Iatrogenic Articular Cartilage Injury in Arthroscopic Hip and Knee Videos and the Potential for Cartilage Cell Death When Simulated in a Bovine Model

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Purpose: To determine the incidence and characterize the severity of iatrogenic cartilage injuries. **Methods:** Technique videos of arthroscopic femoral acetabular impingement procedures and meniscus repairs on VuMedi (n = 85) and *Arthroscopy Techniques* (n = 45) were reviewed and iatrogenic cartilage injuries were identified and graded (minor, intermediate, and major injury) by 2 independent reviewers. To demonstrate that even minor injuries on a cellular scale result in damage, a bovine osteochondral explant was used to create comparable minor iatrogenic injuries at varied forces that do not disrupt the articular surface (1.5 N, 2.5 N, and 9.8 N). Dead chondrocytes at the site of injury were stained with ethidium homodimer-2 and imaged with an Olympus FV1000 confocal microscope. χ^2 tests were used for analysis; all results with $P < .05$ were considered significant. **Results:** In total, 130 videos of arthroscopic meniscus and femoral acetabular impingement procedures were analyzed and the incidence of iatrogenic cartilage injury was 73.8%. There were 110 (70.0%) minor, 35 (22.3%) intermediate, and 11 (7.0%) major iatrogenic injuries. All forces tested in the minor injury bovine model resulted in chondrocyte death at the site of contact. **Conclusions:** Iatrogenic articular cartilage injuries are common in arthroscopy, occurring in more than 70% of the surgeon-published instructional videos analyzed. At least some chondrocyte death occurs with minor simulated iatrogenic injuries (1.5 N). **Clinical Relevance:** The high rate of cartilage damage during arthroscopic technique videos likely under-represents the true incidence in clinical practice. Cell death occurs in the bovine minor injury model with minimal contact forces. This suggests iatrogenic cartilage damage during arthroscopy could contribute to clinical outcomes.

The frequency of arthroscopy has increased steadily in the past decade[1] to the extent that it is the most frequently performed orthopaedic procedure in the developed world.[2] Arthroscopic management of intra-articular conditions has expanded into increasingly anatomically constrained locations.[3] These are considered safe procedures, with minor complications reported that relate to the techniques themselves.[4-6] For example, one of the most common minor complications of hip arthroscopy is iatrogenic chondrolabral damage, occurring up to a reported 7.9% of the time.[7] In the literature, only 1 study of iatrogenic cartilage injury (in ankle arthroscopy) has been published with a rating system to assess severity of the injury.[8] A study in iatrogenic injury in canine stifle joints has also been published.[9] Both these studies have limitations and do not firmly establish a specific classification system by which to report incidence or severity of iatrogenic cartilage injury. It has already been noted that the rate of iatrogenic cartilage damage due to mechanical trauma from instrumentation has not been more intently investigated despite being ubiquitous in practice.[2]

In this study, we used publicly available academic training videos to assess the frequency of iatrogenic articular injury in hip and knee arthroscopic procedures as demonstrated in academic training videos. Injuries were classified as minor, intermediate, or major

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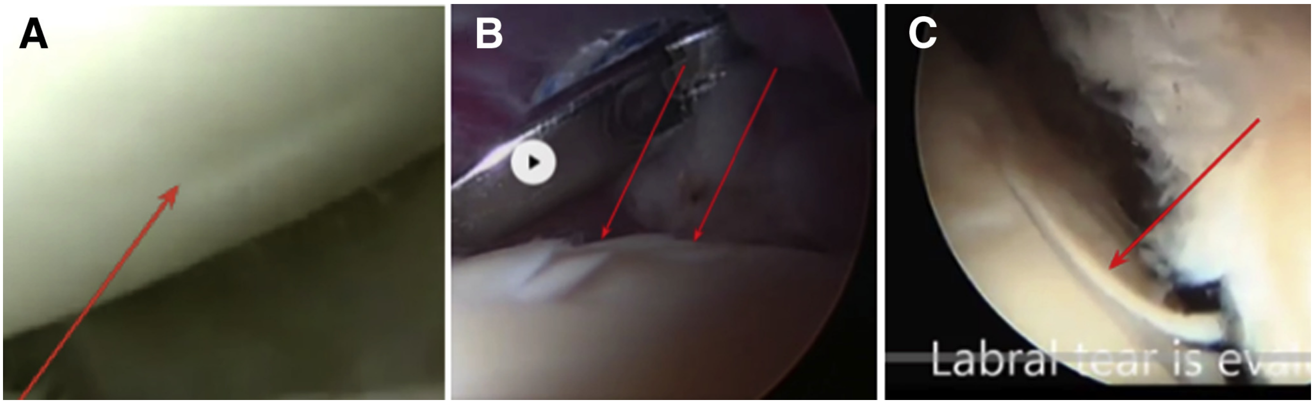

Fig 1. Cartilage injury severity. Example of (A) minor (deformation of the articular surface without laceration or tear of tissue); (B) intermediate (laceration or tear of articular cartilage without visualization of subchondral bone); and (C) major (laceration or tear of articular cartilage with subchondral bone visualization) iatrogenic cartilage injuries observed in technique videos.

severity, with the latter 2 categories indicating disruption of the articular surface. In contrast to intermediate and major injury from injuries, minor injuries did not involve laceration or tear of the articular surface. Therefore, we assessed the cellular effect of minor injury from arthroscopic tool contact to bovine articular cartilage to demonstrate that even minor injuries induce observable, quantifiable cellular injury. The purpose of this study was to determine the incidence and characterize the severity of iatrogenic cartilage injuries. We hypothesized that the rate of iatrogenic injury observed in published academic training videos would be greater than previously appreciated in the literature and that the impact of cartilage injuries as modeled in the laboratory would demonstrate cell death.

Methods

Incidence of Iatrogenic Articular Cartilage Injuries in Hip and Knee Arthroscopy

To assess the incidence of iatrogenic cartilage injury during arthroscopy, online technique videos of arthroscopic femoral acetabular impingement procedures and arthroscopic knee meniscus repair procedures on VuMedi (www.vumedi.com, from 2012-2017) and *Arthroscopy Techniques* (arthroscopytechniques.org, Elsevier, 2018, from 2009 to 2018) were reviewed. Reviewing every available joint for arthroscopy was not within the scope of this study; the hip and knee meniscal videos represent more highly constrained procedures clinically. Videos were limited to the hip and knee because the bovine model (which is requisite weight bearing) most closely models a full weight-bearing articular surface. The upper extremity does not experience the same physiologic loading as the lower extremities and thus likely responds differently on a cellular level to iatrogenic injury due to variable metabolic activity and cartilage thickness. These procedures were examined due to the greater level of constraint in the hip joint and during meniscal repair procedures clinically.

Videos were excluded if (1) less than 10 seconds of arthroscopic footage was shown, or (2) intentional mechanical cartilage disruption was demonstrated (as in cases of microfracture, curettage, etc.). Meniscal repair only was included; medial collateral ligament pie-crusting, meniscectomy, and meniscal transplant procedures were not included. Cartilage injury due to non-mechanical mechanism, such as electrocautery, or chemical reaction were excluded. All languages were included.

During analysis of videos, cartilage injuries were only recorded for incidence and scoring analysis if the injury was directly observed during the video and was clearly caused by visually confirmable instrument contact. Cartilage injury due to other mechanisms (such as heat/chemical burn) were excluded. Mechanical injuries due to instrument contact to any aspect of the articular cartilage were included (e.g., tibial, femoral, acetabular). A single reviewer (M.S., medical student) identified each occurrence of iatrogenic cartilage injury and compiled still-frame images of these iatrogenic injuries; 2 independent reviewers (J.C., orthopedic surgery resident; R.W., fellowship-trained sports surgeon) assigned a severity grade to each identified lesion (minor, intermediate, or major injury; Fig 1). Minor injuries were considered deformation of the cartilage by any arthroscopic tool without disruption by tearing or laceration of tissue; intermediate injuries involved laceration of tissue by a tool without subchondral bone visualization; major injuries resulted in cartilage laceration severe enough to visualize subchondral bone as a result of iatrogenic injury. Inter-rater reliability was assessed using SAS software (SAS Institute, Cary, NC). χ^2 tests were used for analysis; all results with $P < .05$

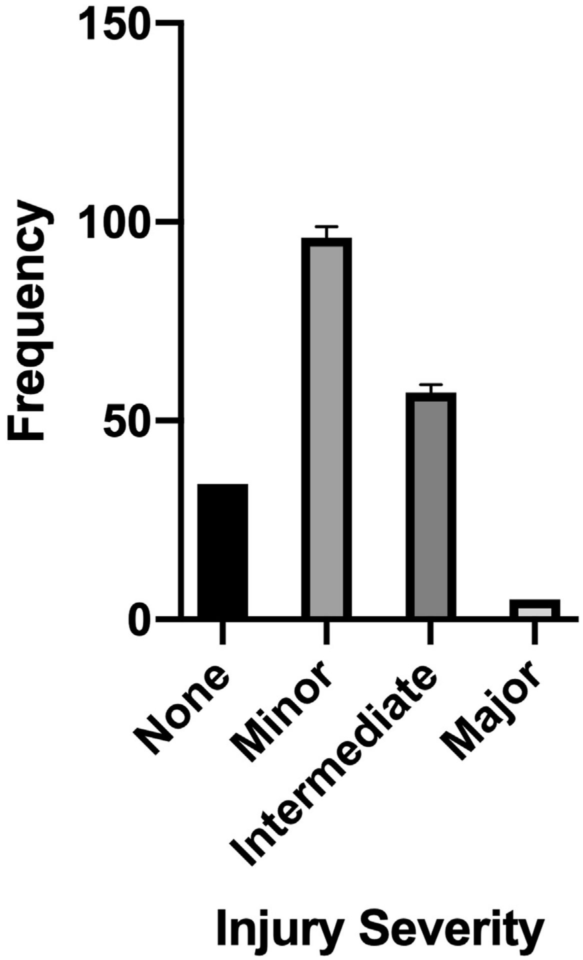

Fig 2. Incidence of observed iatrogenic injury in technique videos. Overall, the observable incidence of injuries was high, with minor injuries being the most common. In total, 110 injuries were graded as minor injuries (70.0%), 35 injuries were graded as intermediate injuries (22.3%), and 11 injuries were graded as major injuries (7.0%). Interobserver reliability was 0.73.

were considered significant. Pearson's correlation coefficient was used to calculate the correlation between length of video and number of iatrogenic cartilage injuries.

The Impact of Minor Iatrogenic Cartilage Injury on Cellular Viability

Although most patients are presumed to be concerned by unplanned disruptions of an articular cartilage surface, it is important to note that minor injuries that do not clearly disrupt the articular surface might be dismissed by some patients and surgeons. To better understand the damage caused by these injuries, a conical arthroscopic trochar was used to mimic minor iatrogenic injuries in bovine femoral condyle osteochondral explants. Bovine femoral condyle osteochondral explants demonstrate similar stiffness and biomechanical behavior to human knee cartilage; bovine cartilage thickness measures ∼1.2 mm on average.[10,11] Fresh osteochondral explants, at least 10 mm in diameter and containing at least 3 mm of subchondral bone, were cut from load-bearing and non−load-bearing surfaces of the femoral condyle of bovine stifle (knee) joints (Bud's Custom Meats, Riverside, IA). Osteochondral plugs with uniform cartilage coverage and thickness (∼1.2-1.6 mm) were selected for experimentation. The cartilage was allowed to equilibrate in standard media (1:1 Dulbecco's Modified Eagle Medium and F12, supplemented with 10% fetal bovine serum, 50 μg/mL L-ascorbate, 100 U/mL penicillin, 100 μg/mL streptomycin, and 2.5 μg/mL fungizone) for 24 to 48 hours at 37°C in 5% CO_2 and 5% O_2.

After this equilibration period, an arthroscopic blunt trochar (5-mm diameter shaft) was set perpendicular to the surface of the bovine articular condyle and translated at a speed of 5 mm/s to create a single linear injury. Varied forces were used to press the trochar into the tissue (1.5 N, 2.5 N, and 9.8 N). In this model, cartilage was not displaced or grossly torn/fractured and returned to its natural shape in moments after each injury. For all experiments, each force was replicated 3 times per bovine knee, and 3 total bovine knees were used (n = 9 per force). The explant was placed in 0.9% normal saline for 2 hours at 37°C to replicate the conditions of a 2-hour procedural arthroscopy. The explant was then placed back into standard media and incubated with 1 μg/mL ethidium homodimer-2 (ThermoFisher Scientific, Waltham, MA) for 30 minutes at 37°C. The fluorescence in the zone of injury was visualized with an Olympus FV1000 confocal microscope (Olympus Scientific Solutions America Corporation, Waltham, MA) at 535 nm at t = 0, 0.5, 6, and 24 hours. On visualization, cartilage distant (4-5 mm) from the site of injury was used as a control to confirm the uniform viability of injured cartilage from that of uninjured stifle cartilage. Olympus Fluoview Version 4.2b (Olympus Scientific Solutions America Corporation) software was used to measure the width of the zone of injury. Analysis of measurements was performed using Prism 8 (GraphPad Software, San Diego, CA). Measurements were analyzed by analysis of variance, and *P* values <.05 were considered significant.

Results

Incidence of Iatrogenic Injury

In total, 130 unique videos of arthroscopic hip and meniscal procedures were identified on VuMedi (n = 85) and *Arthroscopy Techniques* (n = 45) databases. No duplicates were encountered. A total of 94 videos were hip procedures and 36 videos were knee procedures. The average video length was 5 minutes and 36 seconds (minimum 46 seconds, maximum 24 minutes, standard deviation 3 minutes 34 seconds). In total, 34 videos did not show evidence of iatrogenic cartilage

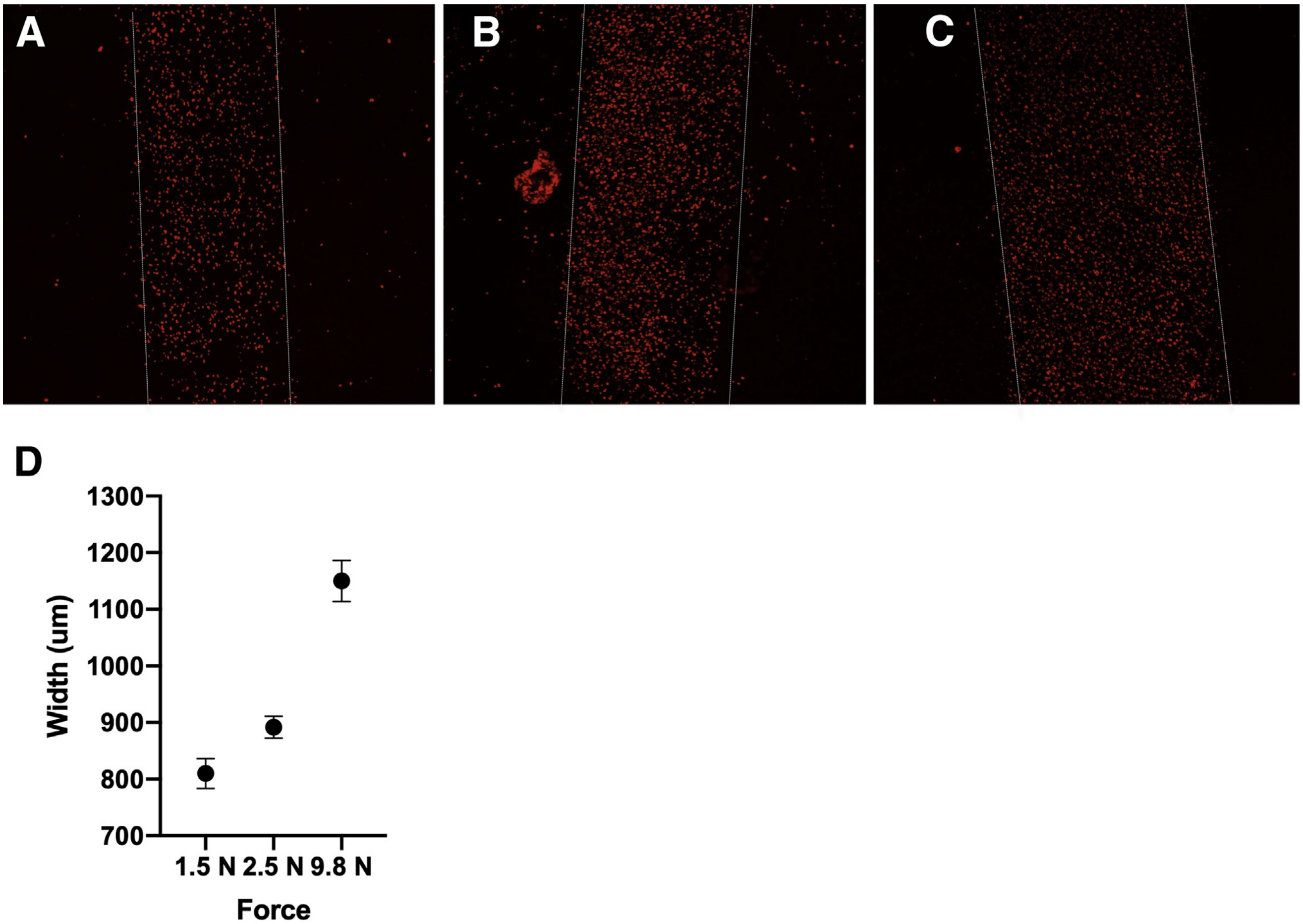

Fig 3. Iatrogenic cartilage injury results in cell death. Bovine femoral condyle explants were injured using a standard arthroscopic trochar loaded with 1.5 N (A), 2.5 N (B), or 9.8 N (C) and translated across the cartilage surface to mimic minor iatrogenic arthroscopic injury. Dead cells were imaged using ethidium homodimer and confocal microscopy. With increasing force applied to a conical arthroscopic trochar, the width of the zone of injury increases in bovine articular explants as demonstrated at 1.5N, 2.5N, and 9.8 N ($P < .001$) (D).

injury; however, 96 (73.8%) videos showed at least 1 iatrogenic injury. A total of 157 iatrogenic injuries were observed during 130 videos, with the number of discreet injuries ranging from 1 to 3. The rate of iatrogenic injury was not significantly different between the knee and hip procedures ($P = .34$). In total, 110 injuries (70.0%) were graded as minor injuries, 35 injuries (22.3%) were graded as intermediate injuries, and 11 injuries were graded as major injuries (7.0%) (Fig 2). The interobserver reliability of the grading system was 0.73. In the hip procedures, 68 of 94 (72.3%) videos demonstrated iatrogenic cartilage injury and in meniscal repair videos, 28 of 36 videos (77.8%) demonstrated iatrogenic cartilage injury. Pearson's correlation coefficient comparing the length of video to number of observed iatrogenic injuries to cartilage was $r(128) = 0.2267$, $P = .0095$.

Cellular Effect of Minor Mechanical Injury

At 1.5 N, the zone of injury was 810 μm wide (standard deviation [SD] ± 26 μm); at 2.5 N the zone of injury was 891 μm wide (SD ± 36 μm), and at 9.8 N the zone of injury was 1150 μm wide (SD ± 36 μm) ($P < .001$) (Fig 3 A-D). Greater force applied through the trochar resulted in a larger width of injury, but all of the forces used caused uniform cell death in the superficial zone at the point of contact. There was no statistically significant difference in the width of injury when comparing the load-bearing and non—load-bearing surfaces with each force applied to the trochar (Fig 4A). For each force, samples returned to media and then imaged after 0.5, 1, 2, 6, and 24 hours did not show significant differences in cell death or injury zone width compared with the 2-hour group. ($P > .05$) (Fig 4B).

Discussion

The data presented in this study suggest that iatrogenic cartilage injury during constrained arthroscopic procedures is common and not benign on a cellular level. Published rates of iatrogenic cartilage injury likely

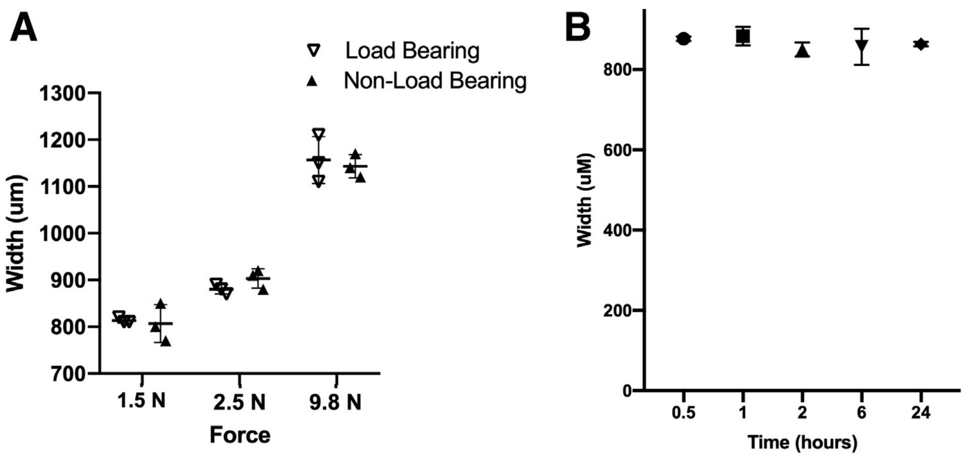

Fig 4. (A) Cell death comparison between load-bearing and non—load-bearing cartilage surfaces. Under conditions described in Figure 3, width of injury was compared between load-bearing and non—load-bearing aspects of bovine femoral condyles. Again, the width of the zone of injury significantly increased with increasing force (A, 1.5 N; B, 2.5 N; C, 9.8 N) in both the load-bearing portion of femoral bovine explants and the non—load-bearing regions. The zone of injury did not vary in width when comparing load-bearing and non—load-bearing regions ($P > .05$). (B) Zone of injury does not propagate over time. After initial injury and 2 hours of normal saline incubation, explants were replaced in media at 37°C and cell death was visualized at t = 0.5, 1, 2, 6, and 24 hours. At 250 N, the area of zone of injury remained stable over time and did not show changes in width.

underestimate the problem, given the high rate of cartilage injury demonstrated in this study of arthroscopic technique videos. In cases in which articular cartilage structural integrity is not damaged by the iatrogenic injury, significant cell death occurs in vitro with minor contact forces.

Iatrogenic cartilage injury was reported as high as 7.9% in a recent systematic review.[7] There are many scenarios in which iatrogenic cartilage injury could occur, including pressure from the side of a cannula on a concave surface, end-pressure injury from the tip of a tool (camera placement, trochar contact), the edge of a tool (cannula, suture passing device) carving a partial or full-thickness divot, or tool penetration to the deep cartilage or subchondral bone (e.g., drill bit, spinal needle), among others. Surgeon-published technique videos from 2 sources due to any of the above mechanisms demonstrated that iatrogenic articular cartilage injuries were common, with 77.6% of knee arthroscopic videos and 72.3% of hip arthroscopic videos demonstrating directly observed iatrogenic injury due to instrumentation. Clear tearing or laceration of cartilage (intermediate or major grade injury) was present in 35.4% of videos. Although 70% of injuries observed were classified as minor, our model system showed clear tracks of chondrocyte death at the site of cartilage—instrument contact, even in cases of modest tissue deformation. These observations suggest strongly that small scrapes with arthroscopic tools that occur during common practice are not benign.

The incidence of iatrogenic cartilage injury in techniques video is much greater than the previously reported rate of up to 7.9%, suggesting that the incidence is likely under-recognized or under-reported. In this study, iatrogenic cartilage injury was only included if it was directly observed occurring during the video due to instrument mechanical contact; thus, in light of ubiquitous video editing, it is likely that some iatrogenic injuries were not included and the actual incidence of iatrogenic injury may be greater than that reported here. There was a weak but statistically significant positive correlation between length of training video and number of observed cartilage injuries, suggesting that longer or more complex procedures may predispose to iatrogenic injury. However, this correlation would likely be more accurately calculated with unedited arthroscopic footage to capture all observable injuries as well as accurate procedure lengths. Similarly, although no statistically significant difference between hip and meniscal repair procedures was detected, it is possible that this represents beta error due to a small number of observed injuries or removal of footage that demonstrated observable iatrogenic injury.

Given that these videos represent the performance of a relative expert in the field, the incidence of >50% likely under-estimates the true rate of iatrogenic cartilage injury in general clinical practice. Mehta et al.[12] found that patients undergoing hip arthroscopy with novice and low-volume surgeons were more likely to require reoperation, concluding that hip arthroscopy presented a demanding learning curve for surgeons. This could represent a prototypic population wherein iatrogenic cartilage injuries accumulate during repeat arthroscopic procedures, possibly accounting for some portion of poorer outcomes in patients who undergo multiple arthroscopies.[13] Cumulative iatrogenic cartilage injury might, therefore, be an unmeasured predictor of patient outcomes.[14]

The minor category of injury may be considered too inclusive of “injury”; thus, to explore the effect of trochar—cartilage contact, minor injury was modeled in a well-characterized bovine explant model. Where significant cartilage laceration or tear seems an obvious injury, it is important to stress that visible scraping of cartilage such as occurred in 70% of the procedures viewed is not entirely benign. Our laboratory model revealed a positive correlation between force and area of chondrocyte death during minor injuries, suggesting that injuries resulting from greater contact forces are likely to be more severe. We modeled these injuries in a manner that closely mimicked arthroscopic procedures in the operating room, including usage of the most common arthroscopic irrigant, normal saline at room temperature. Saline is increasingly recognized as damaging to chondrocytes over this time period and hyperosmolality and increased temperature appear protective of chondrocytes in situ, although the use of these advances has not been widely adopted in the operative suite.[5,15-18] However, we observed little difference in the width of the zone of cell death with incubation in normal saline for either 30 minutes or 2 hours after injury, which likely encompasses the length of most arthroscopic procedures. It appears once samples were placed in adequate nutrition and osmolarity at 37°C, the injury did not propagate over the following 24 hours, suggesting that iatrogenic injuries are stable in nature after occurrence and likely a direct and rapid result of arthroscopic tool contact.

Shear stress occurs when a force is applied parallel to the surface of a fixed material. Previously, physiologic shear stress has been shown to cause altered collagen production, matrix integrity, and cellular metabolism in diarthrodial joints.[19-21] However, iatrogenic injury induced by instrumentation presents a nonuniform shear stress at a single point of contact at the cartilage surface. The effect of direct shear on single chondrocytes in vitro has been studied, showing rearrangement in focal adhesions of chondrocytes as well as differential expression of multiple genes related to proliferation, survival, and matrix homeostasis; however, these models did not use intact cartilage and cell death was not a reported outcome.[22,23] Interestingly, even minor mechanical injury applied to intact cartilage by 1.5 N force through an arthroscopic trochar resulted in clear zones of significant chondrocyte cell death in explants. It may be that sublethal perturbations in cell metabolism or inflammatory pathways occurred at the periphery of our injury sites, but we have not investigated these regions beyond cell viability.

Iatrogenic cartilage injuries during arthroscopy are common, as demonstrated by a high incidence of injury seen in widely available technique videos. The clinical significance of these injuries remains unknown. However, given the results presented here, it seems plausible that iatrogenic injuries may represent clinically significant contributors to pain or inflammation or even osteoarthritis progression after arthroscopic procedures. In particular, patients undergoing arthroscopic procedures for femoral acetabular impingement and posterior medial meniscus root tears are at-risk populations for cartilage disease and joint-preservation surgery and thus may be more sensitive to iatrogenic injury, especially if undergoing multiple arthroscopic procedures. Instrumentation that is plastic or moldable may be a promising new direction for industry, as it may limit both the occurrence and severity of iatrogenic injuries. Given the differences in clinical results and patient-reported outcomes after arthroscopy, and in light of the ubiquity and severity of cell death due to iatrogenic arthroscopic injury, the impact of cellular damage after arthroscopy warrants further investigation.[24,25]

Limitations

There are a variety of limitations to this study of iatrogenic cartilage injury. In the video portion of the study, data for procedures were incompletely reported. For example, on the VuMedi platform, patient information, including age, sidedness, comorbidities, preoperative examination, etc., was not uniformly available. As most videos only include a title and author, more in-depth information for analysis was not obtained for this study. The included databases were selected because the authenticity of the publisher could be verified. This is, uploads via Twitter, YouTube, and other public platforms may be uploaded by the public, researchers, medical students, and others. VuMedi and *Arthroscopy Techniques* offer the advantage of verified authorship by orthopaedic surgeons and are recommended by many residency and fellowship training programs for educational value. Furthermore, these sites allow surgeons to publish their own techniques and likely represent best-case scenarios, with the least likely incidence of observable iatrogenic damage.

Articular cartilage exhibits distinctive organization by layers that are biologically distinct in appearance and metabolic function.[26] In this paper, minor injuries may reflect injury to either or both the lamina splendens and superficial tangential zone. More research is needed to distinguish key differences between minor injuries where the lamina splendens may or may not be disrupted. Intermediate injuries likely affect these layers in addition to the middle and deep zones, whereas major injuries reflect injury to the level of the subchrondral bone, as it was directly disturbed. Furthermore, although the bovine cartilage used in this experiment was relatively uniform, it is important to note that the articular cartilage of the human acetabulum, femoral head, tibial plateau, and femoral condyles are variable (ranging from less than 0.5 mm to greater than 3.0 mm).[27-29] In the absence of histologic analysis, the exact depth of injury as compared with native cartilage thickness was not able to be determined in either the video or bovine studies.

The minor category of injury may be considered too inclusive of "injury"; thus, to explore the effect of trochar—cartilage contact, minor injury was modeled in a well-characterized bovine explant model. Where significant cartilage laceration or tear seems an obvious injury, it is important to stress that visible scraping of cartilage such as occurred in 70% of the procedures viewed is not entirely benign.

Conclusions

Iatrogenic articular cartilage injuries are common in arthroscopy, occurring in more than 70% of the surgeon-published instructional videos analyzed. At least some chondrocyte death occurs with minor simulated iatrogenic injuries (1.5 N).

References

1. Degen RM, Bernard JA, Pan TJ, et al. Hip arthroscopy utilization and associated complications: A population-based analysis. *J Hip Preserv Surg* 2017;4:240-249.
2. Amin AK, Simpson A, Hall AC. Iatrogenic articular cartilage injury: The elephant in the operating theatre: The surgeons' role in chondroprotection. *Bone Joint J* 2017;99-b:1555-1556.
3. Chen XZ, Chen Y, Liu CG, Yang H, Xu XD, Lin P. Arthroscopy-assisted surgery for acute ankle fractures: A systematic review. *Arthroscopy* 2015;31:2224-2231.
4. Blazquez Martin T, Iglesias Duran E, San Miguel Campos M. Complications after ankle and hindfoot arthroscopy. *Rev Esp Cir Ortop Traumatol* 2016;60:387-393.
5. Amin AK, Huntley JS, Bush PG, Simpson AH, Hall AC. Osmolarity influences chondrocyte death in wounded articular cartilage. *J Bone Joint Surg Am* 2008;90:1531-1542.
6. Bush PG, Hodkinson PD, Hamilton GL, Hall AC. Viability and volume of in situ bovine articular chondrocytes-changes following a single impact and effects of medium osmolarity. *Osteoarthritis Cartilage* 2005;13:54-65.
7. Weber AE, Harris JD, Nho SJ. Complications in hip arthroscopy: A systematic review and strategies for prevention. *Sports Med Arthrosc Rev* 2015;23:187-193.
8. Vega J, Golano P, Pena F. Iatrogenic articular cartilage injuries during ankle arthroscopy. *Knee Surg Sports Traumatol Arthrosc* 2016;24:1304-1310.
9. Rogatko CP, Warnock JJ, Bobe G, Verpaalen VD. Comparison of iatrogenic articular cartilage injury in canine stifle arthroscopy versus medial parapatellar mini-arthrotomy in a cadaveric model. *Veterinary Surg* 2018;47:O6-O14.
10. Martin JA, McCabe D, Walter M, Buckwalter JA, McKinley TO. N-acetylcysteine inhibits post-impact chondrocyte death in osteochondral explants. *J Bone Joint Surg Am* 2009;91:1890-1897.
11. Coleman MC, Goetz JE, Brouillette MJ, et al. Targeting mitochondrial responses to intra-articular fracture to prevent posttraumatic osteoarthritis. *Sci Transl Med* 2018;10.
12. Mehta N, Chamberlin P, Marx RG, et al. Defining the learning curve for hip arthroscopy: A threshold analysis of the volume-outcomes relationship. *Am J Sports Med* 2018;46:1284-1293.
13. Spindler KP, Huston LJ, Chagin KM, et al. Ten-year outcomes and risk factors after anterior cruciate ligament reconstruction: A MOON longitudinal prospective cohort study. *Am J Sports Med* 2018;46:815-825.
14. Cox CL, Huston LJ, Dunn WR, et al. Are articular cartilage lesions and meniscus tears predictive of IKDC, KOOS, and Marx activity level outcomes after anterior cruciate ligament reconstruction? A 6-year multicenter cohort study. *Am J Sports Med* 2014;42:1058-1067.
15. Amin AK, Huntley JS, Patton JT, Brenkel IJ, Simpson AH, Hall AC. Hyperosmolarity protects chondrocytes from mechanical injury in human articular cartilage: An experimental report. *J Bone Joint Surg Br* 2011;93:277-284.
16. Eltawil NM, Ahmed S, Chan LH, Simpson A, Hall AC. Chondroprotection in models of cartilage injury by raising the temperature and osmolarity of irrigation solutions. *Cartilage* 2018;9:313-320.
17. Gulihar A, Bryson DJ, Taylor GJ. Effect of different irrigation fluids on human articular cartilage: An in vitro study. *Arthroscopy* 2013;29:251-256.
18. Huang Y, Zhang Y, Ding X, Liu S, Sun T. Osmolarity influences chondrocyte repair after injury in human articular cartilage. *J Orthop Surg Res* 2015;10:19.
19. Lane Smith R, Trindade MC, Ikenoue T, et al. Effects of shear stress on articular chondrocyte metabolism. *Biorheology* 2000;37:95-107.
20. Smith RL, Carter DR, Schurman DJ. Pressure and shear differentially alter human articular chondrocyte metabolism: A review. *Clin Orthop Rel Res* 2004:S89-S95.
21. Gharravi AM, Orazizadeh M, Hashemitabar M. Fluid-induced low shear stress improves cartilage like tissue fabrication by encapsulating chondrocytes. *Cell Tissue Bank* 2016;17:117-122.
22. Lee MS, Sun MT, Pang ST, et al. Evaluation of differentially expressed genes by shear stress in human osteoarthritic chondrocytes in vitro. *Chang Gung Med J* 2009;32:42-50.
23. Ofek G, Dowling EP, Raphael RM, McGarry JP, Athanasiou KA. Biomechanics of single chondrocytes under direct shear. *Biomech Model Mechanobiol* 2010;9:153-162.
24. Wyles CC, Heidenreich MJ, Jeng J, Larson DR, Trousdale RT, Sierra RJ. The John Charnley Award: Redefining the natural history of osteoarthritis in patients with hip dysplasia and impingement. *Clin Orthop Rel Res* 2017;475:336-350.
25. Krych AJ, Johnson NR, Mohan R, et al. Arthritis progression on serial MRIs following diagnosis of medial meniscal posterior horn root tear. *J Knee Surg* 2018;31:698-704.
26. Amanatullah DF, Yamane S, Reddi AH. Distinct patterns of gene expression in the superficial, middle and deep zones of bovine articular cartilage. *J Tissue Eng Regen Med* 2014;8:505-514.

27. Karanfil Y, Babayeva N, Donmez G, et al. Thirty minutes of running exercise decreases t2 signal intensity but not thickness of the knee joint cartilage: A 3.0-T magnetic resonance imaging study. *Cartilage* 2019;10: 444-450.
28. Wyler A, Bousson V, Bergot C, et al. Hyaline cartilage thickness in radiographically normal cadaveric hips: Comparison of spiral CT arthrographic and macroscopic measurements. *Radiology* 2007;242:441-449.
29. Shah RF, Martinez AM, Pedoia V, Majumdar S, Vail TP, Bini SA. Variation in the thickness of knee cartilage. the use of a novel machine learning algorithm for cartilage segmentation of magnetic resonance images. *J Arthroplasty* 2019;34:2210-2215.