Original Article

Spectroscopic Quantitative Measurement of the Cartilage Surface using Arthroscopy Correlates with a Conventional Macroscopic Grading System

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Purpose: To quantify the cartilage surface profile visualized during arthroscopic surgery and examine its clinical utility by comparing the results of quantitative measurements with a conventional grading system. **Methods:** Fifty consecutive patients diagnosed with knee osteoarthritis and who underwent arthroscopic surgery were included in this study. A 4 K camera system was used, and the cartilage surface profile was visualized using the augmented reality imaging program. The highlighted image was displayed in 2 colors: black (the worn cartilage area) and green (the part where the cartilage thickness was maintained). The percentage of the green area was calculated using ImageJ and used as an index of cartilage degeneration. The quantitative value was statistically compared with the International Cartilage Repair Society (ICRS) grade as a conventional macroscopic evaluation. **Results:** In the quantitative measurement, the median percentage of the green area was 60.7 at ICRS grades 0 and 1 (interquartile range [IQR], 67.3-51.0), 47.2 at grade 2 (IQR, 54.1-39.2), 36.5 at grade 3 (IQR, 43.2-30.4), and 34.0 at grade 4 (IQR, 38.5-29.3). There was a significant difference between the macroscopic grades, except for Grades 3 and 4. There was a significant negative correlation between macroscopic evaluation and quantitative measurement ($r = -0.672$, $P < .001$). **Conclusions:** The quantitative measurement of the cartilage surface profile using the spectroscopic absorption technique was significantly correlated with the conventional macroscopic grading system and demonstrated fair to good inter-rater and intra-rater reliabilities. **Level of Evidence:** Level II, diagnostic (prospective cohort study).

Osteoarthritis (OA) of the knee is degenerative disease of cartilage, and there is degradation of proteoglycans followed by degradation of type 2 collagen in early-stage OA. As a result, the water content increases, and softening occurs. As it progresses further, morphological changes such as fibrillation and erosion of the cartilage surface occur.[1,2]

Diagnostic tools for knee OA include radiography, magnetic resonance imaging (MRI), computed tomography (CT), and arthroscopy. These have advantages and disadvantages regarding convenience, invasiveness, medical economy, and the stage of OA evaluated. Arthroscopy is the gold-standard procedure for in vivo articular cartilage evaluation. Although this is the most invasive technique compared to other examinations, the most favorable advantage is that surgeons can see the cartilage directly. Additionally, the softness or instability of cartilage lesions can be determined by probing.

The Outerbridge classification[3,4] or International Cartilage Repair Society (ICRS) classification[5] focuses on these macroscopic changes. These classification systems are widely used to evaluate cartilage degeneration or traumatic cartilage injury. However, it has been suggested that intrarater and inter-rater reliabilities in arthroscopic classification are not high.[6]

Although useful devices and techniques have made impressive advances in arthroscopic surgery for knee

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disorders, quantitative evaluation of degenerative cartilage is lacking. Johansson et al.[7] applied optical reflection spectroscopy technique to arthroscopic surgery to measure cartilage thickness. Optical reflection spectroscopy is based on the fact that cartilage and subchondral bone have completely different absorption characteristics when white light is incident onto the cartilage surface, and it can estimate cartilage thickness through the reflectance spectrum taken from the joint surface. In recent years, this technique has been applied in clinical settings, and it was reported that this technique was suitable for arthroscopic diagnosis.[8] The arthroscopic system can highlight and visualize the articular surface profile in real time; however, the degree of cartilage degeneration is unknown in this arthroscopic system. If the quantitative evaluation of cartilage degeneration can be performed easily, it also provides valuable information from the viewpoint of understanding the patient's pathological condition. Furthermore, it provides surgeons with essential information to determine the therapeutic effect.

The purpose of this study was to quantify the cartilage surface profile visualized during arthroscopic surgery and examine its clinical utility by comparing the results of quantitative measurements with the conventional grading system. We hypothesized that the quantitative analysis of cartilage surface profiles correlates with the traditional arthroscopic cartilage classification.

Material and Methods

Fifty consecutive patients diagnosed with medial early or definitive knee OA and who underwent arthroscopy during the surgery of medial opening wedge high tibial osteotomy in our department between 2018 and 2020 were included in this study (Table 1). This study was approved by the institutional review board.

Two orthopaedic surgeons (S.S. and E.S.) performed arthroscopic surgeries with 25 cases each. A 4 K camera system (Synergy UHD4TM; Arthrex, Naples, FL) was used for all the surgeries. White balance was adjusted using white surgical gauze at the beginning of the surgery. A pneumatic tourniquet was used in all cases and was placed on the patient's proximal thigh. The cartilage surface was observed from the lateral infrapatellar portal using a 30° angle arthroscope in a bloodless environment.

The BioOptico (Arthrex) augmented-reality imaging program mode was used to analyze the articular surface profile quantitatively. This mode is based on the principle that light absorption differs between cartilage and subchondral bone and spectroscopically evaluates the thickness of the cartilage.[7] Arthroscopy was performed with the knee flexed at 90°, but the flexion angle and the scope rotation were adjusted so that the light emitted from the arthroscope shone on the cartilage surface as vertically as possible during surgery. The data obtained from the augmented-reality imaging program is highlighted in real time. The highlighted image is displayed in 2 colors, black and green. The concave part (the part where the cartilage is worn) and the part with relatively thick cartilage compared to the surrounding part in the evaluation area are highlighted in black and green, respectively. The cartilage surface (where the macroscopic assessment was performed) was captured at 4 points (medial femoral condyle, medial tibial plateau, lateral femoral condyle, and lateral tibial plateau), and the cartilage surface profile was measured using Image J (National Institutes of Health, Bethesda, MD). The central part of the highlighted area was extracted with the largest square. The color image split an RGB image (red, green, and blue) into three 8-bit grayscale images containing the original image's red, green, and blue components. The auto thresholding was performed in the grayscale image containing the green component using Image J's IsoData method. The IsoData method divided the image into object and background by taking an initial threshold. Next, the averages of the pixels below and above the threshold were computed. The threshold was incremented, and this process was repeated until the threshold was larger than the composite average.[9] After the green part was distinguished from the black part by the auto thresholding procedure, the percentage of the total area of the green part was measured (Fig 1).

Table 1. Demographic Data of Subjects

Age (yr)	60.0 ± 8.5
Sex	
Male	16
Female	34
Body mass index	25.0 ± 2.9
Evaluation side	
Right	24
Left	26

The severity of cartilage degeneration at the medial femoral condyle, medial tibial plateau, lateral femoral condyle, and lateral tibial plateau was macroscopically evaluated using the ICRS grading system.[5] In this study, grading was performed without probing to evaluate the cartilage surface profile, and each evaluation site was divided into 4 groups (grades 0-1, 2, 3, and 4).

The results of the quantitative analysis were tested using the Shapiro-Wilk test, and a normal distribution was not observed ($P < .001$). The correlation between the macroscopic evaluation and quantitative analysis was examined using Spearman's rank correlation coefficient. The differences in the results of the quantitative analysis for each grade of macroscopic evaluation were compared using the Kruskal-Wallis test and the Dunn-Bonferroni post hoc test. To achieve 80% statistical power with an alpha of 0.05, power analysis revealed that a minimum of 18 values would be

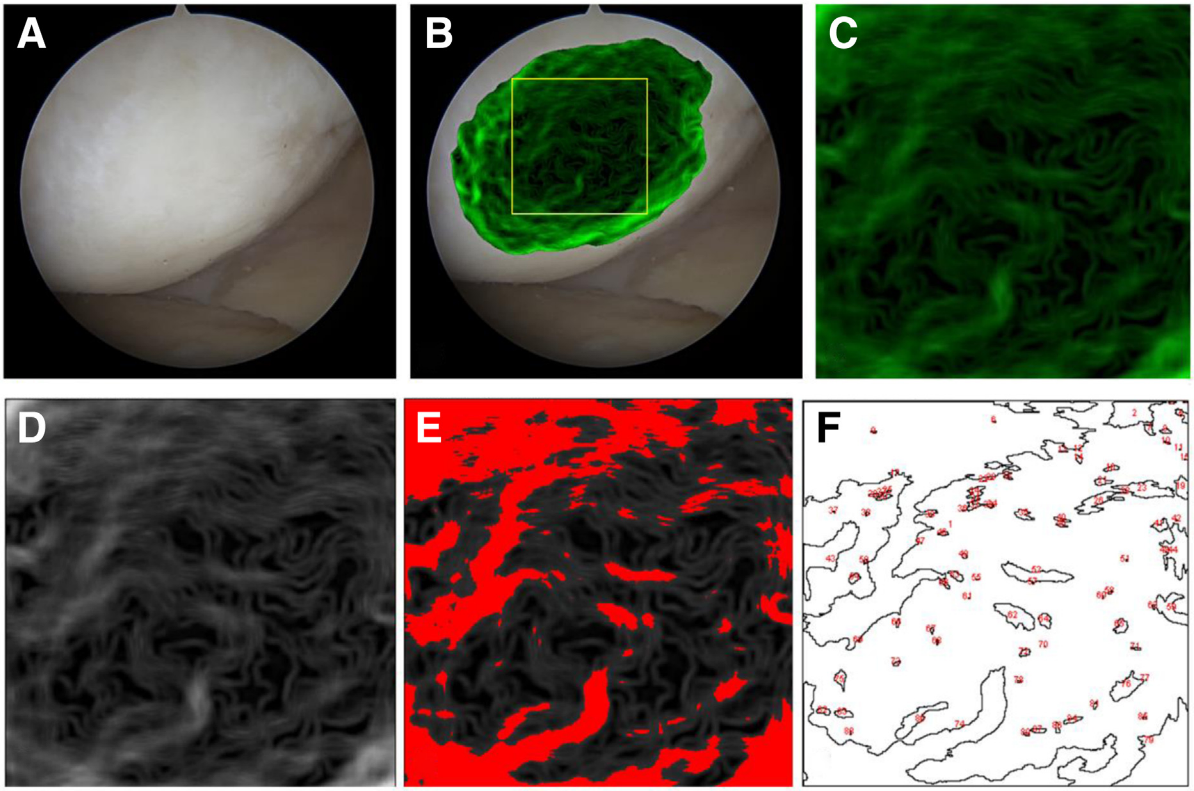

Fig 1. The quantitative measurement of cartilage surface profile. (A) Medial femoral condyle of the right knee from the lateral infrapatellar portal. (B, C) The cartilage surface profile was visualized, and the central part (yellow square) was extracted from the captured still image. (D) The color image split an RGB image (red, green, and blue) into 8-bit grayscale images containing the original image's red, green, and blue components. (E) The auto thresholding was performed in the grayscale image containing green components divided into objects and background. (F) The percentage of the total area of the green part was measured.

required to detect the correlation between the results of the macroscopic evaluation and quantitative analysis. In this analysis, the calculated effect size was 1.000. All statistical analyses were performed using SPSS version 27.0 (IBM Corp., Armonk, NY), and a P value <.05 was considered statistically significant.

Results

In the macroscopic evaluation, grades 0 and 1 were observed at 68 sites, grade 2 at 46 sites, grade 3 at 54 sites, and grade 4 at 32 sites (Table 2). In the quantitative measurement, the median percentage of the green area was 60.7 at grades 0 and 1 (interquartile range [IQR], 67.3-51.0), 47.2 at grade 2 (IQR, 54.1-39.2), 36.5 at grade 3 (IQR, 43.2-30.4), and 34.0 at grade 4 (IQR, 38.5-29.3). There was a significant difference in the macroscopic grades, except between grades 3 and 4 (Fig 2). There was a significant negative correlation between the macroscopic evaluation and quantitative measurement ($r = -0.672$, $P < .001$).

The intra-rater reliability was 0.95 (95% confidence interval [CI], 0.90-0.97; $P < .001$) in the macroscopic evaluation, and 0.84 (95% CI, 0.71-0.91; $P < .001$) in the quantitative measurement. The inter-rater reliability was 0.84 (95% CI, 0.58-0.92; $P < .001$) in the

Table 2. The Results of the Quantitative and Macroscopic Evaluation

	International Cartilage Repair Society classification			
	Grade 0 and 1	Grade 2	Grade 3	Grade 4
Medial femoral condyle	4	4	21	21
Medial tibial plateau	1	19	19	11
Lateral femoral condyle	48	2	0	0
Lateral tibial plateau	15	21	14	0
Percentage of green area (IQR)	60.7 (67.3 - 51.0)	47.2 (54.1 - 39.2)	36.5 (43.2 - 30.4)	34.0 (38.5 - 29.3)

IQR, interquartile range.

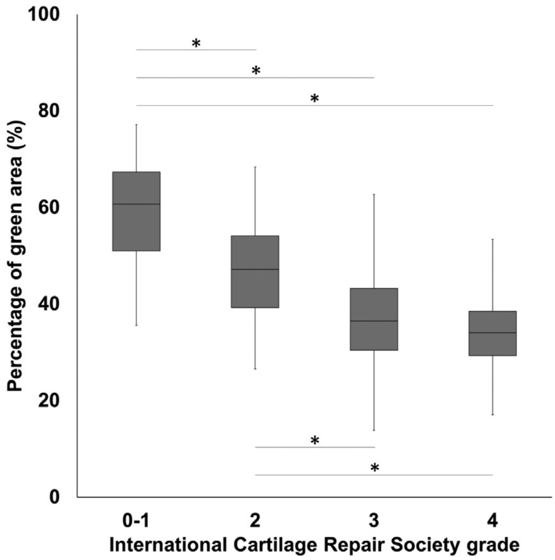

Fig 2. The quantitative measurement results in each International Cartilage Repair Society grade (*$P < .05$). There was a significant difference except between grades 3 and 4.

macroscopic evaluation, and 0.77 (95% CI, 0.68-0.83) in the quantitative measurement.

Discussion

The most important finding of this study was that the intraoperative arthroscopic articular cartilage surface profile evaluation using the spectroscopic absorption technique demonstrated a significant correlation with the conventional macroscopic grading system. The diagnostic tools for knee OA include radiography, CT, MRI, and arthroscopy. Radiography is the most frequently used conventional imaging technique. Although the Kellgren-Lawrence grade is a typical radiographic grading system, it is limited to diagnosing relatively progressive knee OA because the criteria for diagnosis are joint space narrowing or osteophyte formation. Conventionally, CT has been used to evaluate the subchondral bone and osteophyte formation. In recent years, contrast-enhanced CT (CECT) has made it possible to quantify cartilage and subchondral bone thickness.[10,11] Proteoglycan (PG), the main component of the cartilage matrix, becomes negatively charged. In CECT examination, the loss of negatively charged PGs can be detected using an anionic contrast agent. Myller et al.[10] reported that the results of the CECT evaluation were significantly correlated with the ICRS grade.

MRI is a noninvasive examination in terms of radiation exposure compared to radiography or CT. MRI can detect changes in the articular cartilage and the meniscus, ligament, or other soft tissue. Several new MRI techniques have been developed recently. For example, the $T_{1\rho}$ mapping technique, which can detect the decrease in PG content from the extracellular matrix[12-14], and the T2 mapping technique, which can detect changes in collagen alignment or water content,[15,16] are useful for quantitative analysis of early articular cartilage degeneration. MRI is one of the most objective, reproducible, and noninvasive evaluation for cartilage degeneration. However, from the viewpoint of evaluating the outcome of surgical treatment, postoperative evaluation may be affected by metal artifacts.[17]

Although arthroscopy is the only direct evaluation method for cartilage profiles, it is the most invasive procedure compared to other imaging techniques. In recent years, regenerative medicine for cartilage injury or degenerative cartilage has been developed, and the frequency of arthroscopic cartilage evaluation by second-look arthroscopy to determine therapeutic efficacy might increase. However, in arthroscopic evaluation, only the elasticity by probing and macroscopic properties of the cartilage can be evaluated using a grading system, and quantitative evaluation is difficult.

Johansson et al.[7] evaluated the accuracy of cartilage thickness measurements using spectroscopic measurements in an arthroscopic camera. They measured the human knee cartilage thickness obtained from total knee arthroplasty patients by ex vivo arthroscopy and compared thickness values using 3 methods (needle penetration, spiral CT, and geometric measurement). They concluded that the lowest mean errors in the range of 0.28 to 0.30 mm were expected. Recently, this technology has been applied in clinical setting. Makovicka et al.[8] reported the usefulness of clinically visualizing cartilage thickness using the same device as in this study; however, they did not quantify the extent of degeneration.

This study revealed a significant correlation between the quantitative values and the results of the macroscopic grading system. In addition, when comparing the quantitative values between macroscopic grades, the difference was apparent in the lower-grade groups. Therefore this quantitative measurement may be useful for detecting early degenerative changes or minor cartilage damage. Considering this result, the quantitative values from this system might be affected by the amount of cartilage remaining in the case of advanced arthritis, whereas the irregularity of the surface became severe according to the grade progression. Clinically applying the results of this study may determine the therapeutic efficacy of around knee osteotomy in patients with relatively early OA or regenerative therapy.

In this study, the inter-rater reliability was 0.84 (95% CI, 0.58-0.92; $P < .001$) in the macroscopic grading system was 0.77 (95% CI, 0.68-0.83; $P < .001$) in the quantitative measurement. The previous literature demonstrated low inter-rater reliability of macroscopic grading system. Brismar et al.[6] examined the reliability of the macroscopic evaluation of knee OA using videotaped arthroscopies, and the inter-rater reliability was 0.43 to 0.49, and the inter-rater reliability was 0.42 to 0.66 in the arthroscopic classification. In this study, it seemed that relatively high reliability was obtained because 2 experienced orthopaedic knee surgeons evaluated it.

In contrast, quantitative CT and MRI have the advantages of high objectiveness and reproducibility. Gupta et al.[12] and Waldenmeier et al.[16] reported that inter-rater and intrarater reliability of MRI assessment was >0.9, indicating excellent reproducibility. However, the accuracy of these quantitative imaging technique in assessing the postoperative outcome of various knee surgeries, including those with implants, is unclear. Arthroscopic evaluation has no risk of being affected by metal artifacts, and this is one of the advantages superior to conventional quantitative imaging evaluation. Furthermore, regenerative medicine for cartilage injury and osteoarthritis has been developed in recent years. There is a possibility that the therapeutic efficacy cannot be determined only by the grading system based on the macroscopic assessment that has been conventionally used. Although this study demonstrated that the reliability of the quantitative measurement of the cartilage surface profile was slightly inferior to that of conventional macroscopic assessment, it was useful in quantifying cartilage degeneration.

Limitations

A limitation of this study was that the measured quantitative value might change depending on the angle at which the light of the arthroscope hits the cartilage surface. Therefore there is a risk that the results will vary depending on the location of the created portal. In addition, most subjects were patients with medial knee OA, and quantitative measurements were performed only from the lateral infrapatellar portal. Theoretically, although it is desirable to shine light perpendicularly to the cartilage surface, evaluating all lesions in a clinical setting is impossible. To standardize the procedure, quantitative and macroscopic evaluations were limited to those within the observable range from the lateral infrapatellar portal in this study. The effect of portal location on quantitative measurement was unclear from the results of this study; however, it seemed that it is important to shine light from the same portal at the same angle as much as possible when comparing results for the same case (i.e., assessment of therapeutic efficacy).

Second, it is difficult to evaluate cases with extensive cartilage defects because this system visualizes the shape of the cartilage surface. There were individual differences in the amount of cartilage remaining or the profile of the remaining cartilage in grade 4 cases. In the quantitative measurement in this study, the remaining cartilage around the cartilage defect was measured in patients with extensive cartilage defects. This was considered the reason there was no significant difference between the results of grades 3 and 4 in the quantitative measurement.

Third, it is unclear how the data of this study related to the results of established conventional imaging technique such as CT and MRI. Unfortunately, it was not possible to perform these quantitative image evaluations in this series. In the future, if the relationship between quantitative arthroscopic evaluation and quantitative image evaluation is clarified, the true usefulness of this device may be established.

Fourth, the data for the patellofemoral joint could not be presented in this study. Because this system needs to shine a light on the evaluation area as vertically as possible, a 30° angle arthroscope was not possible to highlight the degenerative area in some cases. To assess the patellofemoral joint, it may be necessary to use a 70° arthroscope or to consider portal position.

Conclusion

The quantitative measurement of the cartilage surface profile using the spectroscopic absorption technique was significantly correlated with the conventional macroscopic grading system and demonstrated fair to good inter-rater and intrarater reliabilities.

References

1. Buckwalter JA, Mankin HJ. Articular cartilage: Degeneration and osteoarthritis, repair, regeneration, and transplantation. *Instr Course Lect* 1998;47:487-504.
2. Dijkgraaf LC, de Bont LG, Boering G, Liem RS. The structure, biochemistry, and metabolism of osteoarthritic cartilage: A review of the literature. *J Oral Maxillofac Surg* 1995;53:1182-1192.
3. Outerbridge RE. The etiology of chondromalacia patellae. *J Bone Joint Surg Br* 1961;43-B:752-757.
4. Cameron ML, Briggs KK, Steadman JR. Reproducibility and reliability of the outerbridge classification for grading chondral lesions of the knee arthroscopically. *Am J Sports Med* 2003;31:83-86.
5. Brittberg M, Winalski CS. Evaluation of cartilage injuries and repair. *J Bone Joint Surg Am* 2003;85-A:58-69 (suppl 2).
6. Brismar BH, Wredmark T, Movin T, Leandersson J, Svensson O. Observer reliability in the arthroscopic classification of osteoarthritis of the knee. *J Bone Joint Surg Br* 2002;84:42-47.
7. Johansson A, Kuiper JH, Sundqvist T, et al. Spectroscopic measurement of cartilage thickness in arthroscopy: Ex vivo validation in human knee condyles. *Arthroscopy* 2012;28(10):1513-1523.
8. Makovicka JL, Patel KA, Hassebrock JD, Hartigan DE, Wong M, Chhabra A. Arthroscopic evaluation of knee cartilage using optical reflection spectroscopy. *Arthrosc Tech* 2019;8(4):e399-e405.

9. Ridler TW, Calvard S. Picture thresholding using an iterative selection method. *IEEE Trans Syst Man Cybern* 1978;8:630-632.
10. Myller KA, Turunen MJ, Honkanen JT, et al. In vivo contrast-enhanced cone beam CT provides quantitative information on articular cartilage and subchondral bone. *Ann Biomed Eng* 2017;45:811-818.
11. Kokkonen HT, Mäkelä J, Kulmala KA, et al. Computed tomography detects changes in contrast agent diffusion after collagen cross-linking typical to natural aging of articular cartilage. *Osteoarthr Cartil* 2011;19: 1190-1198.
12. Gupta R, Virayavanich W, Kuo D, et al. MR t(1)ρ quantification of cartilage focal lesions in acutely injured knees: correlation with arthroscopic evaluation. *Magn Reson Imaging* 2014;32:1290-1296.
13. Wang L, Regatte RR. $T_1\rho$ MRI of human musculoskeletal system. *J Magn Reson Imaging* 2015;41:586-600.
14. Wheaton AJ, Casey FL, Gougoutas AJ, et al. Correlation of T1rho with fixed charge density in cartilage. *J Magn Reson Imaging* 2004;20:519-525.
15. Nieminen MT, Rieppo J, Töyräs J, et al. T2 relaxation reveals spatial collagen architecture in articular cartilage: A comparative quantitative MRI and polarized light microscopic study. *Magn Reson Med* 2001;46:487-493.
16. Waldenmeier L, Evers C, Uder M, et al. Using cartilage MRI T2-mapping to analyze early cartilage degeneration in the knee joint of young professional soccer players. *Cartilage* 2019;10:288-298.
17. van der Bruggen W, Hirschmann MT, Strobel K, et al. SPECT/CT in the postoperative painful knee. *Semin Nucl Med* 2018;48:439-453.