

ORIGINAL

Can intraoperative kinematic analysis predict postoperative kinematics following total knee arthroplasty? A preliminary study

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Abstract : The preliminary study analyzed the relationship between intraoperative navigation-based kinematics and postoperative 2-dimensional/3-dimensional (2D/3D) image registration-based kinematics in total knee arthroplasty (TKA). Six knees in 5 patients were analyzed. All TKA procedures were performed using an image-free knee navigation system. Tibial internal rotation was assessed by intraoperative knee kinematics. At 1 year after surgery, tibial internal rotation was evaluated using a 2D/3D image registration technique under loaded and unloaded conditions. The correlation between intraoperative and postoperative data for the tibial internal rotation angle at 10° increments of knee flexion was then assessed. Difference in the knee flexion angle between the intraoperative and postoperative evaluations was adjusted to account for the sagittal cutting angle of the distal femur and proximal tibia. A correlation was found between the intraoperative and postoperative data for loaded knee flexion with this adjustment (Pearson's $r = 0.725$, $p = 0.012$). However, intraoperative kinematics was not significantly correlated with postoperative kinematics in the absence of loading. Larger adequately powered prospective studies are now needed to confirm our preliminary finding that postoperative loaded kinematics can be predicted by intraoperative evaluation. *J. Med. Invest.* 65 : 21-26, February, 2018

Keywords : intraoperative analysis ; postoperative analysis ; knee arthroplasty ; kinematics ; navigation system

INTRODUCTION

Total knee arthroplasty (TKA) is a surgical procedure used to treat pain, disability, and limited motion associated with osteoarthritis. Although previous studies have indicated long-term implant survival after TKA (1, 2), a substantial proportion of patients remain dissatisfied after surgery despite having a favorable clinical outcome. Previous research has reported a patient dissatisfaction rate of 19% (3), which can be explained in part by the change in kinematics after TKA (4).

Various methods of evaluating kinematics in TKA have been reported. A 2-dimensional (2D)/3-dimensional (3D) image registration technique has been widely used for postoperative in vivo kinematic analysis (5, 6). This technique determines the spatial position and orientation of the metallic femoral and tibial implant components by X-ray fluoroscopy as well as creates a computer-aided design (CAD) model of the implant. The advantage of the technique is that it can analyze knee kinematics under active and weight-bearing conditions. Most studies assessing the relationship between deep knee flexion and postoperative knee kinematics have included patients who can achieve deep knee flexion after TKA. Kanekasu *et al.* (7) assessed 18 knees in 12 patients after posterior-stabilized TKA and found that tibial internal rotation increased with greater degrees of knee flexion. Moynihan *et al.* (8)

similarly reported that posterior femoral translation and tibial internal rotation increased steadily at $> 90^\circ$ of knee flexion after posterior-stabilized TKA. Given these previous findings, it is widely accepted that deep flexion of the knee can be achieved with internal rotation of the tibia. In fact, this acceptance also seems to be reflected in other studies using different approaches for TKA (9-11).

Recently, with the widespread use of navigation systems in TKA, reports of intraoperative kinematic analysis using these systems have been increasing. Ishida *et al.* (12) divided femorotibial rotation patterns into four groups and found that preoperative contracture and varus deformity correlated with maximum flexion angles before and after TKA. Matsuzaki *et al.* (13), measuring soft-tissue balance parameters in a navigation system using an offset-type tensor, found that lateral laxity at mid-to-deep knee flexion plays a significant role in tibial internal rotation in postoperative knee kinematics after cruciate-retaining TKA. Klein *et al.* (14) evaluated the effect of two types of tibial insert and found a significant difference in femorotibial rotational motion using a navigation system. Nishio *et al.* (15) described how intraoperative medial pivot patterns, including tibial internal rotation, resulted in significantly greater flexion angles and better subjective outcomes. Intraoperative kinematic analysis using a navigation system relies on accurate positioning of the total knee components. The only opportunity for knee kinematics to be adjusted under passive and non-weight-bearing conditions is during surgery, so it is important to be able to assess the relationship between intraoperative navigation-based kinematics and postoperative 2D/3D image registration-based kinematics for TKA. However, to date, no such investigation has been reported.

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The aim of this preliminary study was to investigate the correlation between postoperative kinematics determined using the 2D/3D image registration technique and kinematics determined intraoperatively using a navigation system.

PATIENTS AND METHODS

From June 25 to July 16, 2010, 33 patients visited the outpatient clinic at our institution for follow-up 1 year after primary TKA. A Scorpio NRG cruciate-retaining total knee prosthesis (Stryker Orthopaedics, Mahwah, NJ) was implanted in 11 of these patients and other implants were used in the remaining 22. The Scorpio NRG prosthesis has an unconstrained fixed-bearing design. Three of the 11 patients who received this prosthesis were excluded because of a diagnosis of rheumatoid arthritis, leaving 10 knees from 8 patients with a diagnosis of osteoarthritis and capable of $> 120^\circ$ knee flexion at 1 year after TKA for analysis.

Preoperatively, all 10 knees had varus deformity. Intraoperative kinematic data were captured using an image-free knee navigation system (Stryker Navigation version 1.0; Kalamazoo, MI) with infrared cameras and light-emitting diodes (16). Postoperative kinematic analysis was performed using the 2D/3D image registration technique. However, complete intraoperative kinematic data were not available for 4 of the 10 knees, leaving 6 knees for 5 patients (4 women, 1 man; mean age at surgery 74.5 years; age range, 69-85 years) for analysis. The intraoperative and postoperative kinematic data for these 6 knees were evaluated to assess the correlation between intraoperative and postoperative knee kinematics.

Surgical procedure

Surgery was performed using a tourniquet and a standard medial parapatellar approach. Registration of the navigation system was done following the manufacturer's protocol. The measured resection technique was used for bone resection. Bony island resection was performed while preserving the posterior cruciate ligament. The femoral rotational axis was set parallel to the surgical epicondylar axis, and the tibial rotational alignment was directed along a line from the medial border of the tibial tubercle to the middle of the posterior cruciate ligament (17). The width of the flexion-extension gap and ligament balancing were checked using a spacer block to avoid laxity, and thickness of the polyethylene insert was determined. The patella was resurfaced in all cases. After releasing the tourniquet, the components of the tibia and patella were cemented. Finally, the cementless femoral component was assembled. The same surgeon performed all 10 procedures.

Evaluation of intraoperative kinematics

After assembling each component and cementing onto the tibial surface, the dissected fascia was closed using two forceps. The rotational axes of the femur and tibia were reset to the axes of the components. Kinematic analysis was performed by the same surgeon using the navigation system. The knee was flexed with the heel supported in the examiner's open palm and the knee supported by the other hand without the tourniquet (Figure 1). Care was taken to avoid axial rotation of the tibia throughout flexion. The navigation system automatically recorded the rotation angle of the tibia (positive for internal rotation) at 10° increments from 10° to 120° of flexion. The reproducibility of this method is described elsewhere (18).

Evaluation of postoperative kinematics

Postoperative kinematic analysis was conducted 1 year after the surgery. Mean patient age at the time of fluoroscopic surveillance was 75.5 years (range 70-86 years). Under fluoroscopic surveillance in the sagittal plane, patients performed sequential deep knee

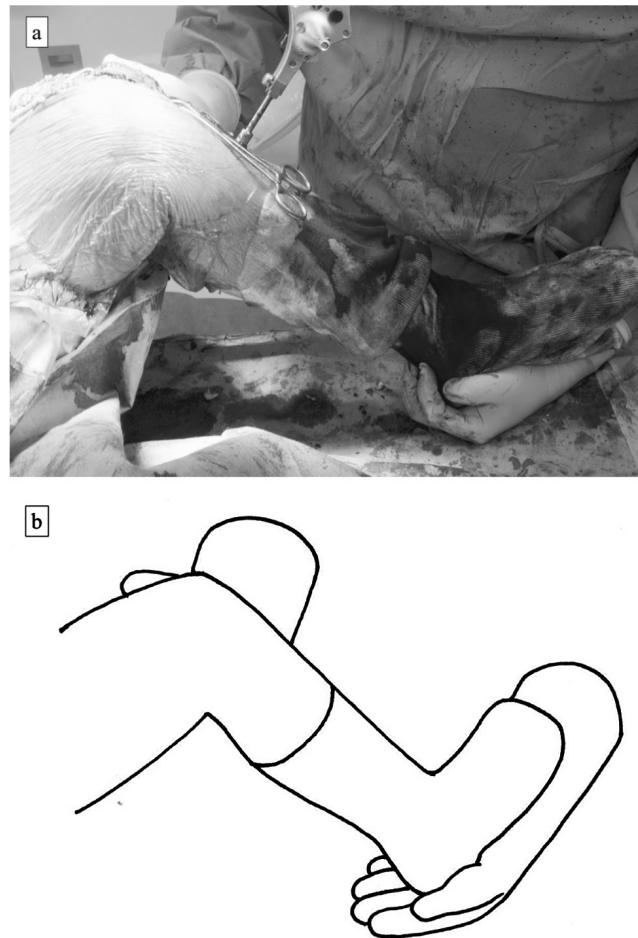


Figure 1 (a) Method for evaluating intraoperative kinematics in patients undergoing total knee replacement. For left knee flexion, the knee is flexed with the heel supported in the examiner's open palm. (b) The simplified illustration of the method for evaluating intraoperative kinematics.

bending under loading from full extension to maximum flexion (Figure 2). They stood with their feet in neutral rotation and were allowed to hold onto a handrail for safety. They were also asked to perform sequential deep knee unloaded bending from full extension to maximum flexion in the sitting position. Successive knee motions were recorded as serial digital X-ray images ($1,024 \times 1,024 \times 12$ bits/pixels, 7.5 Hz serial spot images as a Digital Imaging and Communications in Medicine [DICOM] file) using a 12-inch digital image intensifier system (Digitex Alpha Plus AUD 150-G; Shimadzu Corporation, Kyoto, Japan) and 1.2-2.0-ms pulsed electron beams.

3D in vivo positions of the knee prosthesis were computed using a 2D/3D registration technique that uses CAD models to reproduce the spatial positions of the femoral and tibial components from calibrated (including distraction correction) single-view fluoroscopic images. The registration algorithm (19) uses a feature-based approach to minimize distances between lines drawn from a contour found in the 2D images to the X-ray source and a surface CAD model with iterative computations.

The 2D/3D registration technique was validated by phantom experiments (20). Root mean squares of the relative position of the femoral component in the tibial component coordinate system

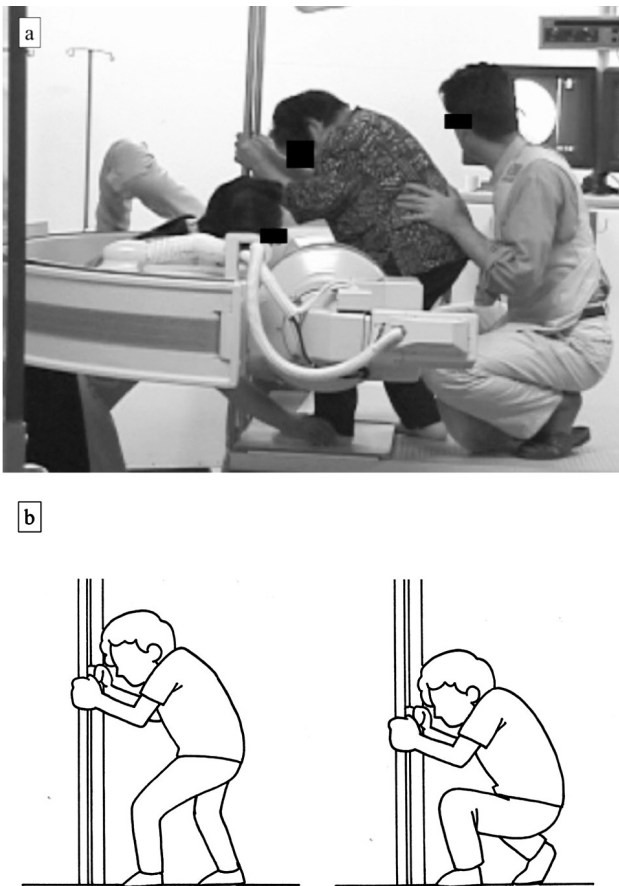


Figure 2 (a) Method for evaluating postoperative kinematics. For safety, the patient holds onto a handrail with an assistant supporting the patient from behind. (b) The simplified illustration of the method for evaluating postoperative kinematics.

were 0.2°, 0.6°, and 0.6° for rotation in the coronal, axial, and sagittal planes, respectively, and 0.6, 0.3, and 1.0 mm for translation perpendicular to the coronal, axial, and sagittal planes. The relative position of the prosthesis was calculated using the 2D/3D registration technique for every frame of the sequential fluoroscopic images during the flexion cycle. The calculated data were sampled at 10° increments from minimum to maximum flexion.

Statistical analysis

Statistical analysis was performed using SPSS for Mac OS X, version 21 software (IBM Corp., Armonk, NY). The correlation was assessed between the intraoperative and postoperative evaluations of the mean tibial internal rotation angle at each 10° increment of knee flexion. A p-value of < 0.05 was considered significant.

It should be noted that the intraoperative and postoperative evaluations reflect different knee flexion angles, in that intraoperative assessment uses the angle of the mechanical axis as the knee flexion angle, whereas postoperative evaluation uses the angle of the component axis. Thus, the navigation data for the sagittal cutting angles of the distal femur and proximal tibia were used to adjust these two angles. In our 5 patients, the mean angle of the femur was 2.25° (range 1-3°) and that of the tibia was 3.25° (range 1.5-4.5°), for a difference of about 5.5° in knee flexion angle between the intraoperative and postoperative analyses (Figure 3). However, the

tibial rotation angle was recorded only at 10° increments in both analyses. Therefore, to adjust the knee flexion angle, the correlation analysis was also performed by shifting 10° between the intraoperative and postoperative evaluation.

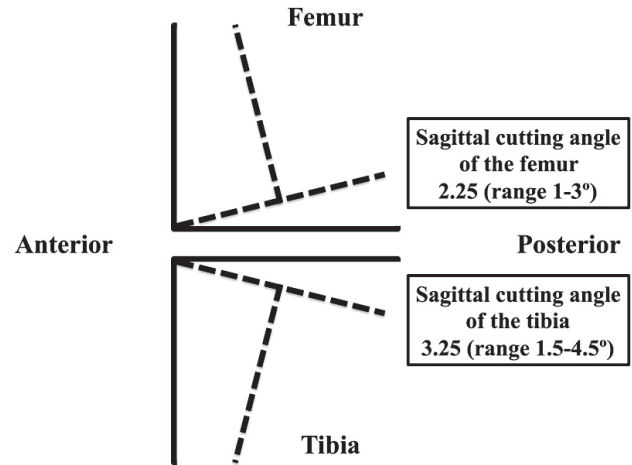


Figure 3 Schema for the method used to adjust the knee flexion angle. Solid lines indicate mechanical axes for intraoperative evaluation. Broken lines indicate component axes for postoperative evaluation.

RESULTS

Intraoperative data for 10-120° degrees of knee flexion were available for all patients, but postoperative data were available for 0-100° only (Figures 4 and 5). Tibial external rotation during the early stage of knee flexion and internal rotation during deep knee flexion are shown in both the intraoperative and postoperative analyses.

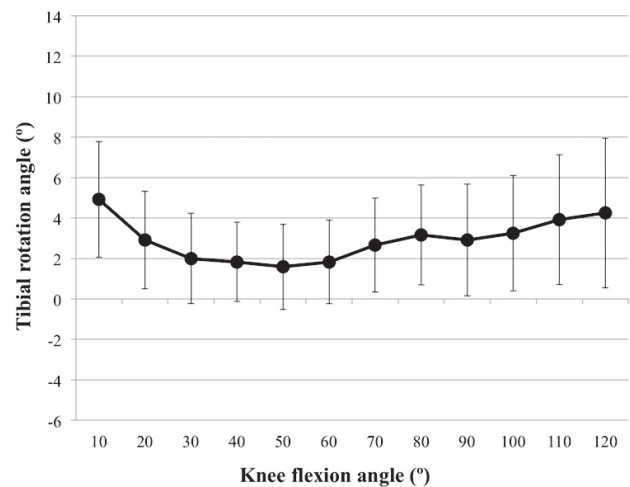


Figure 4 Intraoperative evaluation of tibial internal rotation during knee flexion. Error bars indicate the standard error.

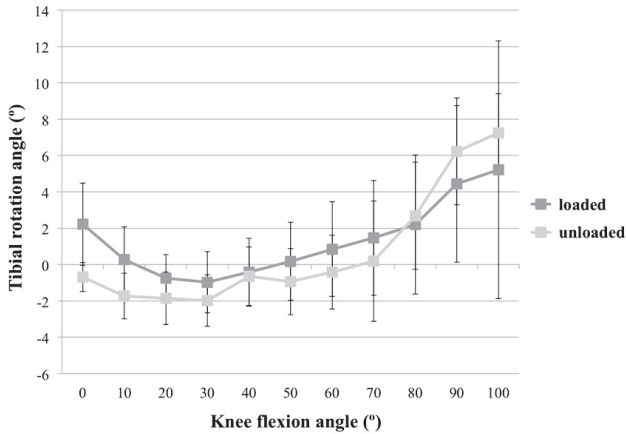


Figure 5 Postoperative evaluation of tibial internal rotation during knee flexion. Error bars indicate the standard error.

There was no significant correlation between the intraoperative data (10° -100°) and postoperative data (10° -100°) in either loaded knee flexion (Pearson's $r = 0.280$, $p = 0.434$) or unloaded knee flexion (Pearson's $r = 0.167$, $p = 0.646$). In contrast, there was a strong correlation between the intraoperative data (10° -110°) and postoperative data (0° -100°) for loaded knee flexion by shifting 10° (Pearson's $r = 0.725$, $p = 0.012$). However, there was no significant relationship between intraoperative and postoperative tibial rotational kinematics in the absence of loading even by shifting 10° (Pearson's $r = 0.420$, $p = 0.198$; Figure 6).

DISCUSSION

To our knowledge, this is the first study to analyze the correlation between intraoperative and postoperative kinematics of the knee in TKA. From our data for 6 knees, the most important finding is that the intraoperative tibial internal rotation angle evaluated using the navigation system was correlated with the postoperative tibial internal rotation angle during loaded knee flexion using the 2D/3D registration technique by shifting 10°. Although our experimental results are preliminary, it is possible that intraoperative evaluation of the passive kinematics of the knee can predict postoperative tibial rotational kinematics under a loaded condition. However, we did not find a correlation between the intraoperative and postoperative analyses without adjustment of the knee flexion angle. For the intraoperative kinematic analysis, mechanical axis was used to assess the knee flexion angle, whereas for the postoperative kinematic analysis the component axis of the CAD model was used. In our 6 knees, the cutting angles of the femur and the tibia were used for adjustment. Unfortunately, the adjustment could not be fully made because the kinematic data was assessed only at 10° increments of knee flexion, meaning our evaluation could only shift the knee flexion angle 10° in this study. Based on our preliminary findings, a more detailed adjustment of the knee angle should be incorporated in a future study.

Most previous studies on intraoperative kinematics had the same two limitations : few assessed the reliability of the method used to evaluate intraoperative knee kinematics, and intraoperative kinematics was evaluated under passive and unloaded conditions. In terms of the first of these limitations, a previous study (18) confirmed the reproducibility of intraoperative kinematic analysis in TKA using a navigation system with passive unloaded knee flexion. In terms of the second limitation, some previous

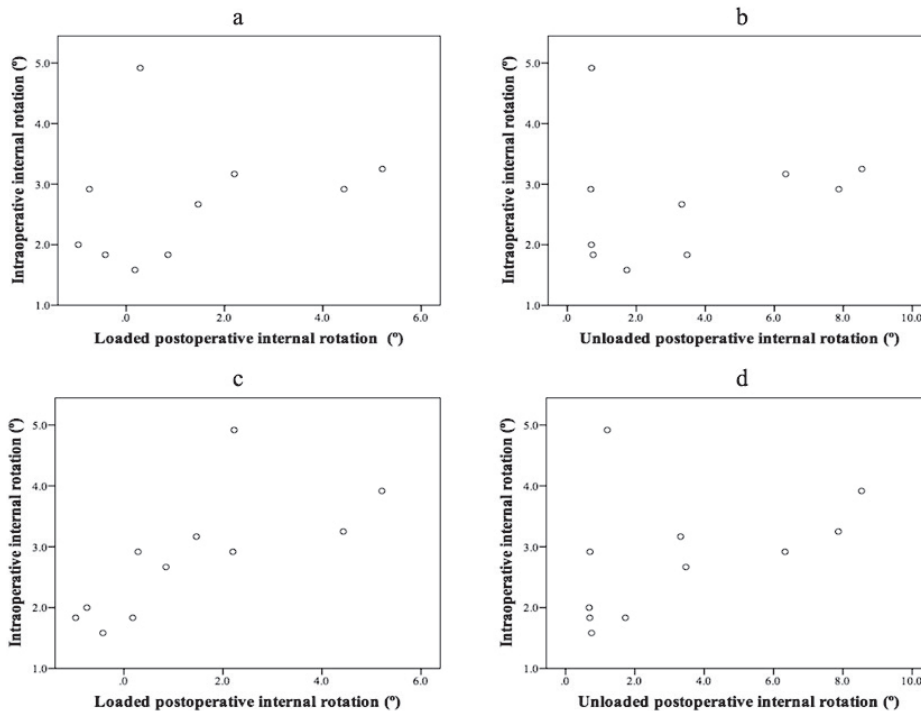


Figure 6 Scatter plot of intraoperative and postoperative evaluation of the mean tibial internal rotation angle at each knee flexion angle. (a) Intraoperative and postoperative loaded evaluation without adjustment of the knee flexion angle. (b) Intraoperative and postoperative unloaded evaluation without adjustment. (c) Intraoperative and postoperative loaded evaluation with adjustment. There was a correlation between the two methods ($r = 0.725$, $p = 0.012$). (d) Intraoperative and postoperative unloaded evaluation with adjustment.

studies reported differences in tibio-femoral rotational kinematics between loaded and unloaded conditions. Johal *et al.* (21), measuring weight bearing and non-weight bearing normal knee kinematics using magnetic resonance imaging, reported that tibial internal rotation occurs with knee flexion under loaded and unloaded conditions, but the magnitude of rotation is greater and occurs earlier in weight bearing. Lu *et al.* (22) evaluated the 3D motion and surface kinematics of the normal knee under loaded and unloaded conditions and found that the loaded condition did not affect the joint angles but significantly altered the lateral contact positions during knee extension, especially at knee flexion angles $> 75^\circ$ as well as also reduced the asymmetry of the surface kinematics between the medial and lateral condyles. They also reported that changes in contact positions under loading appeared to be more consistent between subjects than rigid-body kinematics under the constraints of the articular surfaces. In the present study, the knee was flexed with the heel supported in the examiner's open palm. This method could have applied some load to the articular surface during knee flexion and could explain our finding that the intraoperative tibial internal rotation angle was correlated with the postoperative tibial internal rotation angle under loading by shifting 10° but not under unloading.

This preliminary study has several limitations. First, measurements were performed only for internal rotation of the tibia. Kinematic data for the anteroposterior, mediolateral, and superoinferior aspects are lacking because knee kinematics includes 6 degrees of freedom. However, in previous studies, knee kinematics was usually evaluated using the rotational axis. Further study is needed to assess other parameters for a detailed evaluation. Second, only the Scorpio NRG cruciate-retaining total knee prosthesis was evaluated in this study. Therefore, our results cannot be generalized to other implant systems. Comparative studies are required. Third, our sample size was small. Moreover, intraoperative data for 10° - 120° of knee flexion were available for all patients, but postoperative data were available for only 0° - 100° of knee flexion. Therefore, the number of subjects differed between evaluations with and without adjustment of knee flexion. The knee flexion angle should be checked carefully during postoperative fluoroscopic analysis.

In conclusion, intraoperative evaluation of tibial internal rotation using a navigation system was not correlated with the postoperative evaluation using a 2D/3D registration technique. However, with adjustment the knee flexion angle between two methods, there was a correlation between the intraoperative passive evaluation and the postoperative loaded evaluation. Larger adequately powered prospective studies are now needed to confirm our preliminary finding that postoperative loaded kinematics could be predicted by intraoperative evaluation, despite the lack of loading.

CONFLICT OF INTERESTS

The authors declare that they have no conflict of interest.

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Ethical approval : All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards.

Informed consent : Informed consent was obtained from all patients who participated in the study.

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