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EMERGING IDEAS

Emerging Ideas

Novel 3-D Quantification and Classification of Cam Lesions in Patients With Femoroacetabular Impingement

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Abstract
Background Femoroacetabular impingement (FAI) can lead to labral injury, osseous changes, and even osteoarthritis. The literature contains inconsistent definitions of the alpha angle and other nonthree-dimensional (3-D) radiographic measures. We present a novel approach to quantifying cam lesions in 3-D terms. Our method also can be used to develop a classification system that describes the exact location and size of cam lesions.
Questions/Hypotheses We asked whether automated quantification of CAM lesions based on CT data is a reasonable way to detect CAM lesions and whether they may be classified based on location.
Method of Study We developed a method to quantify femoral head cam lesions using 3-D modeling of CT scans. By segmenting raw DICOM data, we can determine the distance from the cam lesion's surface points to the centroid of the femoral head to quantify the mean bump height, volume, and location. The resulting 3-D femoral and acetabular models will be analyzed with custom software. We then will quantify the cam lesion with 3-D parameters using a modified zoning method. The mean bump height, volume, and location on the clock face, and relative zoning will be calculated. Zonal differences will be statistically analyzed. To assess the ability of this method to predict arthroscopic findings, we will obtain preoperative CT scans for 25 patients who undergo hip arthroscopy for FAI. We will compare measurements with the method with our measurements from arthroscopy. The clinical implications of our method's measurements then will be reviewed and refined for future prospective studies.
Significance We present a novel approach that can quantify a cam lesion's location and size. This method will be used to provide guidelines for the exact amount of bony resection needed from a specific location of the proximal femur. There is also potential to develop software for ease of use so this method can be more widely applied.

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Hypothesis

Quantifying femoral head cam lesions that are analyzed three-dimensionally using the distance from the cam lesion's surface points to the centroid of the femoral head to quantify the mean bump height, volume, and location will effectively define cam lesions and predict arthroscopic measurements.

Background

Femoral acetabular impingement (FAI) includes pathologic features involving abutment of the femoral neck and the acetabular rim at the extremes of ROM [3]. Lesions primarily can be related to the acetabulum (pincer), femoral neck (cam), or most commonly both of these. FAI can lead to labral injury, osseous changes, and even osteoarthritis [2, 8]. Ideally, patients who are currently symptomatic or at risk for disease progression can be identified and stratified for intervention. Unfortunately, FAI remains difficult to reliably diagnose, although much work has been reported to improve imaging-based diagnosis.

The most common means of identifying cam lesions is via the alpha angle, which originally was described using MRI [12]. Normal femoral head alpha angles vary based on gender: Gosvig et al. suggested normal was less than 68° for men or 50° for women [4]. This and other data support that lesions greater than a certain cutoff have increased risk for cartilage damage [1, 12], increased dGEMRIC index [6], and labral damage [7]. Although fairly reliable, the method has been expanded to radiographic imaging secondary to decreased expense and increased accessibility. These benefits have been tempered by studies showing poor interobserver reliability [9] and inconsistency [14]. Even using specific methods, such as the Dunn view, the extent of a given cam lesion can be difficult to quantify [11]. These difficulties are secondary to the attempt of planar description of a complex three-dimensional (3-D) lesion. For example, the appearance of a lesion is subject to subtle differences in rotational angle of the radiograph. Given the osseous nature of cam lesions and the difficulty with radiographic assessment, 3-D evaluation of the femur allows for more accurate and consistent anatomic characterization of the bony lesion.

Even with CT imaging, lesions are not easily describable in quantitative terms. Similarly, 3-D reconstructed images, which allow excellent qualitative descriptions of lesion locations and correlating those descriptions with the position of impingement, do not allow for more rigorous quantitative assessments of the lesion. This lack of quantitative robustness limits the ability to classify these lesions for research studies and we believe limits a more scientific approach to clinical care. This type of approach is invaluable as cam lesions vary in location, size, and morphologic features. This information can be used to guide anatomic reshaping of the femoral head and neck in the operating room.

Through focusing on the use of CT data, we developed a novel, automated method to describe aberrancies in the topography of the femoral head and the head-neck junction. Furthermore, we can subcategorize lesions into zones based on a modification of the grid described by Ilizaliturri et al. [5] for cartilage lesions, along with the classic clock face description.

Other groups also have characterized cam lesions with advanced 3-D imaging modalities. For example, Peters et al. described a program where they can plot cartilage thickness, qualitatively describe asphericity of the femoral head, and provide estimates on contact pressures in the hip [13]. Masjedi et al. also have developed a model to automate quantification of cam lesions on CT [10]. However, their study involved a cross-sectional area at different regions along the femoral head and neck. Our work differs from these groups in that our methodology provides data specific to the lesion. The method we describe in this article can provide detailed reporting of lesion location and lesion extent and height and volume in three dimensions.

Proposed Program

Our primary aim is to create a language to describe cam lesions that can help direct clinical and surgical decision-making. Thus, we will propose a new classification system based on the lesion's location and size (considering height, morphologic features, and volume of the lesion). One step toward achieving this goal is to quantify these lesions using 3-D topographic mapping. We have developed proprietary software and an algorithm to accurately classify and measure cam lesions with a repeatable process.

We will apply our method by conducting a retrospective analysis on patients with symptomatic cam lesions, confirmed via standard radiographs and CT, who have undergone arthroscopic osteochondroplasty. The patients' DICOM data from the surgically treated hip are segmented using Mimics® 13.1 software (Materialise NV, Leuven, Belgium) and predetermined Hounsfield units (> 226 for bone). The resulting 3-D femoral and acetabular models are converted to point-cloud data, which then are analyzed with a custom-written program created in Microsoft Visual C++ with Microsoft Foundation Class (MFC) programming environment (Microsoft Corp, Redmond, WA, USA). To find the gravity center of the femoral head, we assume a perfect sphere. From this, a virtual point near the gravity center is moved ± 5 mm in x, y, and z directions in 1.0-mm increments until the standard deviation of the distance to each point on the surface becomes the smallest. This procedure is repeated within a search range of ± 0.5 mm in 0.1-mm increments to refine the gravity center point. From this point, a virtual sphere is created that mimics the contour of the femoral head as a sphere. The cam lesion then is quantified three-dimensionally using the distance from the cam lesion's surface points to the centroid of the femoral head. These data are observed in one of three methods: axial view, visually presenting the head-neck contours; global view, a 3-D point-cloud model with a color spectrum representing relative valleys and prominences; and atlas view, a planar projection of the entire femoral head with the same color spectrum (Fig. 1). The modified zoning method described by Ilizaliturri et al. [5] is applied to the data (Fig. 2), with Zones 1 to 6 being contained in the acetabulum and Zones 7 to 9 being lateral to the acetabular

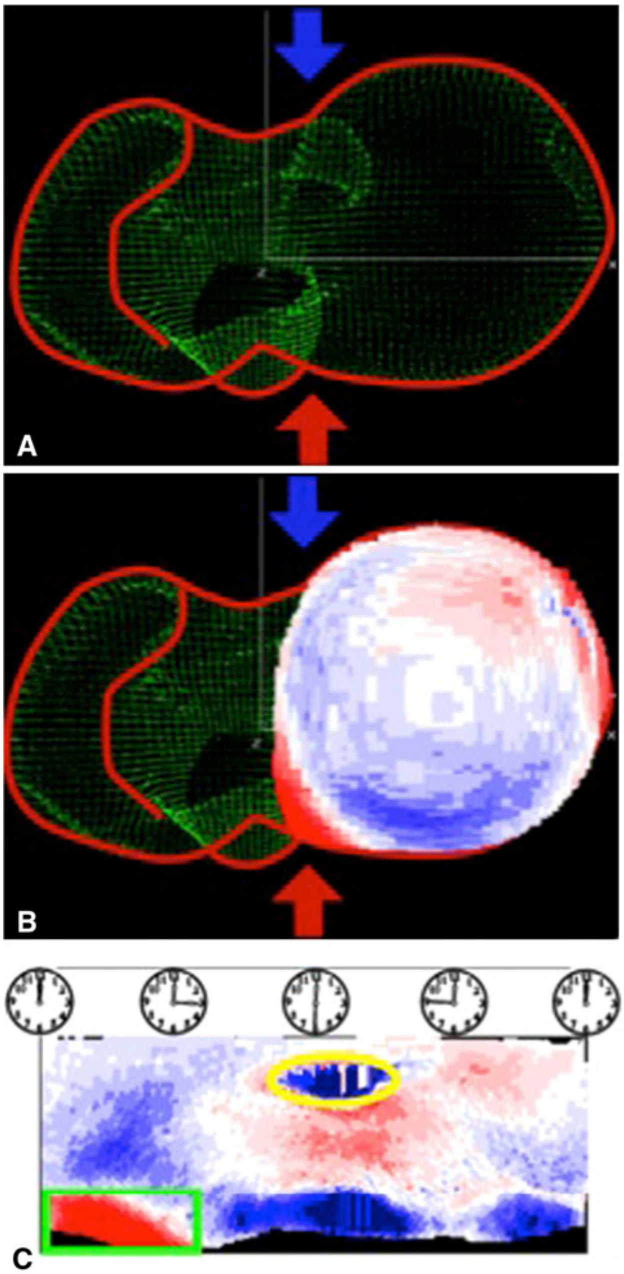

Fig. 1A–C (**A**) An axial view of the femoral point-cloud shows the normal (blue arrow) and abnormal (red arrow) head-neck contours as seen visually. (**B**) A global view is shown of the head superimposed with the spectrum of color representing the amount of boney protrusion (red) or indentation (blue). A red lesion is seen medially. (**C**) The atlas view is a planar projection of the globe with different clock positions represented along the X-axis. The yellow oval is the insertion of the ligamentum teres. The green rectangle is the region of interest for cam analysis.

rim. Zone 6 is omitted as this corresponds with the insertion of the ligamentum teres. Zones 1, 2, and 7 are anterior, while Zone 8 is midlateral. The mean bump height, volume, and location on the clock face and relative zone prominence are calculated. Zonal differences are analyzed

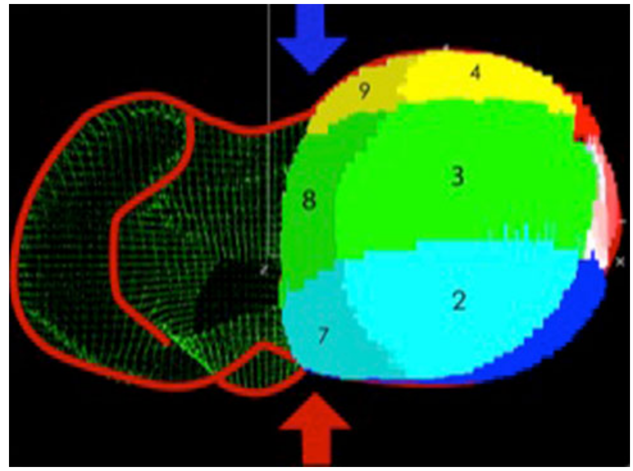

Fig. 2 The modified zoning system applied to the femoral head is shown. Zones 1 to 9 are represented with different colors, and the data from the globe view can be segmented into data specific to each zone.

using ANOVA with post hoc Tukey's test with significance set at $p < 0.05$. The remaining comparisons are completed using unpaired Student's t-tests. All calculations are performed in Microsoft Excel with XLSTAT (Addinsoft, Paris, France).

Our ultimate goal is to decrease pain, improve function, and delay or avoid the onset of osteoarthritis. The next step to bringing this method to clinical use would be accomplished by retrospectively comparing patients who responded or did not respond to surgery and determine if there was a difference in their original CAM lesion size, and determine (based on postresection CT) if the lesions were treated adequately. Information gathered from this analysis may lead to prospective use where treatment decisions are based on lesion parameters.

We envision creating a software package that can be distributed to clinicians treating patients with cam lesions. This software should allow clinicians to upload raw CT data, which then will provide them with a map of the clinically important lesions found on the femoral head and neck.

Limitations

We expect to have several impediments from performing our proposed plan, primarily from clinical and logistical angles. First, our patients likely will have their CT scans performed at various locations, and it is likely that the thickness of the image slices may be variable. As such, the quality of the segmentation will be dependent on the slice thickness. Either setting a minimum standard of CT quality or only selecting scans that were performed in our institution could control for this potential hurdle. Second, from a logistical perspective, we can foresee multiple issues that may prevent its use on a larger scale. One issue is the actual creation of a software tool that is intuitive and user-friendly. Another potential issue is the adaptability of our method with the different types of radiology systems that exist. Third, we also use a software program that assumes a spherical femoral head, then makes refinements to that assumption using a recursive method to find the virtual center of the head. In the case of heads that are grossly aspherical, this method may be difficult to use as a perfectly spherical shape to the femoral head may not be appropriate for the patient. This also points to another limitation in our method which currently does not include the acetabulum. We are aware that the overall interaction of the femoral head and neck with the acetabulum drives a patient's functional status. Future versions of our program will include the acetabulum. Fourth, similar to other imaging-based methods, we provide only a static image (rather than a dynamic pathomechanical model) of the patient's hip. Different patients vary according to activity level and genetic predisposition to osteoarthritis. Correlating the imaging findings with a patient's clinical picture can better guide the next steps in management.

Initial Results

The axial and global views served as a way to observe morphologic features of the femoral head in an anatomically applicable way (Fig. 1A–B). From these views, we were able to observe which aspect of the femoral head-neck junction contained the bony abutment.

The atlas view for the patients with a cam lesion showed a conspicuous red bump on the topographic visualization (Fig. 1C). This corresponds to the anterior aspect of the head-neck junction where the lesion was located. We were able to quantify the bump with the following variables: coordinates of any specific point in the sector, and the height of the specific point (its distance to center minus the mean distance to center). Moreover, we were able to select a rectangular region of interest and quantify the volume of the bump along with average height of the bump in that region.

Except for Patient 2, the mean bump height was larger than the standard deviation of the radii to surface (Table 1). This quantification method allowed us to identify the exact location and size of the bump.

Implications and Future Directions

We describe a novel approach to objectively observe cam lesions in patients with FAI. The quantification of cam lesions is critical for improved understanding of the disorder. This methodology will allow identification of cam subtypes and guide surgeons to perform more accurate femoral osteochondroplasty procedures by prescribing the exact amount of resection needed to normalize the anatomy. Future studies also will attempt to model cam lesions before and after resection to provide additional information about the appropriate amount of resection and eventually will be correlated with hip functional outcome.

Table 1. Quantification of the bump

Patient	Mean radius (mm)	Standard deviation of radii to surface (mm)	Mean bump height (mm)
1	23.96	1.05	1.24
2	22.21	0.90	0.78
3	22.92	1.27	2.54
4	23.48	1.05	2.06
5	23.41	0.94	1.64

We hope to create a method that can be used on a larger scale and be applicable to all institutions and effective in treating patients with cam lesions. In addition, we may consider the use of our technology in other fields of orthopaedics such as shoulder and hip resurfacing. Further adaptations to our method may help guide bony resections in minimally invasive arthroplasties of the hip and knee.

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