Magnetic Resonance Imaging Score and Classification System (AMADEUS) for Assessment of Preoperative Cartilage Defect Severity

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Abstract

Objective. To design a simple magnetic resonance (MR)–based assessment system for quantification of osteochondral defect severity prior to cartilage repair surgery at the knee. **Design.** The new scoring tool was supposed to include 3 different parameters: (1) cartilage defect size, (2) depth/morphology of the cartilage defect, and (3) subchondral bone quality, resulting in a specific 3-digit code. A clearly defined numeric score was developed, resulting in a final score of 0 to 100. Defect severity grades I through IV were defined. For intra- and interobserver agreement, defects were assessed by 2 independent readers on preoperative knee MR images of $n = 44$ subjects who subsequently received cartilage repair surgery. For statistical analyses, mean values $\pm$ standard deviation (SD), interclass correlation coefficients (ICC), and linear weighted kappa values were calculated. **Results.** The mean total Area Measurement And DEpth & Underlying Structures (AMADEUS) score was 48 ± 24 , (range, 0–85). The mean defect size was 2.8 ± 2.6 cm². There were 36 of 44 full-thickness defects. The subchondral bone showed defects in 21 of 44 cases. Kappa values for intraobserver reliability ranged between 0.82 and 0.94. Kappa values for interobserver reliability ranged between 0.38 and 0.85. Kappa values for AMADEUS grade were 0.75 and 0.67 for intra- and interobserver agreement, respectively. ICC scores for the AMADEUS total score were 0.97 and 0.96 for intra- and interobserver agreement, respectively. **Conclusions.** The AMADEUS score and classification system allows reliable severity encoding, scoring and grading of osteochondral defects on knee MR images, which is easily clinically applicable in daily practice.

Keywords

magnetic resonance imaging, articular cartilage, classification, score, interobserver reliability, knee

Introduction

Articular cartilage defects across the knee joint represent a clinical and socioeconomic dilemma.¹ They predispose for an early onset of osteoarthritis (OA), even when surgical cartilage repair is commenced.² Yet, preoperative patient assessment, surgical techniques, co-pathology evaluation, postoperative assessment, and rehabilitation strategies have advanced since the advent of cartilage repair surgery in the 1980s.³ In particular, magnetic resonance (MR) imaging methods are continuously being improved in order to precisely evaluate articular cartilage and subchondral bone pre- and postsurgery.⁴ Multiple semiquantitative MR scoring systems were developed that assess different joint structures, including articular cartilage, such as Whole-Organ Magnetic Resonance Imaging Score (WORMS)⁵ and Boston-Leeds Osteoarthritis Knee Score (BLOKS)⁶. They were designed for assessment of OA severity, but not for specific cartilage defect assessment among non-OA joints. Furthermore, they

are primarily used in clinical research studies. In clinical practice, the Outerbridge scoring system⁷ and the ICRS

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(International Cartilage Repair Society) scoring system⁸ are used to describe focal cartilage defects at the knee. However, both scores were primarily developed for arthroscopic assessment of cartilage defects and have disadvantages. Both scoring systems consider cartilage defect depth but not its width. The ICRS score also considers involvement of subchondral bone, but does not grade it. Recently, the Cartilage Lesion Score (CaLS) was introduced, which specifically aims to longitudinally quantify relatively mild cartilage lesions in osteoarthritic knees on MRI (without taking into account the subchondral bone).⁹ In 1987, Yulish *et al.*¹⁰ described a semi-quantitative MR-scoring system for the evaluation of cartilage defects presurgery (stages 1 through 3). Apart from this score, which is not frequently used, there is no fast and easily applicable clinical MR scoring and classification system, that allows for reliable, objective and quantitative assessment of osteochondral defects and that might help in decision making regarding surgical therapy. All described scores have their advantages and their specific value; however, no MR-scoring systems have been proposed for evaluation of osteochondral lesions before cartilage repair surgery.

Scores, that were specifically developed to assess MR images of patients that receive cartilage repair surgery concentrate on the evaluation of the postoperative tissue. One frequently applied qualitative scoring system to assess cartilage repair tissue is the MOCART (Magnetic Resonance Observation of Cartilage Repair Tissue) score.¹¹ Lately, the cartilage repair osteoarthritis knee score (CROAKS) has been invented in order to assess the repair tissue and the whole joint at once.¹²

Therefore, aim of the current study was to design and test the reliability of a novel MR-based scoring and classification system that includes the 3 essential components: (1) cartilage defect size, (2) depth, and (3) subchondral bone, in order to simply assess chondral and osteochondral lesions at the knee in clinical routine, in particular prior to planned surgical intervention (cartilage repair). The AMADEUS grading and classification system aims to provide a 3-digit AMADEUS code to describe these defect characteristics, a final AMADEUS score and an overall AMADEUS grade. Using this easily applicable tool, clinical radiologists and orthopedic surgeons may estimate cartilage defect severity quantitatively for improved interdisciplinary communication, patient communication, multicenter comparisons in standardized patient registries and to support therapeutic and surgical decisions.

Materials and Methods

The study was approved by our institutional review board. The requirement for informed consent was waived. The study was conducted with the principles of the Declaration of Helsinki (World Medical Association). The data of consecutive patients that received cartilage repair procedures at

the knee at our hospital between 2006 and 2011 was evaluated retrospectively. Inclusion criteria were available pre-operative 3 T or 1.5 T MR examinations with adequate image quality and with MR sequences including intermediate-weighted (IM-w) images (usually with fat saturation [fs]) in at least 2 planes and a T1-w sequence in at least 1 plane (sagittal or coronal; **Table 1**). Additional inclusion criteria were the following: surgical therapy for a cartilage defect using any standard cartilage repair procedure (i.e., osteochondral transplantation, microfracturing, autologous chondrocyte transplantation) and available surgical reports with reported cartilage defect size in surgical reports. Exclusion criteria were insufficient MR quality and presence of osteochondrosis dissecans, since different scores may be applied in those cases. Finally, the study population consisted of a total of 44 patients.

MR Image Analysis

MR images were transferred on Picture Archiving Communication System (PACS) workstations (Easy Vision, Philips, Best, Netherlands) and were evaluated by 1 radiologist (P.M.J.) and by 1 specialized orthopedic surgeon (G.M.S.) independently. One observer (P.M.J.) evaluated all MR images twice with a 6-month interval between the 2 reading sessions.

Assessment of MR images

The AMADEUS (Area Measurement And DEpth & Underlying Structures) scoring system includes the three most important different parameters that describe a focal chondral or osteochondral defect prior to possible cartilage repair surgery: (1) the cartilage defect area, which is measured ("area measurement"); (2) the cartilage defect morphology/depth ("depth"); and (3) the underlying structures with presence of adjacent osseous defects/subchondral cysts and bone marrow edema-like lesions (BME) ("underlying structures"). In addition to the resulting AMADEUS code, subscores were defined for each feature, which sum up to a total score of 100 (no osteochondral defect) to 0 (worst score) (**Table 2** and **Fig. 1**).

Variables AMADEUS Score

Area Measurement. The first digit in the AMADEUS code is the cartilage defect area. Maximum defect size (diameter, cm) was measured in 2 planes and the defect area was calculated (cm²). Defect size included morphological lesions and areas with severe signal changes of the cartilage matrix that were likely to be debrided during following cartilage repair surgery. For defects at the patella or trochlea, measurements were performed on transverse and sagittal images, for the medial and lateral femoral condyle

Table 1. Exemplary Magnetic Resonance Pulse Sequence Parameters at 3 T.

Sequence	2D IM-w TSE	2D TI-w TSE	2D IM-w TSE	2D IM-w TSE
Additional features	fs, BLADE	DRIVE pulse	fs, BLADE	fs, BLADE
Plane	Sagittal	Sagittal	Coronal	Transverse
Echo time (TE; ms)	47	16	47	43
Repetition time (TR; ms)	4000	746	3810	5430
Field of view (FOV; mm)	140	140	140	140
Slice thickness (mm)	3	3	3	3
In-plane resolution (mm ²)	0.36 × 0.36	0.42 × 0.31	0.36 × 0.36	0.36 × 0.36
Flip angle (deg)	90	90	90	90
Number of slices	28	28	28	37
Receiver bandwidth (Hz/pixel)	181	101	181	210
Frequency encoding direction	Column	Column	Row	Row
Distance (mm)	3.6	3.6	3.6	3.75
Acquisition time (min)	5:31	5:26	4:16	5:38

FOV = field of view; w = weighted; TSE = turbo spin echo; IM = intermediate; fs = fat saturated; BLADE = motion correction with radial blades; DRIVE pulse, driven equilibrium pulse.

^aMagnetic resonance imaging was performed at 1.5 T systems and (e.g. Gyroscan NT Intera, Philips Medical Systems, Best, the Netherlands) or 3 T systems (e.g. Siemens Verio, Global Siemens Healthcare Headquarters, Siemens AG, Erlangen, Germany). Dedicated surface coils were used (e.g. 8-channel knee coil, Medical Advances, Milwaukee, WI, USA).

Table 2. Frequency for All AMADEUS (Area Measurement And DEpth & Underlying Structures) Scores.

AMADEUS feature	Points	Frequency ^a (%)
<i>Area measurement</i>		
<i>Defect size</i>		
No defect	40	0
≤1 cm ²	35	30
>1 to ≤2 cm ²	30	30
>2 to ≤4 cm ²	20	20
>4 to ≤6 cm ²	10	2
>6 cm ²	0	18
<i>Defect depth</i>		
(n) No defect	20	0
(a) Signal alteration	15	9
(b) Partial-thickness defect	10	9
(c) Full-thickness defect	0	82
<i>Underlying structures</i>		
<i>Subchondral bone defect</i>		
A. no defect	30	52
B. bony defect/ cyst ≤5mm depth	20	20
C. bony defect/ cyst >5mm depth	0	27
<i>Addendum—potential fourth digit</i>		
No defect-associated BME	10	27
E. defect-associated BME	0	73
AMADEUS total score	100	Mean ± SD= 48 ± 24
AMADEUS grade	(0 worst, 100 best)	
Grade I	>75	9
Grade II	>50 and ≤75	48
Grade III	>25 and ≤50	30
Grade IV	≤25	14

BME = bone marrow edema like-lesion; BMI = body mass index.

^aFrequency in the assessed cohort.

Figure 1. The AMADEUS (Area Measurement And DEpth & Underlying Structures) scoring system. The AMADEUS code includes the 3 most important different parameters that describe a focal chondral or an osteochondral lesion. (1) The first digit describes the cartilage defect area (diameter (d_1 , cm) in one plane multiplied with the diameter (d_2 , cm) in the other plane). (2) The second digit describes the cartilage defect morphology/depth (a, b, or c). (3) The third digit describes the integrity of the underlying structures (subchondral bone; A, B, or C) and bone marrow edema-like lesions (BME; E) as an addendum. The points for the subscores sum up to a total score of 100 (best score) to 0 (worst score).

measurements were performed on sagittal and coronal images. For applicability during daily practice areas were categorized in 5 groups: $\leq 1 \text{ cm}^2$ (35 points) $>1 \text{ to } \leq 2 \text{ cm}^2$ (30 points), $>2 \text{ to } \leq 4 \text{ cm}^2$ (20 points), $>4 \text{ to } \leq 6 \text{ cm}^2$ (10 points), $>6 \text{ cm}^2$ (0 points). If no defect is present it equals 40 points.

Defect Depth. The second digit in the AMADEUS code encodes defect depth (Fig. 2). Presence of severe signal alteration of the cartilage at the later cartilage repair site on IM-w images was encoded as "a" (15 points). Partial thickness defects were encoded as "b" (10 points) and full thickness cartilage defects were encoded as "c" (0 points). If no

Figure 2. Examples for each AMADEUS “depth” code. (a) Sagittal IM-w fs image of a patient with a “depth” digit “a” at the lateral tibia plateau, indicating cartilage signal alterations (AMADEUS 2.0aCE; AMADEUS score, 45 points; grade III). (b) Transverse IM-w fs image of a patient with a “depth” digit “b” at the patella, indicating a partial thickness cartilage defect (AMADEUS 0.5bA; AMADEUS score 85 points; grade I). (c) Transverse IM-w fs image of a patient with a “depth” digit “c” at the patella, indicating a full thickness cartilage defect (AMADEUS 0.5cCE; AMADEUS score, 35 points; grade III). w = weighted; IM = intermediate; fs = fat saturated.

Figure 3. Examples for each AMADEUS code for bony defects (coronal IM-w fs images). (A) Patient with a full thickness cartilage defect at the medial femoral condyle. There is no osseous defect (A), but BME (E; “underlying structures” digit AE) (AMADEUS 2.5cAE; AMADEUS score 50 points; grade II). (B) Patient with a full-thickness cartilage defect at the lateral femoral condyle. There is a small osseous defect of <5 mm (B) and BME (E; “underlying structures” digit BE) (AMADEUS 2.7cBE; AMADEUS score 40 points; grade III). (C) Patient with a full-thickness cartilage defect at the medial femoral condyle. There is a large osseous defect of >5 mm (C) and BME (E; “underlying structures” digit CE) (AMADEUS 8.0cCE; AMADEUS score 0 points; grade IV). BME = bone marrow edema-like lesion; w = weighted; IM = intermediate; fs = fat saturated.

defect is present it equals 40 points. All defects with any small area of full thickness defect were encoded as “c,” despite the fact that the defect size (first digit) included the entire defect (also partial thickness areas), which is frequently larger.

Underlying Structures. The third digit in the total AMADEUS code encodes the involvement of the subchondral bone (Fig. 3). If the subchondral lamina was intact and the

subchondral bone did not show any morphological defects it was encoded as “A” (30 points). Presence of a subchondral bony defect and/ or presence of other subchondral pathologies that need to be treated such as subchondral cysts, (well-delineated lesions of fluid equivalent signal directly adjacent to the subchondral plate), ganglia, necrotic tissue or granulation tissue was encoded as “B” (20 points) if the lesion did not exceed 5-mm depth; it was encoded as “C” (0 points) if the lesion did exceed 5-mm depth and

required surgical osseous repair. Additionally, presence of BME, defined as ill-delineated T1-w hypointense and IM-w FS hyperintense signal within the trabecular bone, adjacent to the defect was encoded as “E” if present (0 points; 10 points if no BME was present). In case of presence of BME the digit “E” was added to the digit “A,” “B,” and “C,” respectively.

Total AMADEUS Code, Score, and Grade. The AMADEUS code may be reported by putting together all features, resulting in a 3- or 4-digit code. The sum of all subscores results in the total AMADEUS score, ranging from 0 to 100. A score of 100 represents intact cartilage and bone (no osteochondral defect). A score of 0 represents the worst score for most severe cartilage defect. Based on the total AMADEUS score overall cartilage defect severity was defined additionally as AMADEUS grades I-IV as follows: grade I, >75 points; grade II, >50 and ≤75 points; grade III >25 and ≤50 points; grade IV ≤25 points. The AMADEUS grade gives an estimation of overall defect severity of the osteochondral defect.

Surgical Reports

Operative reports were retrospectively analyzed by means of digital medical records. Defect location was noted. Additionally, repaired defect size reported was noted in order to correlate intraoperative findings with MR imaging defect size.

Statistical Analysis

Statistical processing was performed with SPSS version 17.0 (SPSS, Chicago, IL, USA) (P.M.J.). All tests were performed based on a 0.05 level of significance. Frequencies of subscores in our analyzed cohort were calculated. Means ± SD were calculated for subject characteristics and total AMADEUS scores. For intra- and interobserver reliability of the total AMADEUS score and for continuous variables interclass correlation coefficients (ICC) were calculated.¹³ Intra- and interobserver reliability of the individual categorical features was determined using linear weighted kappa statistics.¹⁴ Furthermore, Pearson correlations and paired *t* tests were calculated for comparisons between defect size measured on MR images and defect size given in the surgical reports.

Results

Subject and Defect Characteristics

MR scans of 44 patients (30 males, 14 females) with a mean ± SD age of 31 ± 10 years at the time of MRI were assessed. There were 22 right knees, and 22 left knees in the analyzed

Table 3. Intra- and Interobserver Agreement for AMADEUS Scores.

	Intraobserver Agreement (95% CI)	Interobserver Agreement (95% CI)
<i>A: ICC scores for continuous variables</i>		
<i>Area measurement</i>		
Absolute defect size (cm ²)	0.92 (0.85-0.96)	0.90 (0.82-0.95)
Score “area measurement”	0.97 (0.94-0.98)	0.94 (0.89-0.97)
<i>Defect depth</i>		
Score “depth”	0.91 (0.83-0.95)	0.63 (0.33-0.80)
<i>Underlying structures</i>		
Score “underlying structures”	0.97 (0.94-0.98)	0.96 (0.92-0.98)
AMADEUS total score	0.97 (0.94-0.98)	0.96 (0.92-0.98)
AMADEUS grade	0.96 (0.92-0.98)	0.93 (0.86-0.96)
<i>B: Linear weighted kappa values for categorical variables</i>		
Area measurement	0.87 (0.78-0.96)	0.76 (0.63-0.89)
Depth	0.82 (0.63-1.0)	0.38 (0.12-0.63)
<i>Underlying structures</i>		
Bony defect	0.90 (0.80-1.0)	0.85 (0.73-0.96)
BME	0.94 (0.83-1.0)	0.82 (0.63-1.0)
AMADEUS grade	0.75 (0.62-0.89)	0.67 (0.50-0.84)

ICC = interclass correlation coefficient. kappa = linear weighted kappa. 95% CI = 95% confidence interval; BME = bone marrow edema-like lesion.

cohort. Cartilage defects were most often located at the medial femoral condyle (18/44), the patella (11/44), and at the lateral femoral condyle (11/44). The defect was located at the trochlea and at the lateral tibia plateau in 2/44 cases each.

AMADEUS Scores

The frequency for all AMADEUS digits, total score and gradings are given in **Table 2**. Overall, the majority of the reproducibility measures reached perfect agreement for continuous variables (ICC) and for categorical variables (linear weighted kappa) (**Table 3**).¹⁴ The only exemption with inferior agreement was the interobserver agreement for defect depth (second digit). **Figs. 2-4** demonstrate MR imaging examples for the different AMADEUS features with its grades and subscores.

Area Measurement. The mean defect area was 2.8 ± 2.6 cm² (range 0.2-9.9 cm²). The most frequent sizes were ≤1 cm² and ≤2 cm² with 13 of 44 cases each. However, also large-sized cartilage defects with defect areas greater than 6 cm² (8/44) were found in the assessed cohort. Using the continuous numeric scale with absolute area measurements, ICC

Figure 4. Coronal IM-w fs magnetic resonance images of patients with small full thickness cartilage defects and without adjacent bony defects. **(A)** Patient with BME and an “underlying structures” digit AE (AMADEUS 0.8cAE; AMADEUS score 65 points; grade II). **(B)** Patient without BME and an “underlying structures” digit A (AMADEUS 1.0cA; AMADEUS score 75 points; grade I). BME = bone marrow edema-like lesion; w = weighted; IM = intermediate; fs = fat saturated.

scores were 0.92 (95% confidence interval [CI], 0.85-0.96) and 0.91 (95% CI, 0.90-0.95) for intra- and interobserver agreement, respectively.

Defect Depth

Most patients that received cartilage repair surgery presented with full thickness cartilage defects. Observer 1 scored 36 of 44 defects as full-thickness defects (grade c; $n = 4$ partial-thickness defects, grade b; $n = 4$ signal alterations, grade a). Observer 2 scored 30 of 44 defects as full-thickness defects (grade c; $n = 11$ partial thickness defects, grade b; $n = 3$ signal alterations, grade a). According to the definition of Landis and Koch,¹⁴ kappa values were almost perfect for intra-observer agreement (0.82; 95%CI, 0.63-1.0). However, interobserver agreement was only fair (0.38; 95%CI, 0.12-0.63). ICC scores were 0.91 (95%CI, 0.83-0.95) for intraobserver agreement and 0.63 (95%CI, 0.33-0.80) for interobserver agreement.

Underlying Structures. Pure chondral defects without any involvement of the subchondral bone (neither defect nor BME) were found in 8 of 44 cases (grade A). Osseous defects or subchondral cystic changes were found in nearly half the cohort (21/44 cases). Of the defects reported, more than half showed a defect depth of more than 5 mm. BMEs were found in 32 of 44 cases. In case of grade C, osseous defects (>5 mm), 80% of patients had additional BMEs. Kappa values for osseous defects were 0.90 (95%CI, 0.80-1.0) for intraobserver agreement and 0.85 (95%CI, 0.73-0.96) for interobserver agreement. Kappa values for the

presence of additional BME were 0.94 (95%CI, 0.83-1.0) for intraobserver agreement and 0.82 (95%CI, 0.63-1.0) for interobserver agreement.

Total AMADEUS Score

The AMADEUS score may be reported by putting together all components, for example, AMADEUS 2.0aCE, AMADEUS 0.5bA, AMADEUS 0.5cCE, and so on. (**Figs. 1-4**). The mean total AMADEUS score was 48 ± 24 , (range, 0-85). AMADEUS grades II and III were the most frequent severity grades with 21 of 44 and 13 of 44 patients, respectively. Only few patients received surgery for less severe cartilage defects (grade I, $n = 4$) or extended severe cartilage defects (grade IV, $n = 6$). Also for the total AMADEUS score, ICC scores were excellent (intraobserver agreement, 0.97 [95% CI, 0.94-0.98]; interobserver agreement, 0.96 [95% CI, 0.92-0.98]). Kappa values for the AMADEUS grade were 0.75 (95% CI, 0.62-0.89) and 0.67 (95% CI, 0.50-0.84) for intra- and interobserver agreement, respectively.

Surgical Findings

The mean defect area reported in surgical reports was 2.4 ± 2.6 cm² (range 0.6-10.0 cm²), which was not significantly different from the defect area measured on MR images (paired t test, $P = 0.54$). The Pearson correlation was 0.71 (95%CI, 0.49-0.93; $P < 0.001$). The ICC score was 0.83 (95% CI, 0.69-0.91).

Discussion

While the widely applied MOCART score is used for post-operative assessment after cartilage repair surgery, the presented AMADEUS score was designed to represent an intuitive, easily applicable and reliable MR imaging score for assessment of osteochondral defects at the knee prior to possible surgery. Its application may improve clinical communication between patients, radiologists and orthopedic surgeons. It may also be helpful with respect to systematical multicenter research approaches using, for example, patient registries. The AMADEUS score is a 3-part, 12-item scoring system leading to an AMADEUS code, an AMADEUS score (100 [no defect] through 0 [severe defect] points) and additionally to an AMADEUS grade, using a 4-grade severity classification system. It was designed in a simple way in order to assess the most important components of osteochondral defects (size, depth, subchondral bone) quickly and independently of MR scanners or MR imaging parameters. For nearly all features, a relatively high intra- and interobserver reliability was confirmed. Thus, it can be considered to have clinical relevance not only in MR-assisted cartilage repair studies but also in the clinical routine.

To date, the most commonly used score for quantification of existing cartilage defects is ICRS score.⁸ It is related to the traditional Outerbridge classification system.⁷ The ICRS score has been shown to be well accepted by users. However, the score was primarily developed for macroscopic evaluation of cartilage defects. It was transferred to MR image evaluation, since no other appropriate score existed so far. The limitations of the ICRS score are the missing information on defect size, and the missing subscores for subchondral bone involvement. Within the ICRS score, any involvement of the subchondral bone results in a score of 4 (worst score; grade 4B if it involves the entire defect diameter, otherwise grade 4A). Using the ICRS score, there is no difference between BME or small or large bony defects. However, in particular large defect may influence treatment decisions and strategies.

In 1987, Yulish *et al.*¹⁰ already transferred arthroscopic findings to an MR score for chondromalacia patellae. This preoperative MR score is similar to the ICRS score and also considers cartilage signal abnormalities as stage 1 (such as the Outerbridge score) and does not include ICRS grade 4 (no scoring of involvement of subchondral bone). Recently, the quantitative CaLS system was developed monitoring progression of morphological cartilage defects and was described to show an improved detection rate for change over time.⁹ By including defect diameter, MR image slice thickness, defect depth and a shape factor, the score gives a good quantitative measure of the cartilage defect volume, which is sensitive for cartilage volume loss over time. However, this score does not aim to assess defects prior to cartilage repair surgery. Resulting in a single volume measure, specific characteristics of the chondral defect are not obvious for the clinician. Since not aiming for preoperative assessment of osteochondral defects, the CaLS score does not categorize defect size according to cartilage repair guidelines and does not assess subchondral bone. There are other knee MR scores that also implement cartilage defect evaluation, such as WORMS,⁵ MOAKS,¹⁵ BLOKS,⁶ or KOSS.¹⁶ All these MR scores have their advantages, but they aim to assess osteoarthritic changes and are not designed to assess focal osteochondral defects. The new AMADEUS score combines the preoperatively and clinically essential features of being MRI-based and of implementing defect size and subchondral bone, which are of major importance regarding treatment decisions.

The MOCART classification is one of the most frequently used MR score for postoperative cartilage repair tissue evaluation.^{17,18} The MOCART score is a 9-part and 29-item scoring system, also resulting in a final cartilage repair tissue score between 0 and 100 points; 0 points represent the worst imaginable score, 100 points represent the best imaginable score.

Inspired by the MOCART and ICRS scores, we chose 0- to 100-point scoring and 4-grade grading system

for realization of the AMADEUS, in order to allow easy comparisons to those scores. The parameters we included are the most essential parameters of a joint surface defect, which need to be taken into account if cartilage repair surgery is considered. Reading the AMADEUS code allows to imagine the osteochondral defect seen on MRI, which helps decision making regarding indication of different cartilage repair procedures. The parameters cartilage defect size, defect depth and subchondral involvement need to be evaluated to indicate cartilage repair surgery. Also, these parameters influence the decision on the cartilage repair technique and help planning of the surgery. The authors are aware of the fact that a score of 100 equals to “no osteochondral defect,” which may sound contradictory to a “cartilage defect scoring system.” However, a perfect score of 100 was implemented on purpose to represent the optimum situation, which may be achieved by prevention strategies or treatments. Also, a “perfect cartilage” score of 100 was chosen to allow comparability with the postoperative MOCART score, in which “perfect cartilage” is also represented by a score of 100.

In contrast to most other cartilage scoring systems, in AMADEUS score the parameter defect size was included, since the choice of cartilage repair techniques may change for example from microfracturing, which is commonly used for small cartilage defects to osteochondral transplantation or autologous chondrocyte implantation.¹⁹⁻²² For large defects, autologous chondrocyte implantation (ACI) is currently the cartilage repair technique of choice, although other techniques such as allografts or the Mega-OATS procedure exist.²³⁻²⁵ Defect morphology/ depth was included, since first, indication for cartilage repair surgery may be made to a different time point if there is no full-thickness defect—but second, progression of defect morphology/ depth over time may be detected by implementation of this parameter.⁹ Subchondral bone involvement is critical regarding the decision of the best treatment strategy. In contrast to other scores, it is unique for the new AMADEUS score that it differentiates between no, superficial and deep (>5-mm depth) bony lesions; the latter potentially requiring surgery/osteochondral transplantation. It is most useful to decide preoperatively whether bone replacement with either cancellous grafts or osteochondral transplantation is required. If the subchondral bone is involved, the applied cartilage repair technique may switch, for example, from ACI or microfracturing to osteochondral transplantation or ACI plus a bone substitution graft.^{26,27} Therefore, it seemed indispensable to implement this parameter in a score that aims to describe osteochondral defects, possibly prior to cartilage repair surgery.

In our study, comparing defect sizes measured on MRI correlated significantly with intraoperative defect sizes and did not show significant differences. However, the intraoperative cartilage defect size was slightly (non-significantly)

smaller than the defect size measured on MRI (2.4 vs. 2.8 cm²). This is in contrast to the study of Campbell *et al.*²⁸ who reported larger defect sized for intraoperative measurements than for MR measurements (3.0 vs. 1.0 cm²). In our study, the difference was far smaller and the agreement was almost perfect. This confirms our assumption, that the entire defect area should be measured for the first digit, including the partial thickness parts, since these will also be considered pathological during surgery and will most likely be debrided.

In the assessed cohort, most patients presented full thickness defects. This was expected, since all patients received subsequent cartilage repair surgery. However, reader 1 scored 36 defects as full thickness defects, reader 2 only scored 30 defects as full thickness defects. It may be due to the fact that we aimed to score defects as full thickness, even if only a small part is full thickness and the remaining defect is partial thickness and if the edges were not sharp. In the discrepant cases, the full-thickness part was tiny. Therefore, scoring seemed more challenging and interobserver agreement was inferior for this feature (fair). However, we wanted to keep the score simple and therefore did not implement another parameter. In case of surgical treatment, the entire defect is treated independent on the full thickness percentage. In contrast to the ICRS score signal alteration is considered separately, accounting for its importance as explained above. As expected, in our cohort signal alteration was only scored in 4 of 44 cases; this represents clinical practice. The parameter describing involvement of the subchondral bone showed good reproducibility. There were only minor differences in case of tiny defects, which are clinically not relevant and do not influence the treatment decision. We implemented cystic changes in the bony defect, since these also represent an indication for bone replacement.

There are some limitations of this study. First, the study design was retrospective. The present study is the first study, which aims to develop the AMADEUS score and to validate its reproducibility. Further prospective investigations are needed to correlate the score with clinical symptoms, surgical indication, surgical treatment, follow-up, and outcomes. For designing and evaluating the score, we only included patients that received cartilage repair surgery in the following. However, application may also be useful in patients that are treated conservatively and do not receive surgery. The advantage of this inclusion criteria was the ability to correlate MR findings with intraoperative findings. The evaluated MR images represent a cross-sectional sample orthopedic surgeons are routinely confronted with, and based on which cartilage repair surgery was indicated. Aiming clinical implementation of AMADEUS scores, this selection of MR images may represent an ideal and realistic scenario. Almost perfect agreement despite varying MR image quality and sequences, confirms that the AMADEUS score may be universally applicable and reliable. In AMADEUS score, we did not differentiate between partial

cartilage defects of >50% of cartilage thickness and partial cartilage defects of >50% of cartilage thickness. Based on our experience, in clinical practice in particular at the femoral condyles it is challenging to decide between these 2 options and we aimed to keep the AMADEUS score meaningful but simple. The AMADEUS code includes the defect size as the first digit. It gives a good estimate of the area treated. However, it does not consider the shape of the lesion such as round versus linear. While most lesions are of oval shape, linear defects may be underrepresented by the score. Last, the thresholds, the weighting and scoring and the grading of AMADEUS score is based on the current literature and clinical experience. Clinical outcomes may define which parameters are most relevant.

In summary, the AMADEUS scoring system represents the first knee MR imaging score for focal osteochondral defects that may subsequently be treated with cartilage repair surgery. The AMADEUS score may be applied preoperatively, while the MOCART score is applied postoperatively in patients that received cartilage repair surgery. This easily applicable and highly reproducible score assesses the most important defect characteristics including size, morphology and involvement of the subchondral bone. The AMADEUS grading and classification system provides (1) a 3-digit AMADEUS code, which describes these main characteristics of the osteochondral defect in order to allow treatment planning; (2) a final AMADEUS score, which may be used in clinical studies, allow follow-up evaluation and comparisons with other clinical and follow-up parameters such as the MOCART score; and (3) an AMADEUS grade, which estimates overall defect severity. Applying this systematic classification system may homogenize reporting of articular joint surface defects prior to surgery for better communication between physicians in clinical practice and for better inter- and intrastudy comparisons for research purposes.

Authors' Note

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Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Ethical Approval

The study was approved by the local institutional review board (Klinikum rechts der Isar, Technische Universität München, Munich, Germany).

Informed Consent

The requirement for informed consent was waived.

Trial Registration

Not applicable.

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