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Technical note

Detection of osteoarthritis using acoustic emission analysis☆

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ABSTRACT

Osteoarthritis (OA) of the knee is a widespread disease, often resulting in pain, restricted mobility and a reduction of activities and participation. Initial studies gave hints that Acoustic Emission Analysis (AEA) is capable of detecting early changes in cartilage structure. However, up to date no *in vivo* validation studies have been conducted. A prospective pilot study was conducted to investigate this diagnostic capability and the accuracy of the AEA, using magnetic resonance imaging (MRI) as a reference standard. Additionally, potential factors influencing false positive or negative results were studied.

Twenty-eight patients, receiving MRI due to discomfort of the knee, were examined with AEA.

Sensitivity was 0.92 for the whole knee and 0.86 to 1 for different parts of the knee. The specificity was 0.7 and 0.59 to 0.78, respectively. Confidence intervals varied between 0 and 0.33 for sensitivity and 0.1 and 0.24 for specificity.

The diagnostic accuracy of the AEA was shown to be good to very good. However, because of the relatively small number of patients involved, interpretation of the data should be handled with care. Future studies with greater sample sizes have to be conducted to confirm the results of this investigation.

1. Introduction

Previous studies indicated that Acoustic Emission Analysis (AEA) can detect osteoarthritis OA earlier than other techniques [1–4]. In principle, AEA measures acoustic emissions (AE) produced by any material under load or strain. Lesions, e.g., in cartilage, lead to characteristical alterations in the AE during load [1–5]. These emissions can be detected and interpreted for diagnosis. AEA has the potential for the early diagnosis of OA, e.g., at stages, when cartilage regeneration is still possible [6–9], but the assessment of the diagnostic accuracy of AEA is necessary. Therefore, we designed a pilot study on patients who had the clinical diagnosis of OA and received MRI of the knee – used as reference - due to acute knee complaints [10–16].

2. Material and methods

2.1. Study design

The prospective cohort study was performed in 2008 to evaluate AEA for the detection of osteoarthritis. Patients with the clinical diagnosis (NRS test) of OA of the knee were enrolled when MRI of the knee was performed. Further inclusion criteria were: older than 18 years and ability to bear full weight on the affected knee. AEA measurements were performed within five days before or after the MRI to avoid disease progression bias (QUADAS criteria) [17]. Patients with knee instability were excluded [18–21].

2.2. Clinical diagnosis

Patients rated the pain of the affected knee using the numeric rating scale (NRS), [22–24]. A "0″ on the NRS was defined as "having no pain at all" or "having no restriction at all". A rating of "10″ on the NRS was defined as "having the greatest imaginable pain" or "being totally restricted" [25].

2.3. MRI-scans

A Magnetom Symphony 1.5 T scanner (Siemens, Erlangen) exploited a transversal T1-weighted pd-fs-TSE (*proton densed fat saturated Turbo Spin Echo*)-sequence, a sagittal T2-weighted pd-fs-TSE-sequence, a coronar T1-weighted pd-fs-TSE-sequence und a coronar T1-weighted SE (*Spin Echo*)-sequence. MRI-scans lasted 15 minutes on an average.

☆ In vivo pilot study.

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The MRI-images were assessed by two radiologists at blinded reading. In case of conflicting diagnoses, radiologists reached consensus by discussion.

The degree of cartilage damage was determined according to a 5-point scale (0–4) [6], ranging from grade 0 (normal cartilage) to grade 4 (full-thickness wear of cartilage with exposure of subchondral bone) [26,27]. Meniscal tears were diagnosed using the Mesgarzadeh classification [13]. Raunest grades were used to diagnose degeneration of the menisci [14].

2.4. Acoustic emission analysis (AEA)

AEA measurements used the BoneDias®-System consisting of a piezoelectric sensor with a mechanical resonance frequency of 78 kHz, allowing to record AE from the lateral and medial parts of the whole knee joint cartilage, except the patellar cartilage.

All participants performed 4 sets of 3 squats. During exercise, they stood on a 20° tilted ramp to elevate the position of the heels to allow knee bends of at least 90° without risking instability or falling. Care was taken in order to provide comparable cartilage conditions during each set of measurements as described by Mascaro et al. [28].

In earlier studies the analogous broad band signals from the sensor were transformed, applying a Fourier Transformation in order to reveal that range of frequencies – found between 70 and 85 kHz – with the maximum distance between desired signal amplitudes and surrounding noise amplitudes [1,2]. Then band pass filters were used allowing only these frequencies to pass. A root-mean-square algorithm was applied, which qualitatively describes the sequence of AE from areas of load transfer in moving knee- and hip-joints.

Cartilage lesions in the area of load transfer and micro cracks in bone occur frequently and are characterized by elevated levels of acoustic emission. The time course of AE allows to distinguish between signals due to friction in joints and those due to bone cracking.

Crack-typical emission, so called bursts, are characterized by a very short rise time of signals (not more than 3 oscillations necessary to reach the peak amplitude) and an exponential signal decay. The software automatically detected and notified burst signals characterized as described before [1,2].

Emission due to friction, called continuous emission, is characterized by longer rise times (more than 5 oscillations necessary to reach peak amplitude). Since friction causes new AE continuously there is an overlay of and no defined decay of signals. All signals with a long rise time and undefined decay are considered as signals due to friction. This discrimination of signals due to friction is based on time-domain-features as shown in Fig. 1 (detailed in [1]) and exploits signal duration, peak amplitude of the signal, rise time, decay and thresholds. All acoustic spectra were inspected by two investigators to assess all of the lesion-typical patterns in emission due to friction. In case of disagreement a third reader was involved to generate consensus.

Findings were declared positive when at least one pattern indicating a cartilage lesion was found. Only signals surpassing a threshold of detection were selected. The time course of signal amplitudes of lesion-typical emission is characterized by the slope steepness when the corresponding joint surfaces delve into and out of the lesion. When many signal oscillations are necessary to reach the peak amplitude, it took much time, evidently, to delve into a lesion. This indicates that the dampening capability of the cartilage is high. When only few oscillations (≥ 5) are necessary to reach the peak signal amplitude, the time to compress the cartilage is low, indicating a low dampening capability of the cartilage which coincides with thin residual cartilage layers [1,2,5].

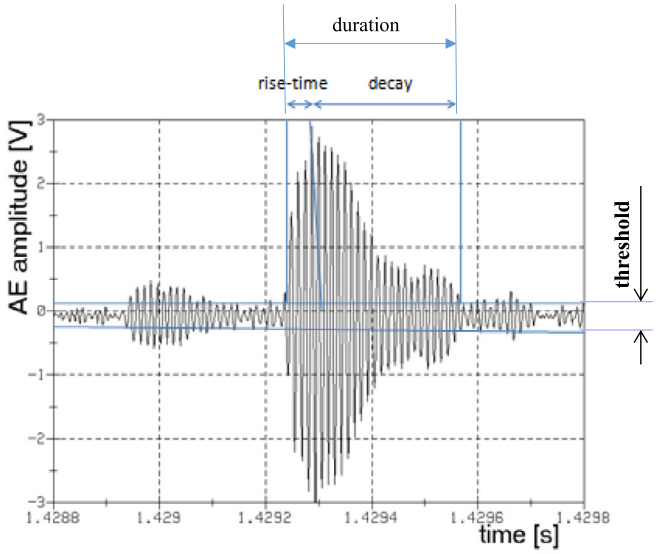

Fig. 1. Continuous acoustic emission of a cartilage lesion with a well-defined rise-time and an undefined signal decay.

Table 1
Baseline data of all participants.

	n (%)	Mean ± SD	Range (min-max)
Gender			
Male	17 (56.70%)	–	–
Female	13 (43.30%)	–	–
Age (years)	–	42.9 ± 14.8	53 (20–73)
Height (cm)	–	174.7 ± 6.2	33 (158–191)
Weight (kg)	–	78.2 ± 10.3	43 (59–102)
BMI	–	25.7 ± 3.4	14.4 (19.3–33.7)
BMI 25+	16 (53.33%)	–	
BMI 30+	4 (13.33%)	–	

Abbreviations: BMI: Body Mass Index, *n*: number of participants SD: standard deviation.

2.5. Statistical analysis

For all samples mean ± standard deviation (SD) are given; for categorical data frequency or percentage. Gaussian distribution of the samples was checked using Kolmogoroff-Smirnow test.

Diagnostic accuracy of the AEA was tested using 2×2 contingency tables. Specificity, sensitivity as well as positive and negative predictive values (PPV, NPV), were calculated from AEA and MRI data.

3. Results

3.1. Study population

260 patients received MRI-scans of the knee. Of these, 156 were asked to be enrolled in the study. Thirty-one of these patients with the clinical diagnosis of OA agreed to participate. Reasons not to participate were age under 18 ($n = 15$) or the inability to perform squats ($n = 26$) or no time or no interest ($n = 84$).

The remaining 31 patients participated in the study. Of these, two patients had to be excluded (one with cardiac insufficiency, another one due to a rupture of the ACL. One patient received MRIs and AEA in both knees. Therefore, 30 knees of 29 patients were examined. Twenty-nine of these examinations were made on the same day as the MRI-scan (one happened three days after the MRI). Demographic data are given in Table 1. Age, height, weight and body mass index were Gaussian distributed.

Table 2
2 × 2 contingency table for all measured regions.

	Whole knee[a]	MF[b]	MT[b]	LF[b]	LT[b]
AEA positive	43 (35.8%)	11 (36.7%)	13 (43.3%)	6 (20.0%)	13 (43.3%)
MRI positive	12 (10.0%)	7 (23.3%)	3 (10.0%)	1 (3.3%)	1 (3.3%)
True positive	11 (9.2%)	6 (20.0%)	3 (10.0%)	1 (3.3%)	1 (3.3%)
False positive	32 (26.7%)	5 (16.7%)	10 (33.3%)	5 (16.7%)	12 (40.0%)
False negative	1 (0.83%)	1 (3.3%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
True negative	76 (63.3%)	18 (60.0%)	17 (56.7%)	24 (80.0%)	17 (56.7%)

Abbreviations: MF, medial femur, MT, medial tibia, LF, lateral femur, LT, lateral tibia. Values for the diagnostic accuracy of the AEA are summarized in Table 3.
[a] relative data relating to all measurements.
[b] relative data relating to all measurements of the respective region.

Table 3
Diagnostic accuracy of the AEA with MRI used as a reference standard.

	Whole knee	MF	MT	LF	LT
Sensitivity	0.92±0.17	0.86±0.29	1 ± 0	1 ± 0	1 ± 0
Specificity	0.7 ± 0.10	0.78±0.19	0.63±0.23	0.63±0.15	0.59±0.24
Pos. predictive value	0.26	0.55	0.23	0.17	0.08
Neg. predictive value	0.99	0.95	1	1	1
Prevalence	0.1	0.23	0.1	0.03	0.03

Abbreviations: MF, medial femur, MT, medial tibia, LF, lateral femur, LT, lateral tibia.

All patients reported knee pain within the last 7 days according to the NRS test. 7 patients reported permanent pain under resting conditions (NRS: 0.73±1.57) and 21 patients reported actual pain during movement (3.03±2.63). Two patients had pain during movement within the last 7 days.

3.2. Diagnostic accuracy of the AEA

Table 2 shows AEA and MRI data representing the diagnostic outcomes for the whole knee.

3.3. Deviations from the protocol

Of the 120 measurements, 12 had to be repeated. No injuries or complaints occurred during measurements.

4. Discussion

While the sensitivity for OA of the knee was always around 90%, the specificity was markedly lower (between 59% and 78% (Table 3)). Placing the sensor at the trochanter major, the sensitivity was clearly lower; however, the specificity was higher.

The negative predictive value was very good. The positive predictive value, however, was not satisfactory, probably due to the relatively low prevalence of advanced OA.

The findings of this study are in line with studies of AEA in diagnosing cartilage damage during *ex vivo* [29,30] as well as during *in vivo* studies [31–34]. Diagnostic accuracy appeared to be good to very good overall, with similar results for the whole knee and knee regions.

Although the results appear promising, it is too early to generalize the findings of AEA diagnostic accuracy. MRI was used as reference standard. MRI-scans, however, have certain drawbacks concerning the diagnosis of OA. Whiting et al. [12] found an unsatisfactory sensitivity for the diagnosis of increased signal intensity, which is associated with very early stages of OA [35]. Alternative MRI sequences like T2-Mapping, $T1_{\rho}$-Mapping and dGEMRIC, which may specifically detect early changes in cartilage, are time-consuming, expensive and also invasive due to the application of MRI contrast agents like Gd-DTPA^{2-} (complex of gadolinium with DTPA (diethylene*tri*amine*penta*cetate). To compensate for this limitation, we had two radiologists performing the diagnosis of the whole knee with a high level of agreement. Both radiologists, in some cases needing a third reader to reach agreement, had in the end no uncertainty about the final diagnosis.

Standardization of the squatting turned out as a problem in our study. Several items were established to enable standardized squatting. These comprised a metronome, standing on a ramp, and using handrails when necessary. Despite all these efforts a wide intra- and interpersonal variability of the squats was observed. It is unclear whether this variability could negatively affect the results of the AEA.

The relatively wide confidence intervals seen in some of the results are a problem (Table 3). This makes a more profound interpretation of the results difficult. To reach conclusive results, the sample size has to be increased. However, this pilot study enables an accurate sample size calculation for future studies, taking into account the prevalence of OA in the population where the recruitment takes place.

To our knowledge this is one of the first studies to demonstrate the diagnostic accuracy of the AEA and its suitability to the clinical diagnosis of OA of the knee [34]. Further studies will be conducted in order to verify the results presented here.

4.1. Limitations of the study

As this study was one of the few to examine knee cartilage *in vivo* with AEA, it was difficult to determine the sample size which would yield adequate statistical power. Sample sizes in the literature on the reference standard (MRI) were generally small and no power calculations were presented. It was then decided to examine 30 patients, who received a MRI and AEA of the knee, because a normal distribution of data could be expected according to the central limit theorem.

5. Conclusion

Since the number of participants was rather low: the interpretation of the results has to be made with caution. However, we found the diagnostic accuracy of the AEA for the *in vivo* diagnosis of knee OA to be good to very good.

Conflicts of interest

None.

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Ethical approval

The study protocol was approved by the ethics committee of the medical faculty of the Philipps University Marburg in Germany (reference number 137 / 08) on the 1. Oct. 2008.

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