Osteoarthritis and Cartilage 25 (2017) 790–798

Osteoarthritis and Cartilage

Multimodality scoring of chondral injuries in the equine fetlock joint *ex vivo*

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ARTICLE INFO

Article history:
Received 16 May 2016
Accepted 1 December 2016

Keywords:
Cartilage
Reproducibility
Reliability
Injury
Scoring

SUMMARY

Objective: We investigate the potential of a prototype multimodality arthroscope, combining ultrasound, optical coherence tomography (OCT) and arthroscopic indentation device, for assessing cartilage lesions, and compare the reliability of this approach with conventional arthroscopic scoring *ex vivo*.

Design: Areas of interest (AIs, $N = 43$) were selected from equine fetlock joints ($N = 5$). Blind-coded AIs were independently scored by two equine surgeons employing International Cartilage Repair Society (ICRS) scoring system via conventional arthroscope and multimodality arthroscope, in which high-frequency ultrasound and OCT catheters were attached to an arthroscopic indentation device. In addition, cartilage stiffness was measured with the indentation device, and lesions in OCT images scored using custom-made automated software. Measurements and scorings were performed twice in two separate rounds. Finally, the scores were compared to histological ICRS scores.

Results: OCT and arthroscopic examinations showed the highest average agreements (55.2%) between the scoring by surgeons and histology scores, whereas ultrasound had the lowest (50.6%). Average intraobserver agreements of surgeons and interobserver agreements between rounds were, respectively, for conventional arthroscope (68.6%, 69.8%), ultrasound (68.6%, 68.6%), OCT (65.1%, 61.7%) and automated software (65.1%, 59.3%).

Conclusions: OCT imaging supplemented with the automated software provided the most reliable lesion scoring. However, limited penetration depth of light limits the clinical potential of OCT in assessing human cartilage thickness; thus, the combination of OCT and ultrasound could be optimal for reliable diagnostics. Present findings suggest imaging and quantitatively analyzing the entire articular surface to eliminate surgeon-related variation in the selection of the most severe lesion to be scored.

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Introduction

Evaluation of articular cartilage injuries by traditional imaging methods, such as radiography and magnetic resonance imaging, has been shown to correlate poorly with an arthroscopic examination[1–4]. Hence, decision on the optimal treatment is often based on arthroscopic findings during the surgery. Several scoring systems have been proposed for the evaluation of cartilage lesions in arthroscopy, including International Cartilage Repair Society –

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http://dx.doi.org/10.1016/j.joca.2016.12.007
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ICRS[5], Outerbridge[6], and French arthroscopic society – SFA[7]. However, the validity of these classifications is restricted by surgeons' subjectivity in determining the depth of cartilage lesion and chondral softening, resulting in poor intraobserver and interobserver reproducibility[8–10]. Therefore, more quantitative and objective approaches, such as acoustic and optical techniques, as well as computer-assisted cartilage lesion scoring, are desirable[9,11–15].

Several non-destructive techniques, including intra-articular ultrasound (US)[13,16], optical coherence tomography (OCT)[14,17], near infrared (NIR) spectroscopy[15,18,19] and arthroscopic indentation[20,21], have been proposed for arthroscope guided quantitative and objective evaluation of cartilage integrity. US and OCT provide cross-sectional images of tissue structure, but are also complementary to each other: the superior resolution of OCT enables the high-resolution characterization of the articular surface, whereas US provides detailed information on the inner structures of cartilage[22] and enables subchondral bone evaluation[13]. Clinical intravascular US and OCT catheters are suitable for imaging narrow joint cavities and have been shown to be feasible for enhancing the accuracy of cartilage lesion scoring during arthroscopy[13,14,23]. However, the reproducibility of lesion scoring based on the US and OCT images is also restricted by the subjectivity of a surgeon[23].

Visual arthroscopic evaluation is supported by assessment of cartilage stiffness by palpating the articular surface with an arthroscopic probe, thus enabling the detection of chondral softening and cartilage flaps. A number of hand-held devices have been developed for determining cartilage stiffness during the arthroscopic surgery[20,24]. The stiffness of cartilage depends on its biochemical composition; thus, subtle compositional changes can alter the biomechanical response of cartilage[25,26]. Furthermore, cartilage stiffness is site-dependent[27–29] and may not be directly evaluated with imaging methods such as US and OCT.

In this study, we applied a prototype multimodality arthroscopic system, combining US, OCT and arthroscopic indentation device[20], for quantitative assessment of cartilage injuries. We investigated the intraobserver and interobserver reproducibility of the imaging techniques for assessing different levels of cartilage injury, and compared the outcome with conventional arthroscopic evaluation based on the ICRS scoring. Furthermore, OCT images obtained by the surgeons were automatically scored by custom-made software. Biomechanical assessment with arthroscopic device was compared with that using a laboratory indentation system. We hypothesized that the scoring of cartilage lesions from US and OCT images provides better reproducibility than that via conventional arthroscopy. Additionally, software-based scoring was expected to offer superior reproducibility compared to the individual techniques.

Materials and methods

Sample preparation

Fetlock joints were extracted from mature equine cadavers ($N = 5$) and stored at −20°C until required for the experiment (Fig. 1). The joints were opened prior to the experiment to guarantee inclusion of cartilage defects with various severity and to permit the marking of the areas of interest (AIs), thus ensuring well-confined AIs and reliable location tracking for the blind-coded scoring. Sample preparation was performed by researchers to eliminate any surgeon-related bias. Out of the two experienced board-certified equine surgeons (~900 arthroscopies, Diplomate European College of Veterinary Surgeons), the more experienced surgeon (~500 arthroscopies) selected the AIs ($N = 44$, Area ≈ 0.8 cm^2) based on visual evaluation to include both intact and damaged cartilage regions. Distinct lesions were centralized within the AIs. Throughout all the measurements, samples were submerged in room temperature phosphate-buffered saline (PBS).

The most severe lesion within each blind-coded AI was independently scored twice by both surgeons according to the ICRS cartilage injury classification system[5]: normal cartilage is classified as grade 0; fibrillated or superficially lacerated cartilage as grade 1; deeper lacerations but defects extending less than 50% of cartilage thickness as grade 2; defects extending deeper than 50% of cartilage thickness as grade 3 and defects extending into subchondral bone as grade 4. The scoring system was reviewed in detail with both surgeons prior to the experiments; furthermore, the scoring guidelines were visible for the surgeon throughout the measurements. During the lesion evaluation, the measurement instruments were submerged in PBS.

Conventional and prototype multimodality arthroscopes

First, cartilage was evaluated by examining the whole AI with an arthroscopic system, including a conventional clinical arthroscope (lens inclination = 30°, diameter = 4 mm, 28731 BWA, Karl Storz, GmbH & Co, Germany), a light source (Xenon XL, Smith & Nephew, Dyonics, Memphis, Tennessee, USA) and an arthroscopic hook probe (28145S (90°), Karl Storz). As a result of removing the joint capsule and other overlying tissues, the surgeons had unrestricted access to the defects from an optimal angle and distance. Subsequently, a prototype multimodality arthroscope [Fig. 2(A), (D)], including clinical US (ClearView Ultra, Boston Scientific Corporation, Marlborough, MA, USA) and OCT systems ($\lambda = 1300 \pm 55$ nm, Ilumien PCI Optimization System, St. Jude Medical, St. Paul, MN, USA), was utilized in similar examination. Intravascular catheters (US: Atlantis SR Pro, $f_c = 40$ MHz, Boston Scientific Corporation; OCT: C7 Dragonfly, St. Jude Medical) were used for real-time cross-sectional visualization and scoring of cartilage integrity. The quality of the imaging live feed was monitored throughout the experiment to ensure optimal image acquisition for scoring with the automatic software. The superior resolution of OCT (axial resolution ≤20 μm, lateral resolution 25–60 μm) enables high fidelity imaging of cartilage surface [Fig. 2(B), (E)], while US (axial resolution ≥43 μm) is capable of penetrating deep into the tissue, allowing better assessment of the cartilage–bone interface [Fig. 2(C), (F)]. Both surgeons were relatively unfamiliar with the novel imaging modalities (US and OCT); however, the modalities are easily adaptable and require no extensive practicing.

In the multimodality arthroscope, the imaging catheters were attached on the opposite side than the indenter of the Artscan 200 indentation device; thus, the prototype was rotated 180° to change between the imaging and indentation modalities. Throughout imaging the distance between the catheter and cartilage surface was kept minimal to ensure optimal image quality as the lateral resolution decreases with increasing distance from the catheters. The shape (curvature) of articular surface had no significant effect on the imaging modalities as no quantitative reflection or backscattering parameters were determined. Furthermore, the geometry of the arthroscopic indentation device limits its application at extremely concave surfaces; however, all the AIs could be evaluated.

Biomechanical testing

The stiffness of cartilage within AIs was determined with a hand-held arthroscopic indentation device – Artscan 200 (Artscan Oy, Helsinki, Finland)[20], which was part of the prototype multimodality arthroscope. The functionality of the device has been described previously[21], and is summarized here. The reference plate is gently pressed against the cartilage surface with minimum threshold force of 5 N, allowing a spherical indenter protruding

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