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ORIGINAL STUDY

Can a ratio between medial and lateral meniscal volumes be calculated to determine critical meniscal volume in view of post-meniscectomy symptoms?

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Partial meniscectomy is a frequently performed treatment strategy for non-suturable meniscal tears. However, the meniscal volume which can be resected without compromising the load-bearing, shock-absorbing function of the meniscus remains a topic of ongoing research. The aim of this study was to calculate the medio-lateral meniscal volume ratio to estimate this volume.

In 90 patients (98 pairs of menisci) without meniscal injury, medial and lateral menisci were segmented on MRI imaging and 3D surface models were created to calculate volume.

The mean medial meniscal volume was 1928,9mm³ and the mean lateral meniscal volume was 1681,7mm³. A fixed ratio of the medial over the lateral meniscal volume was calculated to be 1,16. The standard deviation of the prediction errors based on this ratio equals 217mm³.

This ratio seems a useful parameter in follow-up research to determine whether there is a critical volume which can be resected without post-operative pain and osteoarthritis.

Keywords : Meniscectomy ; volume calculation ; MRI

INTRODUCTION

The main function of the fibrocartilagenous meniscus of the knee is to increase the cartilage contact area in load bearing conditions, thus decreasing contact stresses within the tibiofemoral joint *(1,15,16)*. Furthermore they act as shock absorbers. Finally, the menisci have been described to play an additional role in anteroposterior stabilization, proprioception as well as the lubrication and nutrition of the articular cartilage *(10,19)*. Meniscal tears are known to alter these functions. By secondarily adversely affecting the articular cartilage metabolism, meniscal tears induce an increased risk for the onset of osteoarthritis in the affected knee joint *(2,3,6,8,12,13,17,18)*.

Partial meniscectomy is routinely performed as a treatment for non-suturable meniscal tears. The torn portion of the meniscus is removed, while the unaffected, stable portion is left intact. This procedure is usually associated with good results, but post-operative pain and an earlier onset of osteoarthritis are well known complications *(2,3,6,8,12,13,17,18)*. It is generally believed that the resection of more meniscal tissue is associated with

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a greater risk for postoperative pain and discomfort. Unfortunately, the precise relationship between the amount of remaining meniscal tissue and subsequent pain or osteoarthritis remains unknown. Of clinical interest is whether there is a critical amount of meniscal tissue that can be removed during surgery without compromising it's load bearing, shock-absorbing functions. While the amount of removed tissue is not the only factor affecting the outcome of surgery, it almost certainly plays a significant role. Both retrospective and prospective studies determining the critical amount that can be removed, could aid surgeons in identifying patient at risk of osteoarthritis. A quantitative method that can reliably assesses the meniscal volume changes pre- and post-operatively is therefore of great importance.

Quantitative magnetic resonance imaging (qMRI) has been used to evaluate meniscal volume ex vivo using phantom and cadaver models *(4)*. Bowers et al. validated qMRI to evaluate meniscal volume in vivo and volume changes after partial meniscectomy *(5)*. However, no accurate way to determine the pre-operative volume and subsequently the removed amount of meniscal tissue has been reported to date. It is possible that a loss of meniscal volume at the time of injury may affect the pre-operative meniscal volumes *(5)*. Therefore a diagnostic pre-operative MRI after injury may confound the preoperative meniscal volume results. Preliminary data have shown that it could be possible to use the volume of the contralateral, uninjured meniscus to estimate the pre-injury volume of the damaged meniscus *(5)*. However, to date no clinically usable method has been postulated to determine the pre-injury volume of the damaged menisci.

The purpose of this study was therefore to determine the volumetric relation between the lateral and medial meniscus in healthy, uninjured knees and determine to what extent this can be used to predict the pre-injury volume of either the lateral or medial meniscus in an injured knee. These data can be used in further research to determine the critical volume that can be removed during partial meniscectomy.

PATIENTS AND METHODS

Following ethical approval, 512 patients were retrospectively selected from the patient database of the University Hospitals of Pellenberg. Patients who were diagnosed with chondromalacia patellae and who received MRI were included in the preliminary data set. Chondromalacia patellae was pragmatically selected as inclusion criterion as tibiofemoral or meniscal morphological abnormalities were not expected in these patients and MR-imaging was standard-of-care. A senior radiologist and the senior clinical investigator of this study manually reviewed the MRI and clinical history of each patient, respectively. All patients with a medial or lateral meniscal tear or with any other meniscal abnormality or with abnormalities in the medial or lateral tibiofemoral compartment were excluded.

Finally, 90 subjects (28 males, 63 females) with a mean age of 28,6 years (range 15-60) were included. 8 had bilateral MRIs, which were both included. In total there were 98 pairs of menisci included in this study.

The MRI images used in this study were obtained by an Intera 3-tesla MR scanner (Philips Medical Systems, Best, The Netherlands) using a circular polarized knee coil. All knees were examined with a T2*-weighted gradient-echo sequence. The reconstructed images had an effective in-plane resolution of 0.39x0.39mm or smaller, and a maximal slice thickness of 3.4mm.

Medial and lateral menisci were each manually segmented using the Boundary Line Editor in 3D-DOCTOR (Able Software Corp. Lexington, Massachusetts, USA). Following segmentation, 3D surface models were created and their volume measured by using the "Complex Surface Rendering" and "Object Volume" functions respectively.

First, the intra-rater reliability of the medial and lateral meniscus volume measurements was analyzed through three repeated calculations of the medial and lateral meniscal volume in five randomly selected subjects by one single rater with a time interval of several days using intraclass correlation coefficients (ICC ; two-way mixed model, single measure) and their 95% confidence intervals *(11)*. Likewise, the inter-rater reliability

coefficient was quantified by comparing medial and lateral meniscus volume measurements in the same five subjects between 2 different examiners using ICC (two-way random model, single measure) and their 95% confidence intervals.

Next, a linear regression model was used to relate the medial or lateral meniscal volume to the contralateral volume of the same knee. The root mean squared error (RMSE) was calculated, reflecting the standard deviation (SD) of the prediction error. Furthermore, as assuming a fixed ratio between both volumes forces the regression to go through the origin, the resulting impact of this assumption on the RMSE was statistically verified. Finally, a similar approach was used to relate, in the subsample of the population for which bilateral MRI's are available, the medial volume with the medial volume of the other knee, and the lateral volume with the lateral volume of the other knee. The ratios were compared between males and females using a Mann-Whitney U test. All analyses were performed using SAS software, version 9.2 of the SAS System for Windows.

RESULTS

The volume measurements showed excellent intra- and inter-rater reliability for both the medial and lateral meniscus with all ICC values surpassing 0.99 (Table I).

Table 1. — Intra- and interrater variability of MRI-based medial and lateral meniscal volume measurements

outcome	Intrarater Reliability ICC(3,1) and 95% Confidence Interval	Interrater Reliability ICC(2,1) and 95% Confidence Interval
medial volume	**0.9954** [0.9769,0.9995]	**0.9946** [0.9608,0.9994]
lateral volume	**0.9912** [0.9567,0.9990]	**0.9935** [0.9526,0.9993]

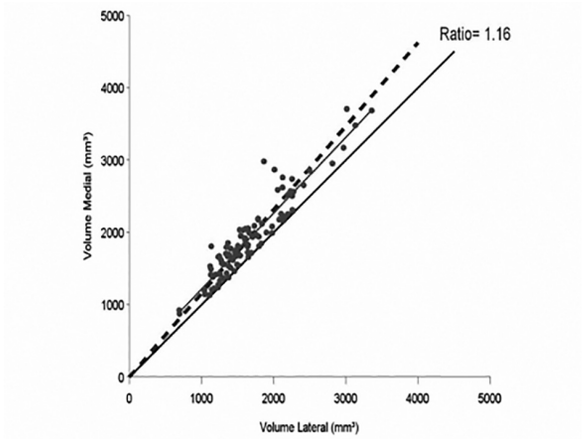

Figure 1. — Prediction of medial volume based on the lateral volume. For illustrational purposes, the black line indicates the indentity line. The green solid line represents the regression line in the unrestricted linear regression model (RMSE=208mm³). The red dashed lines is the prediction assuming a fixed ratio (hence, the regression line if forced going through the origin), yielding a RMSE equal to 217mm³.

The mean medial meniscal volume in our population measured 1928,9 mm³ (SD 560,7 mm³) whereas the mean lateral meniscal volume measured 1674,9 mm³ (SD 504,8mm³).

Figure 1 shows the result of predicting the medial volume based on the lateral volume. If a fixed ratio is assumed between both volumes, the standard deviation of the prediction errors (the RMSE) equals 217mm³ (Table II). Hence, 95% of the prediction errors are expected to fall in the range ±1.96*201.4mm³= ±395mm³. Note that a comparison of the regression line representing the fixed ratio with the regression line from the unrestricted model confirms that this is appropriate

Table 2. — RMSE in mm³ if a fixed ratio is assumed for the relation between the two volumes

outcome	predictor	Total (N=99)	Male Knees (N=28)	Female Knees (N=71)
medial volume	lateral volume same knee	216.6	268.5	192.4
lateral volume	medial volume same knee	186.1	229.0	166.2
				(N=9)
medial volume	medial volume same knee			213.4
lateral volume	lateral volume same knee			180.1

Table 3. — Results from a split descriptive statistical analysis of males and female knees

Variable	Statistic	Female	Male	P-value
Ratio Medial/Lateral (%)	N	71	28	0.870
	Mean	116.2	116.7	
	Std	12.42	18.99	
	Median	114.2	111.2	
	IQR	(105.1; 122.7)	(102.5; 123.2)	
	Range	(100.0; 159.9)	(100.6; 191.8)	

to assume as a fixed ratio. Likewise, there is no evidence for a relation between the lateral volume and the ratio of the medial over the lateral volume (rho=0.1, p=0.33).

Although the mean ratio did not differ between males and females, a higher variability in ratios was obtained for males compared to females (Table III).

The results on knees from female subjects with bilateral information shown in table II indicatively suggests that the use of information from the other knee (medial to predict medial and lateral to predict lateral) has a lower performance (higher RMSE) compared to the use of contralateral information from the same knee. However, a larger sample of bilateral knees is needed to confirm this.

DISCUSSION

Partial meniscectomy as treatment for meniscal injuries is generally associated with good results, although in some cases partial meniscectomy may lead to early osteoarthritis *(6,7,8)*. The precise cause-effect relationship has however so far not been established, but one could expect that volume and morphology changes might play an important role. An accurate method to quantify the meniscal volume and morphology changes in vivo would allow an evaluation over a long period of patients after partial meniscectomy and thus help to elucidate the mechanism involved in the development of early osteo-arthritis. Quantitative MRI is sensitive enough to detect changes in volume pre- and post-operatively *(5)*. This would allow further evaluation of the effect of meniscal tears and partial meniscectomy involved in early osteoarthritis.

During meniscal injury, there is a possibility of loss of meniscal volume that may affect the pre-operative meniscal volumes. This phenomenon may confound the results when comparing the pre- and post-operative meniscal volumes. A reliable method is thus needed to determine the pre-injury volume of the affected meniscus. Preliminary data suggests that it is possible to use the volume of the contralateral, uninjured meniscus to evaluate the pre-injury and pre-operative volume of the injured meniscus *(5)*. However, no extensive research has been performed to date to validate these findings. A second disadvantage is that either two MRI's are needed, or that a double coil MRI is needed which is not available in every clinical setting.

In this study we proposed a method for estimating the pre-injury and pre-operative meniscal volume based on the unaffected contralateral meniscus within the same knee. In our study we found a fixed ratio of the medial meniscal volume over the lateral meniscal volume as 1.16 associated with a 95% confidence interval in terms of predicted volume in the range of ±395mm^3. Thus, after an injury the pre-injury medial or lateral volumes can be estimated by measuring the unaffected meniscus within the same knee. Within a small subsample of our population, our results suggest that the use of information from the other knee has a lower performance compared to the use of contralateral information from the same knee. However, a larger sample of bilateral knees is needed to confirm this.

Since the relationships between meniscal injury, post-meniscetomy pain, and OA are not well understood, it is possible that the volume of meniscal tissue removed during surgery may not be as meaningful as the location from which it is removed. Preservation of the peripheral meniscal rim of the meniscus could be an equally important factor. The 3D segmentation we used allows to determine both volume and morphology, so it will be possible to use these models to assess not only the

volume of meniscal tissue removed during surgery, but also the location from which it is removed and the status of the meniscal rim *(5)* in follow-up research.

Our study has a number of limitations. First, our population was predominantly female. However, our results do not indicate gender to affect the volume ratio. Secondly, the small bilateral knee group does not allow for accurate comparison between the single and the bilateral knee group.

Despite these limitations, we are confident that the ratio that we have defined forms a reliable way to predict the volume of the native meniscus. This should open the door to further investigation of meniscal volume change after partial meniscectomy and thus to further investigation of the link between partial meniscectomy, post-operative pain and early osteoarthritis.

CONCLUSION

A fixed ratio is found to between the medial and lateral meniscal volume. This ratio can be used in further studies to see if a critical volume size can be calculated which can safely be resected in meniscectomy to prevent postoperative pain and osteoarthritis.

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