relatively larger producing more waves.

For all researchers working in this field, reproducibility of phonoarthrographic values was a major concern. For that purpose ten knees were selected randomly and recorded 5 consecutive times. The mean values for every single reading were obtained and then readings were compared. The P values were insignificant between the readings assuring reproducibility (M H Bassiouni, 1995).

In an attempt to link modern therapies with phonoarthrography, recording the knee sounds was done before and after hyaluronic acid intraarticular injections (Matsuura & Masatoshi, 2000) two microphones were used in this piece of work, the authors placed them over the patella, 10 mm apart. The work was done on cases with end stage OA of the knees patellofemoral disorders and bucket-handle meniscal tears. The patients were divided into two groups, the first was given hyaluronic acid injections and the second was given steroid injections, both intraarticular. It was found that the sound frequency was significantly reduced (p=0.001) immediately and 24 hours after the hyaluronic acid administration while it did not differ after steroid injections. The frequency returned to pre-administrative levels when the recording was done 48h and 1 week after the administration of hyaluronic acid. The authors attributed the frequency lowering to a better joint lubrication.

In an attempt to explain the previous results, it must be remembered that the molecular structure of glycosaminoglycans allows them to attract and hold countless water molecules through electrostatic forces and weak chemical interactions as hydrogen bonds, which are easily formed and broken. The water-holding capacity of these glycosaminoglycans is so great that, when they are incorporated into the molecular complex, they can hold up to 50 times its own weight in water. This enables the complex to cushion the effects of physical impacts, which when occur, water is squeezed out of the glycosaminoglycans, and when the compressive force dissipates, the water rebinds to these thirsty molecules (Kawano et al., 2003). An important finding also is the fast return of frequency to pre-administrative levels which may suggest a short action of the injected hyaluronic acid.

6. Calibration of signals

The waves obtained in phonoarthrography like others have a frequency/recording and amplitude. Figure 2 shows a control case while figure 3 and 4 show moderate and severe case of osteoarthritis respectively. The frequency will be the number of waves crossing the midline every second and will be measured as number of waves/second. When the number gets higher it means directly more degenerated areas in cartilage. As for the amplitude, it is simply the difference between the highest and lowest points of the wave. The specially designed software has the capability to analyze the waves in average and extreme amplitude. Analogue scale divided into units was used to compare the different amplitudes. When using the amplitude, it is best to use the average values for the all waves in the same recording and this is known as the average amplitude (M H Bassiouni et al. 1995). In some cases where the click of a torn meniscus is recorded, the sound will appear once during flexion and repeated again during extension. The rest of the recording time will not record any other sounds if the knee was healthy until the meniscal problem happened (Figure 5).

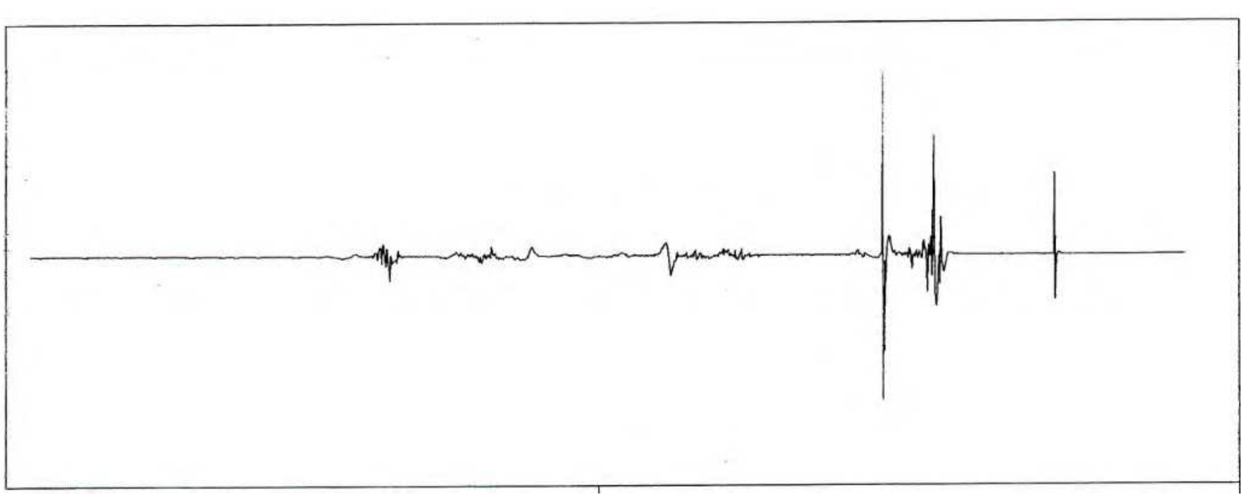

Fig. 2. Phonoarthrography of a control knee with average amplitude of 27.55 units/recording.

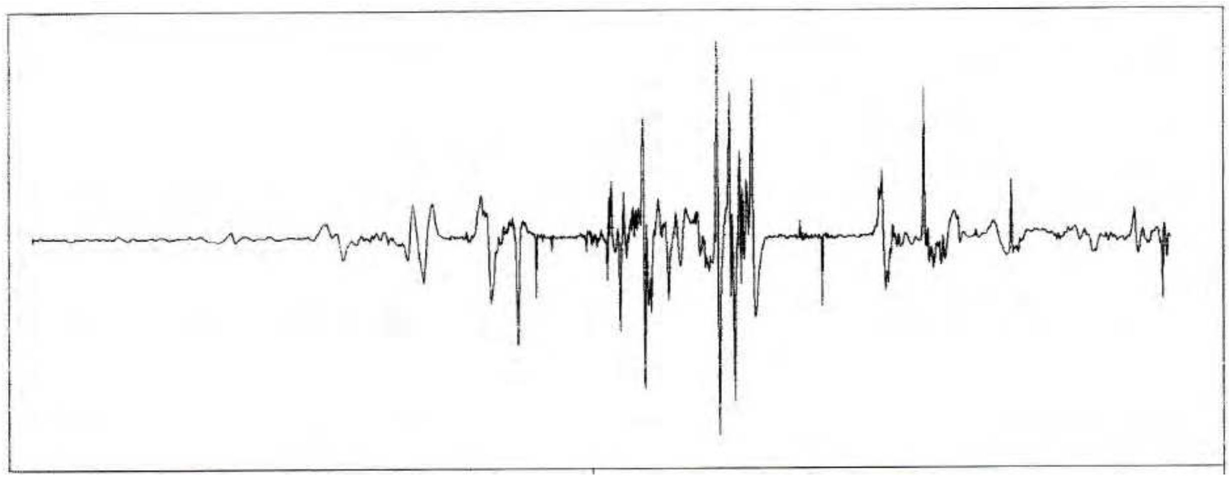

Fig. 3. Phonoarthrography of a moderate case of osteoarthritis (OA), with average amplitude of 47.53 units/recording.

Fig. 4. Phonoarthrography of a severe case of OA, with average amplitude of 64.65 units/recording

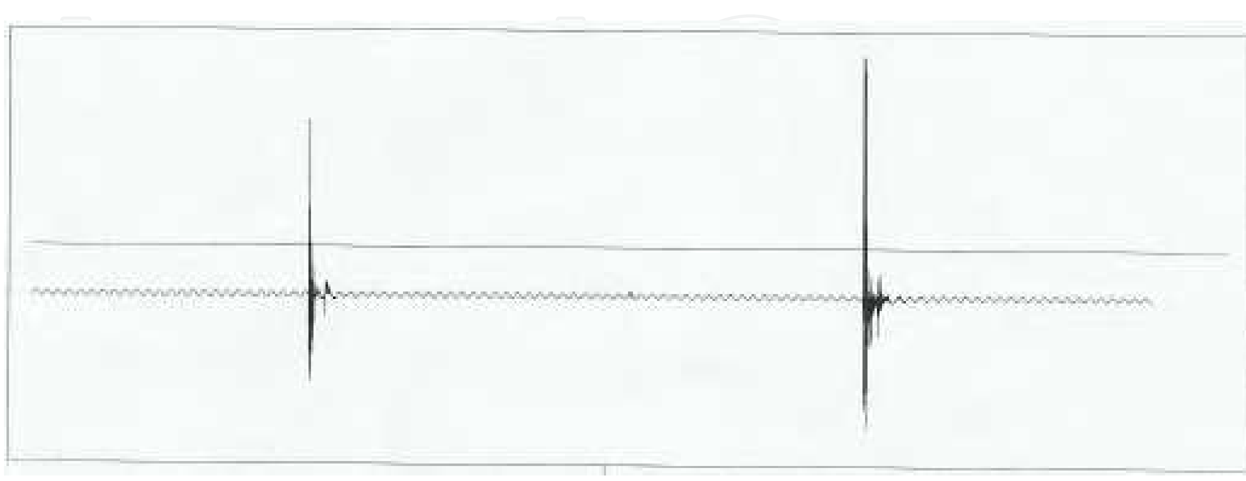

Fig. 5. Phonoarthrograph of a case of torn meniscus showing the sharp sound wave appearing twice during the recording of flexion and extension.

7. Cracking knee sounds

These sounds may be confusing with others. Actually what we call "normal joint sounds" may be produced through a mechanism different from a degenerated cartilage. When the two articulating surfaces, of a synovial joint are forcefully separated from each other, the volume within the joint capsule increases suddenly, creating a negative pressure within. Synovial fluid normally present cannot fill the created extra space and the gases dissolved in the synovial fluid- such as carbon dioxide) are liberated swiftly to fill the space leading to the formation of a bubble (Unsworth et al, 1971). This process is known as cavitation. Cavitation in synovial joints results in a high frequency 'cracking' sound (Watson et al., 1989).

8. Phonoarthrography, a simple parameter for cartilage degeneration

Aging must impose its print on cartilage as it does to many other organs in the human body. In a previous work that performed phonoarthrography on normal controls, rising values went side by side with advancement of age (Figure 6). Logically thinking, this could be expected, however, it still was statistically less than those who had clinically symptomatic osteoarthritis. Another important observation in the same work was that phonoarthrography was found to show abnormally high values in all cases with radiological OA, proving to be 100% sensitive for radiology. Positive values were also present in 32.5% of cases with normal radiology, giving more credit to phonoarthrography as being more sensitive than radiology for detecting cartilage degeneration. All Cases with clinically felt crepitus had abnormal phonoarthrographic values while in those with no felt crepitus, 13% had high phonoarthrographic values (M H Bassiouni et al., 1995).

9. Relating phonoarthrography to other standard investigative tools

9.1 Phonoarthrography versus standard knee radiology

Being relatively a new parameter, phonoarthrography had to be tested against standard used parameters such as radiology in order to discover its potentials properly. The work done by M H Bassiouni et al in 1995, dealt with this point; as the patients had their knees phonoarthrographied and classified using the radiological Kellgren-Lawrence classification grades (K-L) (Kellgren & Lawrence, 1957). The K-L classification as previously known is presented into 4 grades according to radiological severity of the knee joints. The average amplitude and frequency were defined for each K-L grade. A marked statistical difference was found between the phonoarthrography values in each grade and the following grade (P =0.0001) denoting a positive correlation between both parameters (M H Bassiouni et al., 1995).

In a recent work (H M Bassiouni et al., 2011), comparing phonoarthrographic values obtained from patients with bilateral OA of the knees with K-L classification, the authors plotted the average amplitude against each grade and found that it rose steadily with higher radiological grades (35.04 in grade 1, 39.55 in grade 2, 44.27 in grade 3, 50.53 in grade 4) (table 1).

TMJ has a clinico-radiologicalarthropathic index (CRAI) that includes the duration of the occurrence of noise, pain in the TMJ area, the tenderness on lateral palpation of the TMJ, and linear and computer tomography of the craniomandibular complex. The CRAI ranged from

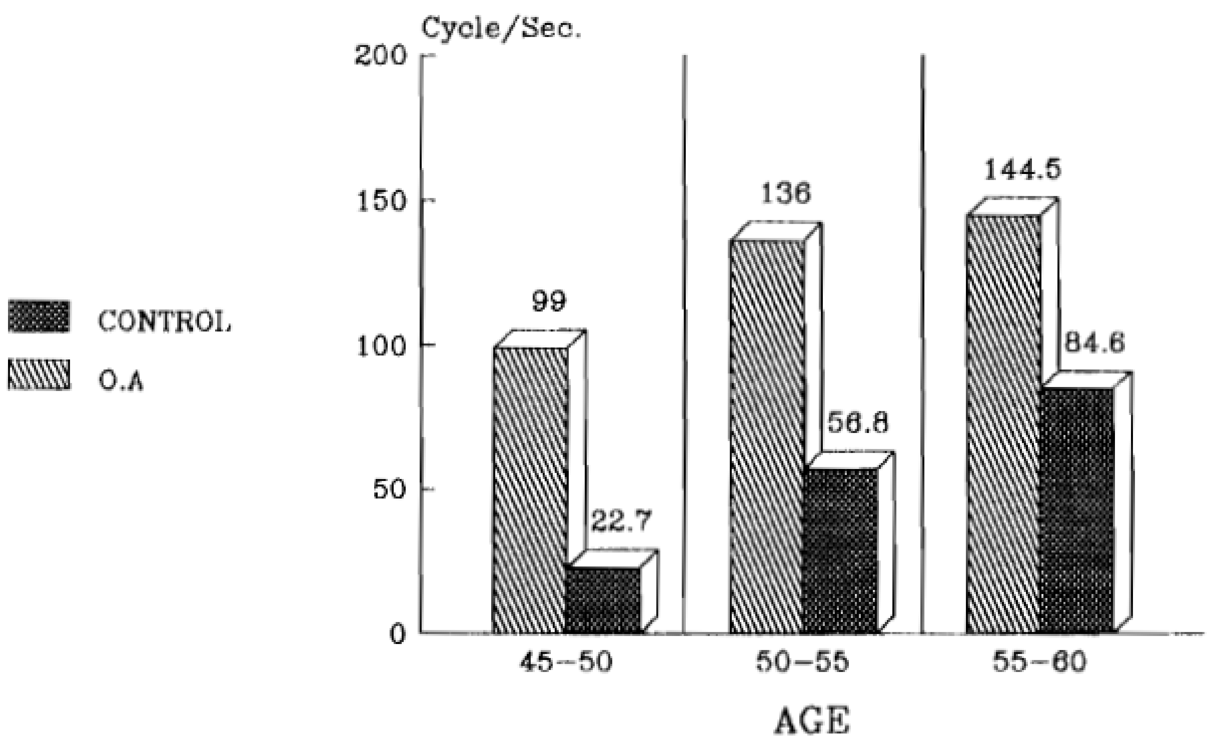

Fig. 6. Showing the frequency/sec from normal controls and from OA patients in different age groups.

O (no arthropathy) to 13 (severe arthropathy). A previous paper where the authors used clinical exam, tomograms and JVA to diagnose TMJ internal derangement versus an artificial neural network (ANN) program trained to recognize vibration patterns. The results of this work showed that ANN correctly identified 98.2% of the diagnosis made previously (Knutson & Radke, 1995).

9.2 Phonoarthrography versus musculoskeletal ultrasonography and MRI

Musculoskeletal ultrasonography (MSUS) has been proposed previously for assessing periarticular and intra- articular abnormalities involved in the pathophysiology of knee OA (Naredo et al., 2005).Before linking parameters to each other, one must know what the capabilities of each are. Musculoskeletal ultrasonography (MSUS) has the capability of studying many structures around the knee joint; it can also measure the thickness of the cartilage peripherally but cannot give information about the surface of the cartilage. On the other hand Phonoarthrography provides an evaluation about the smoothness or roughness of the articular cartilage.

The cartilage thickness from the 4 condyles was measured by MSUS in cases of OA of the knees and Phonoarthrography was performed to same patients (H M Bassiouni et al., 2011). The study provides important information about the thickness of cartilage in both OA patients and control groups and it shows clearly that there was a high statistical difference between the thickness in both groups (P=0.0001). This difference was present in all 4 condyles. Table 1 shows the cartilage thickness from the patients group measured from the 4 condyles in each grade of OA. There was also an inverse correlation between thickness of cartilage and radiological grading.

Phonoarthrography inversely correlated with the thickness of cartilage i.e. the lesser thickness (denoting more degeneration), the higher the average amplitude. An example correlating the medial femoral cartilage thickness to the average amplitude shows r =-0.77, p=0.01.

In a single work in literature that was done to correlate magnetic resonance imaging (MRI) findings of effusion, disc displacement, condylar bony changes and disc form with clinical findings of pain and sounds in patients with bruxing and non-bruxing behavior, the authors found that a higher prevalence of condylar bony changes occurred in reducing joints in patients with bruxing behavior and also they highlighted the importance of phonoarthrography in diagnosing unilaterally affected joints. In non-reducing joints, 30% of painful joints in the patient group and 59% of controls showed a strong signal in the joint space on T_2 weighted imaging (Guler et al., 2003).

9.3 Phonoarthrography versus cartilage biomarkers

In the same work where the authors correlated the cartilage thickness with the average amplitudes (H M Bassiouni net al., 2011); they also measured the MMP-3 and TIMP-1 as to detect if changes in these markers would influence the outcome of phonoarthrography (table 1). MMp-3 was selected because many proteolytic enzymes, secreted by chondrocytes and synovial cells, cause degeneration and destruction of the cartilage matrix of the joints. Matrix metalloproteinase-3 (MMP-3) (stromelysin) is a major player in cartilage destruction; it degrades proteoglycan and collagen types II, IX, and XI (Wu et al., 1991), and also activates other MMPs (Okada et al., 1989).

Parameters Percentage of cases in each grade	OA grade 1 10%	OA grade 2 36%	OA grade 3 30%	OA grade 4 24%
TIMP1 Mean ±SD Median	7570±1678.76 7350	6719.44±2682.1 6300	8356.67±2447.1 8250	9808.33±4135.4 9975
P		F = 2.68, p=0.0662	MW= 6.56, p=0.0871	
MMP3 Mean ± SD Median	36.06±4.98 36.44	109.18±54.61 100.31	121.73±56.43 130.56	93.93±59.78 73.45
P		F=3.33, p=0.0274	MW=12.77, p=0.0051	
Phono-A Rt Mean ± SD Median	35.04±1.85 35.53	39.55±1.55 39.38	44.27±1.5 43.5	50.53±4.57 49.39
P		F=59.87, p=0.0000	MW=44.68, p=0.0000	
Phono-A Lt Mean ± SD Median	35.71± 0.85 35.25	40.54±1.23 40.77	45.04±1.41 44.78	49.62±1.59 49.99
		F=171.55, p=0.0000	MW=44.55, p=0.0000	
MFC Rt Mean ± SD Median	2.73±0.17 2.71	2.37±0.25 2.36	1.97±0.26 1.86	1.38±0.31 1.33
		F=46.86, p=0.0000	MW=36.28, p=0.0000	
MFC Lt Mean ± SD Median	2.93±0.27 3	2.48±0.2 2.49	2.04±0.42 2.01	1.38±0.32 1.22
		F=41.18, p=0.0000	MW=35.17, p=0.0000	
LFC Rt Mean ± SD Median	2.88±0.44 3.1	2.72±0.24 2.76	2.58±0.24 2.65	1.86±0.33 1.79
		F=26.48, p=0.0000	MW=29.05, p=0.0000	
LFC Lt Mean ± SD Median	3.17±0.26 3.04	2.77±0.31 2.69	2.48±0.33 2.6	1.86±0.34 1.98
		F=27.54, p=0.0000	MW=31.21, p=0.0000	
MTC Rt Mean ± SD Median	2.9±0.43 2.94	3.43±0.29 2.37	2.05±0.17 2.12	1.45±0.33 1.41
		F=41.16, p=0.0000	MW=34.93, p=0.0000	
MTC Lt Mean ± SD Median	2.88±0.35 3	2.57±0.24 2.54	2.19±0.24 2.31	1.74±0.42 1.56
		F=25.49, p=0.0000	MW=28.66, p=0.0000	
LTC Rt Mean ± SD Median	3.19±0.29 3.37	2.9±0.31 2.86	2.63±0.32 2.71	2.0±0.34 1.95
		F=25.2, p=0.0000	MW=32.82, p=0.0000	
LTC Lt Mean ± SD Median	3.44±0.19 3.55	2.77±0.25 2.84	2.49±.32 2.59	1.91±0.68 2.02
		F=19.62, p=0.0000	MW=29.46, p=0.0000	

Table 1. This table shows the 4 OA grades in relation to biomarkers (MMp-3 and TIMP-1), phonoarthrography, and cartilage thickness from the 4 condyles.

Interestingly, MMP-3 did not correlate with the real-time status of cartilage elaborated by phonoarthrography, and the reason for that is that this marker denotes only episodes of joint destruction, while Phonoarthrography describe the present cartilage condition.

10. Conclusion

Phonoarthrography is a simple, non-invasive tool that should be present in any rheumatology clinic. A trained doctor or nurse can perform the test easily. A point of strength for Phonoarthrography is that it provides early and sensitive information about cartilage that other imaging machines cannot do, except when the disease is prominent. This information is related to motion, which involves two articulating surfaces gliding over each other at the same time. Magnetic resonance imaging (MRI), a known strong tool for the diagnosis and follow-up of OA, remains handicapped in the domain of detecting any changes related to cartilage surfaces' functioning together, which is provided by Phonoarthrography.

So far only 2 joints have been studied which are the knees and temporomandibular joints. Other joints such as the elbow, metacarpophalangeal, shoulder and other articulations should be candidates for phonoarthrography.

More works are needed to prove that we can use phonoarthrography in diagnosis and follow ups of patients in diseases where the etiologies are different from OA such as in rheumatoid arthritis.

11. Acknowledgement

The idea of recording knee sounds is fully credited to the late Prof. Mohamed Bassiouni who strived to make the idea possible and clinically achievable. The devices and programming were attributed to Prof Fahmy E Fahmy and Prof Mohamed B El-Feki. Delta Software Company also provided the latest version of the program used currently for the recording.

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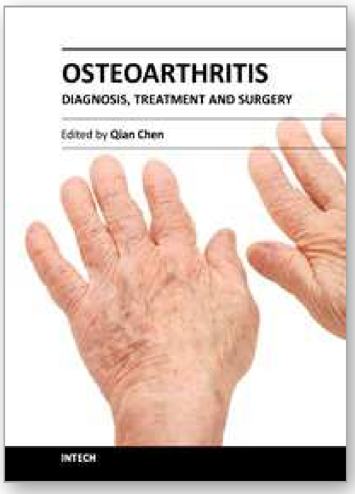

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Osteoarthritis is one of the most debilitating diseases affecting millions of people worldwide. However, there is no FDA approved disease modifying drug specifically for OA. Surgery remains an effective last resort to restore the function of the joints. As the aging populations increase worldwide, the number of OA patients increases dramatically in recent years and is expected to increase in many years to come. This is a book that summarizes recent advance in OA diagnosis, treatment, and surgery. It includes wide ranging topics from the cutting edge gene therapy to alternative medicine. Such multifaceted approaches are necessary to develop novel and effective therapy to cure OA in the future. In this book, different surgical methods are described to restore the function of the joints. In addition, various treatment options are presented, mainly to reduce the pain and enhance the life quality of the OA patients.

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