Timing of surgery for benign periacetabular tumor: virtual finite element analysis and clinical verification on 39 cases

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Research

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Abstract

Background

The treatment of periacetabular tumor has always been met with great challenges, including the lack of a standard for the timing of surgery. The purposes of this study were to predict the risk for fracture by finite element analysis of benign periacetabular tumor; to guide the timing of operation; and to verify the practical application of this standard through clinical cases.

Methods

Bone defects in different areas of the acetabulum were constructed, and the fracture risk was predicted by finite element analysis. According to the results of finite element analysis and Enneking classification, the patients with benign periacetabular tumor were divided into the low fracture risk noninvasive lesion, low fracture risk invasive lesion, and high fracture risk groups. The grouping was used to guide the timing of operation.

Results

This study included 39 patients who were followed-up for at least two years to verify the effectiveness of this program. The 12 patients in the low risk noninvasive lesion group that did not undergo operation showed no obvious pathological changes and no pathological fracture; there was no significant difference in the MSTS-93 score between the first and last visits ($P > 0.05$). The 7 patients in the low risk invasive lesion group were treated with adjuvant therapy before the operation; the MSTS-93 score was significantly lower on the first visit than on the last visit ($P < 0.05$). The 20 cases that had high risk for fracture underwent surgery after the diagnosis; of these, 13 patients achieved osseointegration of the graft bone and 7 patients had no prosthesis loosening, detachment, displacement or rupture after prosthesis replacement. The MSTS-93 score significantly improved from a preoperative value of 19.61 ± 7.32 to a final follow-up value of 26.28 ± 15.59 ($P < 0.01$).

Conclusions

Our study confirmed that for benign periacetabular tumor, finite element analysis, combined with the nature of the tumor, can predict the risk for acetabular fracture and guide the appropriate timing and method of operation, thereby, enabling a safe therapeutic effect.

Background

The diagnosis and treatment of acetabular bone tumors has always been a great challenge for bone oncologists [1–3]. Often, several postoperative complications may occur because of the deep location; complex anatomical structures; and the adjacent important nerves, vessels, and organs [4–6]. For malignant bone tumors in this area, surgeons often choose wide resection and reconstruction [7–9]. However, some benign periacetabular tumors are common in this area; some examples are giant cell tumor of the bone, fibrous dysplasia, bone cyst, chondroblastoma, and Langerhans cell dysplasia [1, 5, 6, 10]. For benign periacetabular tumors of different Enneking grades, unified standards on the assessment of fracture risk and timing of operation are lacking [2, 6, 11–14]. The dome of the acetabulum is the weight-bearing part of the articular surface and supports the femoral head; tumors in this area will decrease bone strength. In usual clinical practice, most surgeons make the diagnosis and treatment decisions based on experience. Finite element analysis (FEA) has been successfully applied in

orthopedics and can be a good tool for studying the mechanics of irregular bone structures. In the past, biomechanical analysis of the pelvis has mostly aimed at the normal pelvis, fracture model, and artificial prosthesis replacement model after tumor resection [15–17]. There had been no reports on the biomechanical analysis of benign neoplastic bone defects in the acetabulum. Therefore, this study aimed to establish an acetabular top bone defect model and to perform mechanical analysis for the evaluation of fracture risk in the periacetabular bone defect caused by a benign bone tumor, in order to guide the timing of operation.

Methods

In this study, we constructed a simulated model of neoplastic bone defects in different areas on top of the acetabulum. The fracture risk was predicted by three-dimensional (3D) FEA, the results of which were used to divide patients into the low fracture risk and high fracture risk groups and to guide the timing of surgical treatment of 39 patients with benign acetabular bone dome tumors. Clinical follow-up was performed for at least two years.

Finite element analysis

At the beginning of the study, we established a static biomechanical 3D finite element model of a neoplastic bone defect caused by a benign bone tumor on the top of the acetabulum using thin-slice CT scans from May 2014 to October 2014. Stress loading was carried out in the following positions: sitting, standing on two feet, standing on one foot on the affected side, and simulated one foot jumping state. The magnitude and distribution of stress in each model were analyzed. The fracture risk of the benign acetabular dome bone defect was evaluated based on biomechanics, and the decision-making on clinical diagnosis and treatment was further guided using this model.

The CT scan DICOM data of the normal pelvis of one patient (26 years old, 173-cm tall, 60 kg in weight) were imported into Mimics V15.0 software for 3D reconstruction and to simulate a normal pelvis and proximal femur model. According to the gray value of the CT image, the property of the bone material was assigned in Mimics as cortical bone elastic modulus of 17-Gpa, Poisson's ratio of 0.3, and fatigue strength of 150 Mpa for the upper and lower pubic area and 120 MPa for the acetabular area. Different types of acetabular dome bone defect models were simulated in Mimics. All parts were imported into ABAQUS 6.13 for assembly and meshing. The nodes and element number of each model are shown in **Table 1**.

There are six types of bone defect located 5-mm away from the acetabular dome. In type I, the anterior column is resected above the inferior margin of the acetabulum in the pelvic AP position. In type II, the posterior column is resected above the superior margin of the acetabulum in the pelvic AP position. In type III, 50% of the anterior column is resected at the medial part of the acetabulum dome and connected to the posterior column above the lower edge of the acetabulum. In type IV, the anterior column of the acetabulum is resected and connected to 50% of the posterior column. In type V, 50% of the anterior column and 50% of the posterior column are resected and connected to the acetabular dome. In type VI, the entire anterior and posterior columns of the acetabulum dome were removed) (**Fig. 1**).

The six types of bone defects in four different positions were analyzed in a software; the positions were sitting, standing, affected one-legged standing, and affected one-legged jumping. In reference to previous studies [18–20], a vertical downward load of 500 N was imposed on the surface of the sacrum to simulate the gravity of the upper part of the body. The loading power of the stress was 500 N in the sitting, standing, and affected one-legged standing positions and 1000 N on the affected acetabular dome to stimulate a one-legged jumping position.

Based on the previously reported fatigue strength of 120–150 Mpa for the pelvic cortical bone, the acetabular fatigue strength in this study was set as 120 Mpa.

The fracture risk of the acetabulum dome was evaluated by FEA, which showed results that are described in the next sentences. In the normal pelvic model, the maximum stress was 1.5 MPa on the sciatic tuberosity in the sitting position; 0.6 MPa on the superior border of the greater sciatic notch in the standing position; and 3.5 MPa on the upper edge of the greater sciatic notch in the affected one-legged standing position. Among all the positions in the six different types of bone defects, the maximum stress was observed in the affected one-legged jumping position. The maximum stress values of 22.8, 36.0, 40.6, and 30.9 Mpa in the type I, II, III, and V bone defect models, respectively, were far less than the acetabular fatigue strength of 120 Mpa. The maximum stress values of 106.7 Mpa and 114.0 Mpa in the type IV and VI bone defect models, respectively, were close to the acetabular fatigue strength value that was at risk for fracture (**Fig. 2**).

According to the predicted fracture risk outcome of the top of the acetabulum, we divided the bone lesions into the following two groups: the low fracture risk group, which included type I, II, III, and V bone defect models, and the high fracture risk group, which included type IV and VI bone defect models.

Clinical verification

Our study was approved by the institution research ethics board, and informed consent was obtained from all patients. The inclusion criteria were 1) patients with acetabular lesions that mainly involved the acetabular dome and 2) benign bone tumor that was pathologically-proven or highly suspected by the doctor based on symptoms, medical history, and ancillary examination. The exclusion criteria were 1) malignant tumor; 2) pelvic tumor that did not involve the acetabular dome; 3) pelvic lesions that caused severe clinical symptoms and involved the acetabulum, which needed simultaneous surgical treatment; and 4) pathological fractures on the first visit. From January 2015 to July 2018, a consecutive series of patients seen at our institution for benign bone tumors on the acetabulum dome were enrolled in this study.

First, the range of acetabular fornix involved in each patient was divided, based on the results of CT and MRI. The patients were divided into the low and high fracture risk groups, according to the results of the FEA. According to clinical evaluation of the doctor, the low fracture risk group was further divided into the invasive lesion group (Enneking III) or the noninvasive lesion group (static or active lesion, Enneking I and II). The high fracture risk group was not further divided. Finally, all patients were divided into the following three groups: low fracture risk noninvasive lesion, low fracture risk invasive lesion, and high fracture risk groups.

The low fracture risk noninvasive lesion group was followed-up in the outpatient clinic. The following were recorded on the first visit: initial diagnosis of the doctor, acetabular lesion site, and Musculoskeletal Tumor Society Score-93 (MSTS-93) [21]. Subsequently, the patients were followed-up every three months by CT or MRI, according to the doctor's discretion. The main outcome measures were acetabular lesion changes, MSTS-93, and occurrence of pathological fracture. Operation was immediately performed if there was obvious progression of the lesion or pathological fracture of acetabular dome.

Likewise, the low fracture risk invasive lesion group was followed-up in the outpatient clinic. On the first visit, the patient diagnosis, lesion site (acetabular involvement), and MSTS-93 were recorded. The operation was not arranged temporarily, activity was not restricted, and adjuvant therapy with bisphosphonate intravenous injection or dinosemide was administered, according to diagnosis. The patients were examined every two to three months

with CT or MRI examination, according to the doctor's discretion. Changes in the lesions and occurrence of pathological fractures were assessed during each follow-up, and MSTS-93 functional score was recorded on the last follow-up. Operation was performed at the end of the adjuvant treatment or when the lesion changed and became at high risk for fracture, based on the FEA.

The high fracture risk group was examined and underwent surgical treatment after diagnosis. The surgical treatments included the following: 1) curettage with bone grafting or bone cement; 2) tumor resection, total hip replacement, and acetabulum reconstruction with the femoral head; or 3) tumor resection with modular hemipelvic replacement.

Statistical analysis

Continuous data were expressed as mean $\pm$ standard deviation. The normality of continuous data was tested by the one sample Kolmogorov–Smirnov test. Normally distributed parameters were analyzed by the independent sample t-test, and nonnormally distributed parameters were analyzed by the Mann–Whitney U-test. A P value of ≤ 0.05 was considered statistically significant. Statistical analysis was performed by SPSS Statistics software version 23.0 (IBM, Armonk, NY).

Results

The study included a total of 39 patients with a mean age of 42.4 years (14–60 years); 26 were men and 13 were women. The median follow-up period was 33.36 ± 11.41 months (24–67 months).

As shown in **Table 2**, the low risk noninvasive lesion group comprised 12 cases that did not undergo operation. All patients did not undergo pathological examination but were clinically diagnosed by doctors as fibrous dysplasia (n = 5), simple bone cyst (n = 4), and unknown (n = 3). During the follow-up period, there were no obvious pathological changes and pathological fractures in all patients. There was no significant difference in the MSTS-93 score between the first and last visits ($P > 0.05$).

Table 3 shows the data of the patients in the low risk invasive lesion group. There were seven cases that were pathologically diagnosed as giant cell tumor of the bone (n = 3), aneurysmal bone cyst (n = 3), and giant cell tumor of the bone with aneurysmal bone cyst (n = 1). All patients were treated with adjuvant therapy; four cases were treated with bisphosphonate intravenous infusion for 3–4 times and the remaining three cases were treated with dinosemide infusion. The operation performed was enlarged curettage of the focus and inactivated bone grafting in the tumor cavity. One case of giant cell tumor of the bone with recurrent aneurysmal bone cyst had a recurrence rate of 14.29%. The MSTS-93 score was significantly lower on the first visit than on the last visit ($P < 0.05$). The pathological results in all patients were confirmed after operation.

There were 20 cases in the high fracture risk group. The diagnoses were fibrous dysplasia (n = 6), hemangioma (n = 3), Langerhan's cell hyperplasia (n = 1), aneurysmal bone cyst (n = 3), giant cell tumor of the bone with aneurysmal bone cyst (n = 3), chondroblastoma (n = 1), diffuse giant cell tumor of the tendon sheath (n = 1), and giant cell tumor of the bone (n = 2). No distant metastasis was observed after surgery. One case of giant cell tumor of the bone developed local recurrence on the second year after the operation and was treated with extended resection, whereas the other case of giant cell tumor of the bone recurred one year after the operation and was cured by reoperation. The case of diffuse giant cell tumor of the tendon sheath was cured at three months after two-stage reconstruction of the right hip joint. One case had bilateral pleural effusion after the operation. For the

surgical incision site, exudate developed in 4 cases; redness and swelling developed in 2 cases and healed after standard dressing change and antibiotics; fat liquefaction developed in 2 cases and healed after standard dressing change. In 13 patients who underwent curettage and bone grafting, osseointegration of the graft bone and satisfactory bone strength of the acetabular dome on X-ray were achieved at 12–15 months after the operation. In seven patients who underwent tumor resection and prosthesis replacement, there was no prosthesis loosening, detachment, displacement, or rupture observed. The MSTS score significantly improved from a mean preoperative value of 19.75 ± 6.47 to a final follow-up value of 26.30 ± 4.35 ($P < 0.01$). The data of the patients in high fracture risk group are recorded in **Table 4**.

Discussion

The treatment of bone tumors on the acetabular dome remains a challenge. Moreover, assessment of the nature of the tumor and the risk for pathological fracture had been difficult. Based on previous studies, there are no clear criteria for the diagnosis of pathological fractures of the acetabular fornix. However, most scholars believe that there are many postoperative complications that are difficult to avoid because of the complexity of the operation [18–20]. For pathological fracture risk assessment of metastatic tumors, a Mirels score of ≥ 8 implies a high probability of fracture and is an indication for preventive surgery [21]. One study by Damron T et al reported that the prediction of metastatic fractures was more accurate by CT-based structural stiffness analysis than by the Mirels scoring system [22]. However, there has been no risk prediction model for benign tumors of the acetabulum, and the treatment strategy for these lesions remains to be further explored.

In this study, based on the Judet–Letournel classification system, a defect model located 5 mm from the center of the acetabular dome was established by FEA. A 3D FEA of acetabular tumors was carried out to provide scientific data on the stress concentration in the model of a benign bone defect on the top of the acetabulum from the aspect of biomechanics, in order to predict the risk of fracture. To our best knowledge, this has not been previously reported. Our FEA results showed a relatively low fracture risk for lesions in a single anterior or posterior column; lesions that involved 50% of the anterior column and the posterior column; and lesions that involved 50% of the anterior column and 50% of the posterior column on the top of the acetabulum. On the other hand, there was a high risk for pathological fracture when there was involvement of both columns or involvement of the anterior column and 50% of the posterior column.

Among patients who were at low risk for fracture, those who had noninvasive lesions achieved satisfactory results with nonoperative treatment, probably because of the limited scope and the little impact on the stability of the acetabular bone; whereas those who had invasive lesions needed surgical treatment with appropriate adjuvant therapy, when needed. In the latter group, the patients were advised to continue their normal activities, in order to reduce the risk for recurrence and decreased the difficulty of the operation; all patients in this group recovered well and achieved high tumor control after surgical treatment and complete adjuvant therapy. For patients at high risk for fracture, regardless of the nature of the tumor, surgery should be chosen to prevent pathological fractures, which can make the operation more difficult, and to reduce the risk of tumor recurrence.

Invasive benign tumors, such as giant cell tumor of the bone or chondroblastoma, usually require surgical treatment, because they have a progressive growth [8, 23]. Regardless of the risk of fracture, these tumors are surgically removed and treated with intraoperative local adjuvant agents. Tumor resection, bone graft reconstruction, and artificial joint replacement may result in complete removal of the tumor but can lead to many complications [10, 24–27]. In order to reduce the risk of complications, improve function, shorten operation time,

and reduce surgical injury, other aspects may need to be considered. As shown in this study, further improvements in the level of diagnosis and exploration of new auxiliary treatment measures, such as the treatment of low risk invasive tumors, may serve this purpose. In addition, for patients who need prosthesis replacement, improving the prosthesis design has always been the direction of clinicians' efforts. According to the preoperative CT and MRI image data, a 3D printed pelvic tumor model and an osteotomy guide plate were established to simplify the operation procedure and to obtain a more accurate operation boundary. Personalized 3D printed prosthesis was reported to improve individual matching and functional results and will be the future development direction [28–29].

Limitations

Because of the lack of micro-CT and further computer hardware support, the model established in the present study failed to accurately simulate the cancellous bone and reconstruction of the surrounding pelvic muscles. Among the three static pelvic positions, the affected leg standing position had the greatest stress and accounted for only 81% of the body weight. On steady walking, pelvic stress can reach 4–7 times the maximum weight (4 times the weight upon heel landing, 7 times the weight before toe lifting); as the walking becomes faster, the stress increases. When running and jumping, the maximum weight is up to 10 times. Therefore, stress analysis on the bone defect models in this study failed to predict all pathological fracture risks. Moreover, because bone strength is significantly lower in an actual pelvis than in a healthy pelvis, the stress analysis in this study may have underestimated the risk of fracture. During postoperative functional exercise, the stress on the pelvis is 1.5 times as much as that of the body when raising a straight leg. In order to know the safety of a functional exercise, the stress on the pelvis on straight leg raising should be analyzed.

For the clinical case verification, only 39 patients were included in this study; this may have created a selection bias that would limit the generalizability of the present results. A larger sample size may have led to more significant univariate associations. Our study ignores the type of disease and the nature of the tumor, which has a certain impact on the results. The focus was divided according to the acetabulum defects locations, which were not further compared; this may have affected the final results of the experiment to a certain extent. In patients who did not undergo surgery, some of the clinical diagnosis of the doctors may have been inaccurate. Because of the limitations of the follow-up time, the long-term changes in the lesions were not known. All these limitations were important factors that may have led to biases in this study.

Conclusions

The results of this study confirmed that for benign periacetabular tumors, 3D FEA combined with the nature of the tumor may predict the risk for acetabular fracture and guide the decisions on the appropriate timing and method of operation. These would lead to more safe therapeutic effects.

Abbreviations

FEA, finite element analysis; MSTS-93, Musculoskeletal Tumor Society Score 93; CT, computed tomography; GCT, giant cell tumor; MRI, magnetic resonance imaging

Declarations

Availability of data and materials

The datasets used and analyzed during the current study are available from the corresponding author on reasonable request.

Ethics approval and consent to participate

This study has been approved by the Biomedical Ethics Committee of West China Hospital of Sichuan University, approval No. 2014 (189).

Consent for publication

Written informed consent was required from all patients before the start of the study.

Competing interests

The authors declare no conflicts of interest.

Funding

There was no fundamental support in this study.

Authors' contributions

HY: designed the study, collected and analyzed the data, prepared the manuscript. WZ: collected and analyzed the data, prepared the manuscript. YL: collected and analyzed the data, prepared the manuscript. XF: prepared the manuscript. All authors read and approved the final manuscript and agreed to be accountable for all aspects of the work.

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Tables

Table 1 Pelvic model parameters

Model	Type I	Type II	Type III	Type IV	Type V	Type VI	Normal pelvis
Units	205277	210649	206170	205739	208338	204499	204506
Nodes	57205	58512	57613	57522	58051	57256	56913
Minimum unit volume (mm ³)	0.0003284	0.0003284	0.0003056	0.0003031	0.0004396	0.0002472	0.0004418
Maximum unit volume (mm ³)	780	1006	1090	1211	1075	1055	829
Total volume (mm ³)	120604	125509	118827	118006	120459	115890	127133

Table 2 General and follow-up data of the patients in the low risk noninvasive lesion group (n = 12)

Sex/ Age	Diagnosis	Range of acetabular involvement	Follow-up time (months)	First MSTS-93	Last MSTS -93	P value
M/20	Fibrous dysplasia	50% anterior column + posterior column	33	27	29	
F/26	Unknown	The anterior column	27	29	30	
M/35	Fibrous dysplasia	Posterior column	24	25	30	
M/18	Bone cyst	The anterior column	42	27	29	
F/41	Fibrous dysplasia	Posterior column	36	28	29	
M/26	Bone cyst	The anterior column	39	26	28	
F/35	Fibrous dysplasia	50% anterior column + posterior column	28	24	27	
M/16	Bone cyst	The anterior column	36	25	28	
M/36	Fibrous dysplasia	50% anterior column + posterior column	33	29	30	
M/21	Bone cyst	50% anterior column+ 50% posterior column	60	28	30	
M/45	Unknown	Posterior column	24	27	30	
F/37	Unknown	Anterior column	52	29	29	
				27.00±1.71	29.08± 0.99	0.067

Table 3 General and follow-up data of the patients in the low risk invasive lesion group (n = 7)

Sex/ Age	Diagnosis	Range of acetabular involvement	Operated on or not	Follow-up time (months)	Recurrence	First MSTS- 93	Last MSTS -93	P value
M/23	Giant cell tumor	50% anterior column + posterior column	Y	42	N	24	27	
F/29	Aneurysmal bone cyst	Posterior column	Y	27	N	25	26	
F/31	Giant cell tumor	50% anterior column+ 50% posterior column	Y	36	N	24	30	
M/22	Aneurysmal bone cyst	Anterior column	Y	32	N	28	29	
M/34	Aneurysmal bone cyst	50% anterior column + posterior column	Y	40	N	26	29	
M/23	Giant cell tumor with aneurysmal bone cyst	Posterior column	Y	67	Y	26	26	
M/35	Giant cell tumor	50% anterior column+ 50% posterior column	Y	42	N	24	28	
						25.29 ±1.50	27.86 ± 1.57	0.009

Table 4. General and follow-up data of the patients in the high risk of fracture group (n = 20)

Sex/ Age	Diagnosis	Range of acetabular involvement	Operated on or not	Follow- up time (months)	Recurrence	First MSTS- 93	Last MSTS -93	P value
M/44	Giant cell tumor	Anterior column+ posterior column	Y	33	Y	15	27	
F/50	Giant cell tumor with aneurysmal bone cyst	Anterior column+ posterior column	Y	42	N	12	23	
M/16	Fibrous dysplasia	Anterior column + 50% posterior column	Y	24	N	21	27	
F/45	Fibrous dysplasia	Anterior column+ posterior column	Y	36	N	21	29	
F/14	Hemangioma	Anterior column+ posterior column	Y	48	N	17	28	
M/25	Aneurysmal bone cyst	Anterior column+ posterior column	Y	52	N	19	27	
M/22	Langerhans cell dysplasia	Anterior column+ posterior column	Y	60	N	22	29	
M/41	Giant cell tumor with aneurysmal bone cyst	Anterior column + 50% posterior column	Y	36	N	9	25	
M/31	Fibrous dysplasia	Anterior column+ posterior column	Y	28	N	30	30	
F/51	Diffuse giant cell tumor of the tendon sheath	Anterior column+ posterior column	Y	56	N	15	19	
M/49	Hemangioma	Anterior column + 50% posterior column	Y	52	N	12	27	
F/18	Chondroblastoma	Anterior column+	Y	49	N	10	24	

		posterior column					
M/60	Fibrous dysplasia	Anterior column+ posterior column	Y	26	N	30	28
F/40	Aneurysmal bone cyst	Anterior column + 50% posterior column	Y	38	N	19	12
M/40	Diffuse giant cell tumor of the tendon sheath	Anterior column+ posterior column	Y	27	N	18	28
M/34	Hemangioma	Anterior column+ posterior column	Y	56	N	25	28
M/44	Fibrous dysplasia	Anterior column+ posterior column	Y	25	N	30	30
F/42	Fibrous dysplasia	Anterior column + 50% posterior column	Y	30	N	26	30
M/44	Aneurysmal bone cyst	Anterior column+ posterior column	Y	64	N	24	30
M/38	Giant cell tumor with aneurysmal bone cyst	Anterior column+ posterior column	Y	40	N	20	25

Figures

Figure 1

Six different types of periacetabular bone defect models were prepared using finite element analysis; the red part indicates the area of bone defect. a–f: types I–VI bone defect.

Figure 2

Finite element analysis was used to calculate the stress value of periacetabular bone in different states to predict the risk of fracture. a. Stress distribution of the normal pelvis in the affected one-legged jumping position. b. Stress distribution of the type VI bone defect model at 33.0 MPa , 106.7 MPa , 48.1 MPa , 47.4 MPa , 13.8 MPa , c. 17.8 MPa , 114 MPa , 38.9 MPa , 20.4 MPa , and 28.9 MPa .