Original Article

Radiographic Measurement of Femoral Lateral Bowing and Distal Femoral Condyle Resection Thickness: Variances and Effects on Total Knee Arthroplasty Planning

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Abstract

Background: Accurate evaluation of the plain radiography of lower limb is critical for preoperative planning of total knee arthroplasty (TKA). We aimed to investigate the effect of femoral lateral bowing and rotation on the radiographic measurements of distal femoral condyle resection thickness (DRT) and the distal femoral resection valgus angle (FVA).
Methods: We analyzed 246 three-dimensional femoral models generated from computed tomography images of 123 patients, acquiring projected contours in seven positions – 20° and 10° internal rotation; 0° rotation; 10°, 20°, 30°, and 40° external rotation – for each model. Medial and lateral condyle DRTs, femoral shaft lateral bowing angle (FBA), and distal FVA were determined for each position. Linear mixed effect model was used to determine the effect of degree of femur rotation on repeated measurements of DRT or FVA.
Results: FBA significantly affected the FVA and DRT (Pearson's $R = 0.767$ and -0.408, respectively; $P < 0.000$). Samples were divided into three groups according to the FBA measured in neutral position: FBA <0°: DRT 3.75 ± 1.30 mm, FVA 4.53° ± 1.27°; FBA >0° but <3°: DRT 3.39 ± 1.31 mm, FVA 5.92° ± 1.31°; FBA >3°: DRT 2.22 ± 1.31 mm, FVA 7.37° ± 1.31°. From simulated 20° internal rotation to 40° external rotation in each femoral model, the average variation ranges of radiographically measured DRT, FVA, and FBA were 0.50 ± 0.28 mm, 2.93° ± 0.96°, and 10.33° ± 1.90°, respectively, with no significant differences among the FBA groups. The degree of femoral rotation significantly affected the FVA ($F = 62.148$, $P < 0.000$), whereas there was no effect on condyle resection thickness ($F = 0.4705$, $P = 0.494$).
Conclusions: Axial femoral rotation has less effect on radiographic measurements of differences in the DRT than on those of the distal FVA.

Key words: Distal Femoral Resection; Radiographic Measurement; Total Knee Arthroplasty; Valgus Angle

Introduction

To achieve neutral lower limb alignment after total knee arthroplasty (TKA), the femoral and tibial components must be accurately implanted perpendicular to the femoral and tibial mechanical axes, respectively.[1,2] Accurate radiographic evaluation of the lower limb is critical for preoperative planning of TKA, with plain radiographs, computed tomography (CT) images, and magnetic resonance images commonly available.[3] Plain radiography continues to be clinicians' preferred preoperative templating tool for TKA, but the variable measurements found with femoral rotation highlight the importance of standardizing limb positioning and rotation while obtaining these radiographs.[4-6]

Any radiographic measurement, however, is prone to errors stemming from variations in limb deformity and position.[7-9] Despite efforts made to maintain a standardized position in which the patella points straight ahead, this positioning does not necessarily control for some factors, such as unpredictable degrees of rotation of the femur that occur in a severely

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Quick Response Code:

Website: www.cmj.org

DOI: 10.4103/0366-6999.217083

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Received: 01-08-2017 **Edited by:** Li-Min Chen
How to cite this article: Wu PH, Zhang ZQ, Gu MH, Zhao XY, Kang Y, Liao WM, Fu M. Radiographic Measurement of Femoral Lateral Bowing and Distal Femoral Condyle Resection Thickness: Variances and Effects on Total Knee Arthroplasty Planning. Chin Med J 2017;130:2557-62.

deformed, arthritic knee. In addition, bowing of the femur is not uncommon among Asians.[10] It is difficult to measure the true individual parameters and choose the correct distal femoral resection based on radiographic measurements, implying that special care must be taken when measuring these radiographs for planning distal femoral resection.[9]

In the case of the femur, the patient's distal femoral resection valgus angle (FVA) – enclosed by the distal femoral anatomical axis and the femoral mechanical axis – is conventionally measured on weightbearing long-leg radiographs. For conventional TKA, distal femur resection that relies on intramedullary guidance and sets the distal femoral resection angle according to the patient's FVA could significantly improve postoperative femoral component alignment.[11] The potential risk of this operative technology causing an error lies in deviation of the preoperative radiographic FVA measurement followed by intraoperative deviation of the direction of the femoral intramedullary rod from that of the femoral anatomic axis.[12-14] Another surgical technique that confirms the correspondence between measurements of resected condyle thickness obtained with calipers and measured on radiographs could verify the accuracy of distal femoral bone resection during TKA, which could improve the accuracy of conventional surgical techniques.[15]

The discrepancies in measurements obtained from two-dimensional (2D) radiographs arise from the complexity of obtaining a true representation of the 3D lower limb on a 2D image. The present study morphometrically analyzed 246 femurs from adult Chinese patients using 3D models created from CT scans. Projected contours in seven positions (described below) were determined for each femoral 3D model. We quantified and compared the combined impact of femoral bowing and rotation on measured FVAs and differences in the condyle resection thickness to evaluate the validity and reliability of this new radiographic measurement of the distal femoral condyle resection thickness (DRT) for use in planning TKA.

Methods

Ethical approval and patients

Requirements for informed consent were waived because of the retrospective radiographic morphometric study design. In total, 123 patients (71 men, 52 women; mean age: 56.43 years, range: 32–75 years) who had undergone lower-extremity CT angiography between December 2010 and December 2014 were included in this study. Patients with evidence of lower-extremity fracture, avascular necrosis of the femoral head, femoral or tibial plates, hip or knee implants, and/or amputation were excluded.

Study procedure

We examined the bilateral femurs of each patient. All CT scans were performed by a CT system (Toshiba, Tokyo, Japan) with a slice thickness of 0.5 or 0.8 mm and pixel dimensions from 0.459 to 0.912 mm. Based on the CT data in digital imaging and communication in medicine format, 3D models of the whole femur were reconstructed using Mimics software (version 17.0; Materialise, Leuven, Belgium) and transferred to stereo-lithography computer-aided design software 3-matic (version 9.0; Materialise, Leuven, Belgium) for further measurements.

We set the femoral reference coordinates, which were defined by the mechanical axis of the femur in the sagittal and coronal planes, as described by Seo *et al*.[16] The mechanical axis was defined as the line connecting the center of the femoral head and the knee center to the apex of the intercondylar notch. The center of the femoral head was determined by a best-fit sphere technique. The plane perpendicular to the mechanical line was defined as horizontal plane. The plane through two of the most posterior points of both posterior femoral condyles and perpendicular to the horizontal plane was defined as the coronal plane. The direction of the sagittal plane was defined as the projection direction, which was at an angle of 90° to the coronal plane. The mechanical axis was set as the axis of rotation of the femur, and we acquired the projected contours of each femoral 3D model in seven positions: 20° and 10° of internal rotation; 0° rotation; and 10°, 20°, 30°, and 40° of external rotation [Figure 1a].

The measurements on each femoral projection contour are shown in Figure 1b. The center of the femoral head was found using Mose circles, and the center of the knee was defined as at the apex of the intercondylar notch. The mechanical axis of the femur was determined by connecting these two points. The distal femoral anatomic axis of the femur was obtained by connecting the two femoral shaft centers in the middle lower portion of the femur, with the line corresponded to the axis determined with femoral intramedullary rod. The two femoral shaft centers were located 8 cm and 15 cm proximal to the intercondylar notch. The angle between the two axes was defined as the FVA. The femoral lateral bowing angle (FBA) was the angle between the distal and proximal femoral anatomical axes. The proximal femoral anatomical axis was obtained by drawing a line between the two femoral shaft centers in the middle upper portion of the femur. These two femoral shaft centers were separately located, with one at a level immediately distal to the lesser trochanter and another 8 cm distal to it. The planned resection line was drawn perpendicular to the femoral mechanical axis at the apex of the intercondylar notch. The thickness of the planned resected medial or lateral condyle was measured as the shortest distance between the planned resection line and the lowest point of the medial or lateral femoral condyle. The DRT was calculated by subtracting the resected lateral condyle thickness from the resected medial condyle thickness. The distal femoral resection angle between the planned resection line and the line tangential to both distal femoral condyles was also measured. Two technicians independently performed all measurements twice. To identify measurement reliability, all measured radiographs marked with reference lines were checked by an experienced joint surgeon. If there was a disagreement, the measurement was repeated, with agreement concerning the definitions of the reference points.

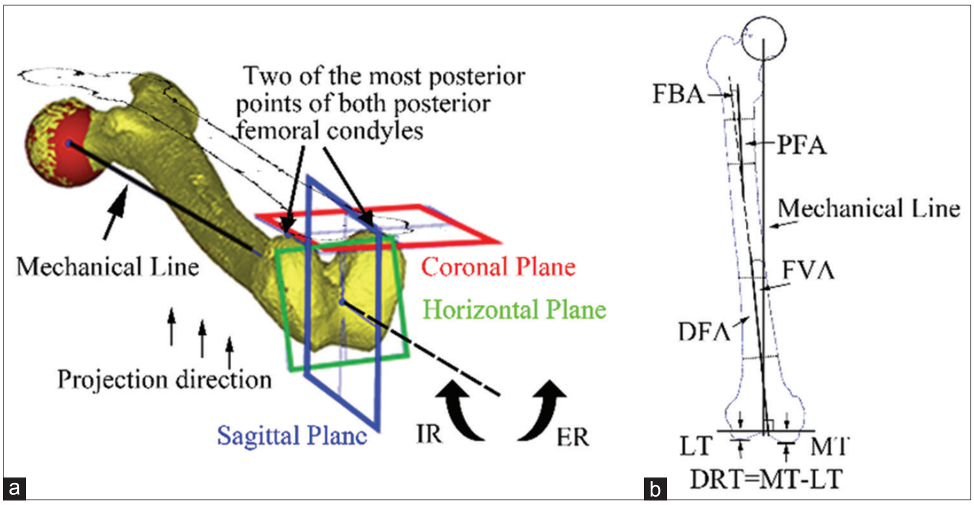

Figure 1: Definition of a femur-customized coordinate system (IR and ER; a). FBA enclosed by the PFA and DFA; FVA enclosed by the mechanical axis and DFA. The difference in the resection thickness of the medial and lateral condyles (DRT) was defined as the thickness of the resected medial condyle (ML) minus thickness of the resected lateral condyle (LT; b). IR: Internal rotation; ER: External rotation; FBA: Femoral bowing angle; PFA: Proximal femoral anatomical axis; DFA: Distal femoral anatomical axis; FVA: Femoral resection valgus angle; DRT: Distal femoral condyle resection thickness.

Statistical analysis

After verifying the normal distribution of the data using the Kolmogorov-Smirnov test, the data with normal distribution were tested using Student's *t*-test. Independent and paired samples were compared between groups and between-laterality differences, respectively, using Student's *t*-test. Linear mixed-effects model was used to determine the effect of degree of femur rotation on repeated measurements of DRT or FVA. Correlations between variables were determined using Pearson's correlation analysis. A linear regression model was applied to investigate the factors influencing the FVA. Statistical significance was set at $P < 0.05$. Statistical analyses were performed using SPSS 20.0 (SPSS Inc., Chicago, IL, USA).

Results

With the femur in the neutral position without rotation, the FBA was measured radiographically as 2.14° ± 2.39°. The FBA has a significant effect on the FVA and DRT (Pearson's $R = 0.767$ and −0.408, respectively; $P < 0.000$) [Figure 2]. Based on the FBAs measured (mean and range) in neutral position, we divided samples into three groups: FBA <0°: 17 right femurs −1.90° ± 1.73° (−6.00° to −0.10°) and 16 left femurs −1.75° ± 1.46° (−4.66° to −0.20°); FBA >0° but <3°: 65 right femurs 1.66° ± 0.79° (0.02°-2.92°) and 67 left femurs 1.54° ± 0.82° (0.04°–3.00°); and FBA >3°: 41 right femurs 4.56° ± 1.39° (3.01°–8.59°) and 40 left femurs 4.35° ± 1.35° (3.06°–7.85°). The mean value of the DRT in the right femur was 3.02 ± 1.73 mm (123 femurs: −1.78 to 7.59 mm), and in the left femur, the DRT was 2.76 ± 1.63 mm (123 femurs: −1.32 to 6.12 mm) ($t = 2.782$, $P = 0.0063$). The mean FVA for the right femurs was 6.27° ± 1.53° (1.89°–11.12°), whereas that of the left femurs was 6.15° ± 1.41° (123 femurs: 3.05°–10.30°) ($t = 1.382$, $P = 0.169$) [Table 1]. There were 107 femurs (43.50%) with DRT >0 but <3 mm, 124 femurs (50.40%) with DRT >3 mm, and 15 femurs (6.10%) with DRT <0 (resected lateral condyle was thicker than the resected medial condyle). Every 0.8 mm of variation in the DRT was approximately equal to 1° of change in the distal femoral resection angle.

From simulated 20° internal rotation to 40° external rotation, each femoral model has sets of radiographically measured ranges of DRT, FVA, and FBA for each femoral set. They were 0.50 ± 0.28 mm, 2.93° ± 0.96°, and 10.33° ± 1.90°, respectively. There was no significant difference among the FBA groups [Table 2]. However, the degree of femoral rotation significantly affected the measured FVA ($F = 62.148$, $P < 0.001$). In the range of 20° internal rotation to 20° external rotation, the FVA increases with femoral external rotation. With further external rotation (from 20° to 40°), FVA decreases. This trend of variation is similar for the right and left femurs and among the FBA groups [Figure 3]. While there was no effect on the differences in the DRT ($F = 0.4705$, $P = 0.494$) [Figure 4], from 20° internal rotation to 20° external rotation, the linear regression ($R^2 = 0.256$) showed a 0.064° change in the measured FVA per degree of femoral rotation. The linear regression was described by: $y = 0.064x + 5.946$ ($R^2 = 0.256$).

The inter-observer interclass correlation coefficients for the DRT, FVA, and FBA were 0.95, 0.95, and 0.99, respectively ($P < 0.000$), indicating the reproducibility of the measurements.

Discussion

The most important finding of this study was that the femoral rotation status on full-length radiographs has significantly less influence on radiographic measures of the differences in condyle resection thickness compared with that of the distal FVA. Distal femoral resection is a vital step in restoring

Table 1: Paired samples of DRT, FVA, and FBA for different lateralities in several FBA groups

FBA	R/L	*n*	DRT (mm)		FVA (°)		FBA (°)	
			Mean ± SD	Minimum–maximum	Mean ± SD	Minimum–maximum	Mean ± SD	Minimum–maximum
<0°	R	17	3.68 ± 1.27	1.35–5.81	4.62 ± 1.50	1.89–7.37	−1.9 ± 1.73	−6.00–−0.10
	L	16	3.8 ± 1.32	1.34–5.64	4.44 ± 1.04	3.05–6.54	−1.75 ± 1.46	−4.66–−0.20
0°-3°	R	65	3.74 ± 1.42	0.25–7.59	5.93 ± 1.72	3.02–8.05	1.66 ± 0.79	1.02–2.92
	L	67	3.03 ± 1.21	0.17–5.22	5.90 ± 0.90	3.51–7.73	1.54 ± 0.82	0.04–3.00
>3°	R	41	2.38 ± 1.44	0.14–6.16	7.48 ± 1.25	5.27–11.12	4.56 ± 1.39	3.01–8.59
	L	40	2.06 ± 1.62	0.05–6.12	7.27 ± 1.36	5.16–10.30	4.35 ± 1.35	3.06–7.85
Total	R	123	3.02 ± 1.73	−1.78–7.59	6.27 ± 1.53	1.89–11.12	2.14 ± 2.39	−6.00–8.59
	L	123	2.72 ± 1.63	−1.32–6.12	6.15 ± 1.41	3.05–10.30	2.03 ± 2.23	−4.66–7.85

DRT: Distal femoral condyle resection thickness; FVA: Femoral resection valgus angle; FBA: Femoral lateral bowing angle; R: Right; L: Left; SD: Standard deviation.

Table 2: Radiographically measured DRT, FVA, and FBA in several FBA groups under simulated internal 20° to external 40° rotation conditions

FBA	R/L	*n*	Range of DRT (mm)	Range of FVA (°)	Range of FBA (°)
FBA <0°	R	17	0.48 ± 0.26	2.92 ± 1.06	10.75 ± 2.38
	L	16	0.44 ± 0.23	2.72 ± 1.06	10.07 ± 1.82
0°< FBA <3°	R	65	0.48 ± 0.27	2.84 ± 0.87	10.32 ± 1.83
	L	67	0.53 ± 0.33	2.73 ± 0.87	10.23 ± 1.96
FBA >3°	R	41	0.48 ± 0.26	3.39 ± 1.09	10.66 ± 1.55
	L	40	0.52 ± 0.27	3.03 ± 0.95	10.06 ± 2.11
Total	R	123	0.48 ± 0.26	3.04 ± 1.00	10.5 ± 1.82
	L	123	0.51 ± 0.30	2.82 ± 0.93	10.16 ± 1.98

DRT: Distal femoral condyle resection thickness; FVA: Femoral resection valgus angle; FBA: Femoral lateral bowing angle; R: Right; L: Left; SD: Standard deviation.

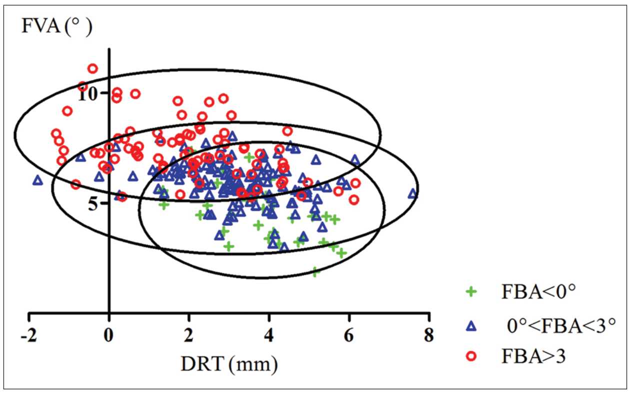

Figure 2: FBA and FVA were positively correlated. FBA and DRT were negatively correlated. FVA and DRT were also negatively correlated. FBA: Femoral lateral bowing angle; FVA: Femoral resection valgus angle; DRT: Distal femoral condyle resection thickness.

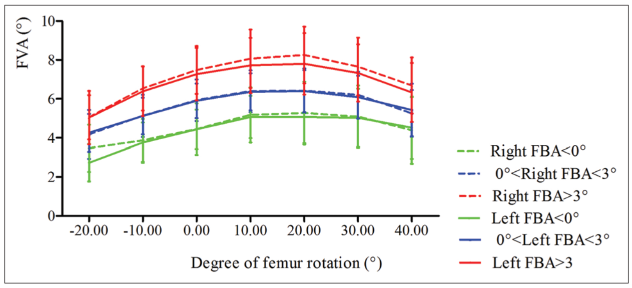

Figure 3: Variations in the radiographically measured FVA that are dependent on femoral rotation. FBA: Femoral lateral bowing angle; FVA: Femoral resection valgus angle.

limb alignment and should be performed perpendicular to the femoral mechanical axis.[17] Accurate measurements are critical for the preoperative planning of TKA. The influence of the results of the radiographic measurements due to femoral rotation is problematic and can be detrimental to the operative outcome. Of importance, for patients with severe varus or valgus deformity of the knee combined with significant femoral rotation, and for whom standardized positioning is not feasible, our findings recommended that clinicians should use full-length radiographs of the lower limb, planning the resection amount of the medial and lateral distal femoral condyles, which are less influenced by femoral rotation status. This situation may demand modification of a conventional intramedullary alignment technique by deciding on the placement of the distal femoral cutting guide based on intraoperative evaluation of lateral and medial DRT.

In the present study, femoral rotation has a statistically significant effect on the distal FVA. From 20° internal rotation to 20° external rotation, the FVA trended toward increasing linearly, with the measured FVA increasing by about 0.064° with each degree of limb external rotation. Radtke *et al*.[4] noted that the measured FVA changed by about 0.059° with every degree of limb rotation within this rotation range. In contrast, from 20° external rotation to 40° external rotation, the FVA decreased with each degree of rotation. During femoral internal rotation, the anterior

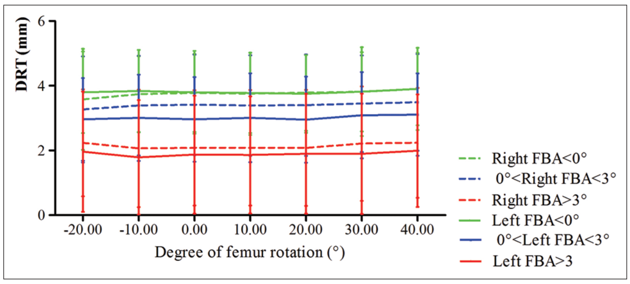

Figure 4: Femur rotation has no significant effect on variations in the radiographically measured DRT in the range of 20° internal rotation to 40° external rotation. DRT: Distal femoral condyle resection thickness.

bowing angle partly converted to a valgus bowing angle of the femoral shaft, as shown by radiography, and the FVA decreased. During the first 20° external rotation, the anterior bowing angle partly converted to a varus bowing angle of the femoral shaft, and the FVA increased. With external rotation beyond 20°, however, the measured FVA decreased mainly because of the shortened femoral neck. These results highlight the importance of evaluating each radiograph for evidence of femoral rotation before calculating the distal FVA as well as understanding the pitfalls of using femoral intramedullary guides when planning a TKA.

Owing to the inherent difficulty of identifying the femoral rotation status in patients with severe varus or valgus lower limb deformity, we altered the preoperative radiographic parameters for measuring the thicknesses of the medial and lateral femoral condyles, depending on the distal femoral cutting plane in which we were operating. We found that the potential for measurement variation of the DRT of distal femoral condyles caused by femoral rotation is relatively small. A possible reason for this situation is that bowing of the femoral shaft has little effect on the shape variation of the distal femur caused by femoral rotation. More importantly, the morphology of the distal femur shows that the distal femoral condyles are spherical and of a similar radius, indicating that the distal femoral condyles' surface changes little during axial rotation. Monk *et al*.[18] reported that the condyles are approximately spherical except for the inferior facet medially, which has a larger radius in the sagittal plane.

In practical application, it is noteworthy that accurate preoperative radiographic measurement and intraoperative measurement of the individual DRTs of distal femoral condyles are mandatory. The individual radiographically measured thickness was required for planning of distal femoral resection. There were 107 femurs (43.50%) with DRT >0 but <3 mm, 124 femurs (50.40%) with DRT >3 mm, and 15 femurs (6.10%) with DRT <0 (the resected lateral condyle was thicker than the resected medial condyle). Every 0.8 mm of DRT variation is approximately equal to 1° change in the distal femoral resection angle. Comparing to the radiographic measurement of the thickness of bony part resection, the intraoperative measured thickness of resected medial and lateral condyles should consider the thickness of remnant cartilage. The thickness of cartilage layer in the unaffected condyle was about to be 2 mm, and in the osteoarthritic condyle, the cartilage was always worn out in weightbearing region. Therefore, this surgical technique provides additional cues to evaluate alignment before distal femoral rescetion, rather than depending entirely on the intramedullary guidance system. So long as the surgeon is aware of the deviation and compensates for it, the misalignment risk is mitigated.

There are several limitations in the current study that warrant consideration. First, the direction of projection was at an angle of 90° to the coronal plane, and so the effect of flexion of the knee joint was not taken into account. The results may therefore be dependent on the femoral flexion status in the sagittal plane. However, the effect on the study results would be minimal by a fully extended knee joint during radiographic acquisition in circumstances in which severe flexion deformity (generally >30°) of the knee joint is present.[19] Advance imaging may be recommended in such a circumstance.[20] Further study is needed to investigate the combined effect of femoral flexion and rotation status on these radiographic parameters in the current study. Second, cases in this study were not the candidates for TKA, and the alignment of lower limb was generally normal without significant varus or valgus deformity. Third, further clinical studies were required to investigate the validation and accuracy of this guiding method based on measurement of differences in medial and lateral condyle resection thicknesses.

In conclusion, the femoral rotation status on full-length radiographs has significantly less influence on radiographic measures of differences in condyle resection thickness compared with that of the distal FVA.

Acknowledgement

We thank Yi-Min Chen, and Jin-Xi Zhang for reviewing the statistical analysis of this manuscript.

Financial support and sponsorship

This study was supported by the grants from the National Natural Science Foundation of China (No. 81501877), Major Program of Science and Technology Planning Project of Guangdong Province (No. 201605122119317 and No. 2015A020212015), and Natural Science Foundation of Guangdong Province (No. 2015A030310207).

Conflicts of interest

There are no conflicts of interest.

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