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Author(s)	Hamasaki, Masanari; Kondo, Eiji; Iwasaki, Koji et al.
Citation	American journal of sports medicine, 52(13), 3255-3265 https://doi.org/10.1177/03635465241285909
Issue Date	2024-10-11
Doc URL	https://hdl.handle.net/2115/94129
Rights	Hamasaki M, Kondo E, Iwasaki K, et al. Stress Distribution Patterns of the Femorotibial Joint After Medial Closing-Wedge Distal Femoral Varus Osteotomy: An Evaluation Using Computed Tomography Osteoabsorptiometry. The American Journal of Sports Medicine. 2024;52(13):3255-3265. Copyright © 2024 by American Orthopaedic Society for Sports Medicine. DOI: 10.1177/03635465241285909.
Type	journal article
File Information	Hamasaki et al MCWDFVO manuscript Am J Sports Med 2024.pdf



Stress distribution patterns of the femorotibial joint after medial closing wedge distal femoral varus osteotomy an evaluation using computed tomography osteoabsorptiometry

¹Masanari Hamasaki, ²Eiji Kondo, ⁴Koji Iwasaki, ¹Yuki Suzuki, ¹Masatake Matsuoka, ¹Tomohiro Onodera, ³Koji Yabuuchi, ²Daisuke Momma, ⁵Masayuki Inoue, ³Kazunori Yasuda, ³Tomonori Yagi, ¹Norimasa Iwasaki

¹Department of Orthopedic Surgery, Faculty of Medicine and Graduate School of Medicine, Hokkaido University, Sapporo, Japan.

²Centre for Sports Medicine, Hokkaido University Hospital, Sapporo, Japan

³Department of Orthopaedic Surgery, Yagi Orthopaedic Hospital, Sapporo, Japan

⁴Department of Functional Reconstruction for the Knee Joint, Faculty of Medicine, Hokkaido University, Sapporo, Japan

⁵Department of Orthopaedic Surgery, NTT East Japan Sapporo Hospital, Sapporo, Japan

*Correspondence to: Eiji Kondo, MD, PhD, Professor, 21 Centre for Sports Medicine, Hokkaido University Hospital (the primary institution) 22 Kita-14, Nishi-5, Kita-ku, Sapporo, Hokkaido 060-8648, JAPAN 23 TEL +81-11-706-5935, Fax +81-11-706-6054 24 E-mail: eijik@med.hokudai.ac.jp

Abstract

Background: Distal femoral varus osteotomy (DFVO) is an established surgical procedure for addressing valgus malalignment across various knee conditions. However, the impact of DFVO on stress distribution within the femorotibial (FT) joint has not been explored through *in vivo* studies.

Purpose: To (1) explore the distribution pattern of subchondral bone density across the proximal tibia in non-arthritic knees without arthritis and in those of patients with valgus knees, (2) assess changes in the pattern of bone density distribution in patients with valgus knees before and after medial closing wedge (MCW)-DFVO, and (3) determine the correlation between leg alignment and changes in bone density distribution.

Study Design: Cohort study; Level of evidence, 3.

Methods: The authors retrospectively analyzed clinical and radiographic data from 14 patients (14 knees; mean age, 44 years; 3 men, 11 women) treated with MCW-DFVO for lateral compartment osteoarthritis (OA) due to valgus malalignment, alongside a control group of 18 patients (18 knees; mean age, 21 years; 4 men, 14 women) without OA. The distribution patterns of subchondral bone density distribution on the femorotibial articular surface of the tibia were examined both preoperatively and .1 year postoperatively using computed tomography osteoabsorptiometry. Quantitative analyses were conducted on the locations and percentages of the high-density areas (HDAs) on the articular surface. The mean time between surgery and the postoperative radiograph and computed tomography absorptiometry imaging was 13.6 months (range, 11-19 months). The mean length of clinical follow-up was 28.7 months (range, 14-62 months) after surgery.

Results: The mean proportion of HDA in the lateral compartment relative to the total HDA (lateral ratio) was significantly greater in the preoperative OA group (58.8%) compared with the control group (41.1%)

($p < 0.001$). After MCW-DFVO, the mean lateral ratio in the OA group notably declined to 45.3% ($p < 0.001$). The lateral ratio exhibited a significant correlation with the hip-knee-ankle angle in both the control ($r = 0.630$; $p = 0.011$) and OA ($r = 0.537$; $p = 0.047$) groups. Moreover, the alteration in the lateral ratio after MCW-DFVO showed a significant relationship with changes in the hip-knee-ankle angle ($r = 0.742$; $p = 0.002$) and the mechanical lateral distal femoral angle ($r = -0.752$; $p = 0.002$). Within the lateral compartment, HDAs in the 3 lateral regions of the 4 lateral subregions diminished after MCW-DFVO, whereas in the medial compartment, HDAs in the 3 lateral subregions saw an increase.

Conclusion: The mean lateral ratio was significantly greater in the preoperative OA group compared to the control group. MCW-DFVO resulted in a redistribution of HDA from the lateral to the medial compartment of the proximal tibial articular surface. The extent of alignment correction post-MCW-DFVO was closely linked to the shifts in HDA distribution, reflecting changes in stress distribution.

Clinical Relevance: MCW-DFVO effectively redistributes stress from the lateral to the medial compartment of the knee.

Keywords: distal femoral varus osteotomy, knee, osteoarthritis, stress distribution, CT-osteosorptiometry

INTRODUCTION

Malalignment of the lower extremities can lead to pain and early degenerative changes.^{14,19,61,64} Recently, lower extremity alignment population norms with alignment variations have been established.²⁵ The current literature has reported that many angular deformities arise from both the femur and tibia; given this, automatically assuming a varus knee should get a high tibial osteotomy and a valgus knee a distal femoral osteotomy is incorrect.^{25,30,47} Genu valgum, arising from trauma, lateral meniscectomy, or other

conditions affecting growth plate morphology, can lead to early osteoarthritis (OA) of the lateral compartment.^{8,9,20,44,55}

Distal femoral varus osteotomy (DFVO) is a documented treatment option for patients with valgus malalignment associated with a diverse range of knee disorders.^{1,7,12,39,49,66} Previous studies have indicated that medial closing-wedge (MCW) DFVO might be beneficial for young patients with focal chondral defects and OA in the lateral compartment.^{3,6,13,16,57,59,67} Biomechanical research has validated the role of DFVO in alleviating the load on the lateral compartment and rectifying the mechanical axis (MA) of the lower limb.^{4,5,68} Previous studies^{50,68} have reported that progressive unloading of the lateral tibiofemoral compartment occurred with increasing DFVO correction angles using cadaveric knees. Nevertheless, the specific alterations in stress distribution across each compartment after DFVO are not fully elucidated, with a dearth of in vivo research on stress distribution patterns in the femorotibial joint. Thus, to our knowledge, no in vivo studies have been conducted to clarify the stress distribution patterns of the femorotibial joint after DFVO. In addition, how the distribution of the actual stress within each compartment changes after DFVO remains unclear.

Pauwels and colleague^{32,48} suggested that the distribution of the subchondral bone mineral density distribution mirrors cumulative stress distribution across the joint surface. With varying degrees of mineralization observed across a joint surface, a materialized field of stress becomes apparent.^{43,53} Muller-Gerbl et al^{36,37} identified computed tomography (CT) osteoabsorptiometry as an analytical technique for assessing long-term stress distribution across individual joints in living subjects by measuring the subchondral bone mineral density. This method provides a detailed map of the distribution pattern of subchondral bone density across different articular surfaces.^{21,24,33,35,42,46} This method is useful for evaluating the in vivo stress distribution at the knee of the femorotibial^{21,35} and patellofemoral joints,^{24,42} as well as the ankle joints,^{33,46} in healthy individuals, those with pathologic conditions, and athletes.

However, it is unclear whether and how the distribution pattern of subchondral bone density changes on the knee joint's articular surface after MCW-DFVO.

Utilizing CT osteoabsorptiometry to create a precise map of the subchondral bone density distribution across the knee joint could shed light on stress distribution across the articular surface of the knee joint with and without OA, and how stress distribution shifts after MCW-DFVO. In terms of clinical relevance, the present study elucidates that MCW-DFVO redistributes stress from the lateral to the medial compartment of the knee. This study aimed to (1) explore the distribution pattern of subchondral bone density across the proximal tibia in nonarthritic knees without arthritis and in those of patients with valgus knees, (2) assess changes in the pattern of bone density distribution in patients with valgus knees before and after MCW-DFVO, and (3) determine the correlation between leg alignment and changes in bone density distribution. Thus, we hypothesized that (1) there are significant differences in the distribution pattern of subchondral bone density across the proximal tibia between nonarthritic knees and arthritic valgus knees, (2) MCW-DFVO leads to a reduction in in vivo subchondral bone density in the lateral compartment of the femorotibial joint in patients with valgus knees, and (3) there are significant correlations between leg alignment and changes in bone density distribution. The purpose of the present study was to assess these hypotheses

METHODS

Study Design

After approval from the Hokkaido University Hospital Institutional Review Board, informed consent was obtained from each participant. The study retrospectively included 23 consecutive patients (23 knees) who underwent MCW-DFVO for symptomatic isolated lateral compartment OA, spontaneous osteonecrosis of the knee, and cartilage injury of the lateral femoral condyle cartilage injury with valgus knees between

June 2016 and May 2020. We chose this 4-year period because we began performing MCW-DFVO using the same surgical method and the same internal fixation material (locking plate) starting in 2016. All patients who underwent MCW-DFVO during the time frame wished to participate. A senior orthopaedic surgeon (E.K.) with 25 years of experience in knee surgery performed all operations. The osteotomy group included patients treated with MCW-DFVO, with the procedure indicated for moderate valgus leg alignment (hip-knee-ankle [HKA] angle $>5^{\circ}$) and no medial femorotibial joint OA (Kellgren-Lawrence [KL] grade²⁶ ≥ 2). Exclusion criteria encompassed medial knee OA (KL grade ≥ 2) or medial knee pain, incomplete follow-up period of at least 1 year, absence of metal removal after DFVO, loss of knee extension $>15^{\circ}$, knee range of motion $<130^{\circ}$, cruciate ligament insufficiency or varus/valgus instability $<10^{\circ}$, and any medial meniscal damage. If metal removal has not been performed, it is considered to potentially affect the CT values because of metal halation. In addition, finite element analysis has been used to demonstrate the stress-shielding effect of the locking plate on the bone around the plate.²⁷ Patients undergoing concurrent surgery affecting articular cartilage were also excluded. Ultimately, 14 knees from 14 patients were evaluated, including 3 men and 11 women with a mean age of 43.5 years (range, 22-73 years) at the time of surgery (Figure 1, Table 1). Clinical and radiological assessments were conducted preoperatively and at the last follow-up (range, 14-62 months). For the control group, 21 patients were reviewed and 3 patients who declined to participate were excluded. Thus, we collected data from 18 patients who had simultaneous radiological and CT examinations of both knees between April 2013 and March 2021 with ipsilateral knee trauma including knee ligament tears (cruciate and/or collateral ligament) and lower limb fractures for comparison. Uninjured contralateral knees served as controls. The control group inclusion criteria were contralateral knee OA of KL grade <1 and age of 15 to 35 years at the time of CT scanning according to previous studies.^{20,33} Exclusion criteria for the control group included current pain in the contralateral knee or previous surgery on that knee.

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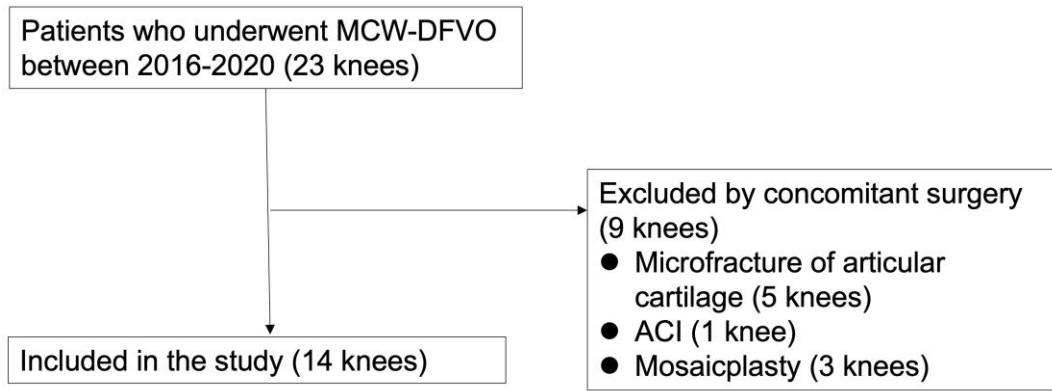


Figure 1. Study enrollment flowchart. Abbreviations: MCW-DFVO, Medial closing wedge-distal femoral varus osteotomy; ACI, Autologous chondrocyte implantation.

Preoperative Planning

Preoperative planning involved determining the correct femoral angle using a standing full-length lower limb anteroposterior radiograph. The Miniaci method,³⁴ as previously reported,^{23,38} guided the preoperative planning process. To ascertain the precise angle for the MCW-DFVO, a long line (A) was delineated from the center of the talar dome through the central aspect of the medial intercondylar eminence of the tibia, which is located around an MA percentage of 42.5% and HKA angle of 2° to avoid an increased risk of medial compartment OA of the knee in the motivated patient (Figure 2). Subsequently, another line, B, extended from the hinge point, P (located proximal to the upper border of the lateral femoral condyle and between the lateral femoral cortex and the contour of the lateral femoral condyle contour), reaching the femoral head's center, with its length recorded. An arc, C, centered at the hinge point P with radius B, was then drawn to intersect with line A. A line, D, from the hinge point to the intersection of lines A and C was then drawn. The angle formed between lines B and D, representing the medial closing angle, mirrors the lower limb alignment's correction angle. However, double-level osteotomy should be considered for valgus knees with the preoperatively anticipated joint line obliquity of >5°.²⁵

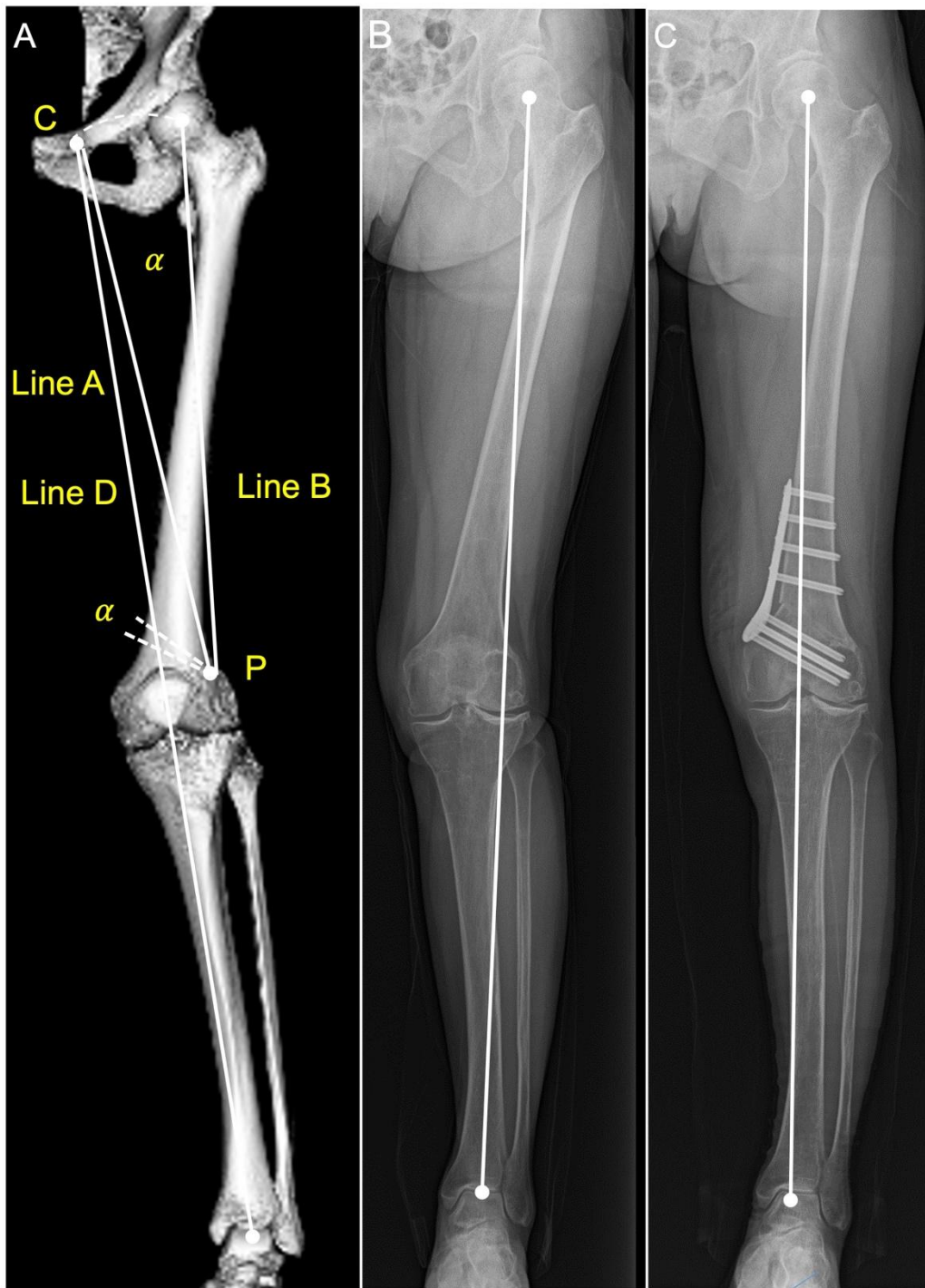


Figure 2. Preoperative planning and pre- and postoperative standing (full-length lower limb anteroposterior radiographs for MCW-DFVO). (A) Preoperative planning. (B) Preoperative standing. (C) Postoperative standing. Abbreviations: MCW-DFVO, medial closing wedge-distal femoral varus osteotomy.

Surgical Technique

Each patient underwent diagnostic arthroscopy immediately before DFVO surgery. Diagnostic arthroscopy was performed with standard anterolateral and anteromedial parapatellar portals to confirm that there was isolated lateral compartment OA, spontaneous osteonecrosis of the knee, or cartilage injury of the lateral femorotibial joint. The methodology for the MCW-DFVO has been detailed in earlier works^{23,38} The procedure commenced with a 7-cm anteromedial longitudinal skin incision on the medial thigh. This incision allowed access to the muscle sheath of the vastus medialis oblique, which was then retracted anteriorly to expose the femur. Utilizing a raspatory and acutely curved elevator, the periosteum at the osteotomy site was carefully detached from the anterior and posterior aspects of the femur. To safeguard the neurovascular structures, a radiolucent retractor (Olympus Terumo Biomaterials) was positioned between the femur and the detached posterior structures. The medial patellofemoral ligament was identified near the attachment site of the vastus medialis oblique to the medial patella, ensuring that the distal femur's anterior, medial, and posterior aspects were fully visible at the osteotomy site. The MCW-DFVO then proceeded with an ascending biplanar osteotomy under fluoroscopic guidance. The lateral hinge point, just at the lateral-proximal section of the lateral femoral condyle, as seen on anterior-posterior fluoroscopic imagery,^{40,41} guided the insertion of a guide wire. An originally developed protractor-installed wedge-cutting guide^{28,29} (Olympus Terumo Biomaterials) facilitated the transverse osteotomy. Guide wires were inserted from a point 4 cm proximal to the medial epicondyle toward the lateral hinge point, with 2 additional guide wires placed distally at the predetermined angle with the installed protractor, using the wedge-cutting guide. The initial ascending cut began 10 mm below the anterior femur aspect, extending proximally at a 20° angle anteriorly relative to the femur's shaft, and was made using a thin oscillating saw and chisel. After the transverse cut along the guide wires and removal of bone blocks. Finally, the wedge osteotomy site was meticulously closed. Fluoroscopic confirmation ensured that the corrected knee MA passed through the medial intercondylar eminence of the tibia, aligning with the preoperative plan. Fixation was achieved using an anatomic locking plate (TriS

medial DFO plate system; Olympus Terumo Biomaterial), carefully positioned to avoid medial patellofemoral ligament interference. Four screws were then inserted into the distal femoral condyle, and after applying a compression force to the wedged osteotomy surface with a compression screw, an additional 4 screws secured the femoral shaft.

Postoperative rehabilitation

Postoperative rehabilitation commenced with continuous passive motion exercises one week following the operation. Transitioning from partial to full weight-bearing was permitted between 3 and 6 weeks post-surgery.

Clinical and radiological evaluations

Clinical evaluation

Patients were assessed using the Japanese Orthopaedic Association (JOA) scoring system^{2,69} (of a total of 100 points) and the Lysholm knee score,³¹ both before surgery and at the last follow-up.

Radiologic Evaluation

Radiological outcomes were appraised both preoperatively and at the last postoperative follow-up. The severity of OA in the femorotibial joint was classified using the KL classification.²⁶ Measurements of various angles were conducted on a standing full-leg anteroposterior radiograph, including the HKA angle, representing the angle between the femoral and tibial MAs; the lateral femorotibial angle, defined as the angle between the anatomic axis of the femoral shaft and the axis of the tibial shaft on the fibular side; and the mechanical lateral distal femoral angle (mLDFA), defined as the angle between the distal femoral joint line and the femur MA. The MA was determined by a line that was drawn from the center of the femoral head center to the midpoint of the proximal talar joint surface midpoint. The MA was calculated as the horizontal distance from the MA to the medial edge of the tibial plateau, divided by the width of the tibial plateau. Two senior orthopaedic surgeons (K.I., Y.S.) with .10 years of experienced in knee

217 surgery performed the measurements

218 CT osteoabsorptiometry

219 Subchondral bone density distribution across the femorotibial articular surface of the tibia was evaluated

220 using CT osteoabsorptiometry before and 1 year after surgery. Axial high-resolution helical CT scans

221 (Aquilion One/Vision Edition; Toshiba Medical Systems) of the knee were acquired with patients in a

222 supine position, knees extended. The slice thickness and interval were set to 0.5 mm. The acquired Digital

223 Imaging and Communications in Medicine images were transferred to a PC, where sagittal and coronal

224 slices at 1.0-mm intervals and 3-dimensional (3D) bone models were generated from axial CT data using

225 a commercial software (Ziocube; Ziosoft Inc). The sagittal and coronal axes were aligned using the distal

226 femoral condyle epicondylar axis. Sagittal and coronal CT images and a 3D CT image of the proximal

227 tibia articular surface guided the manual selection of the medial and lateral compartment outlines to

228 encompass the entire subchondral bone layer of the articular surface in all slices.³ Subchondral bone

229 density in each generated sagittal slice was analyzed with noncommercial software (OsteoDens 4.0)

230 developed in-house.^{21,24,33,35,42,46} The starting point of the region of interest was the maximum increment

231 point in Hounsfield units (HU) from the joint surface, with the maximum point in HU automatically

232 selected within the 2.5-mm region of interest from the starting point. The subchondral bone region

233 radiodensity was determined at each coordinate point at 1-mm intervals, producing a 2-dimensional image

234 mapping the subchondral bone density distribution by stacking sagittal slices. Differences in HU in the

235 mapping images were categorized into 9 grades, creating surface mapping images with a color scale where

236 red and violet represented the highest and lowest bone densities, respectively. The cortical bone or bony

237 spurs at the articular surface periphery were included in the selected areas of the medial and lateral plateaus

238 because of software limitations but were carefully removed and manually excluded from the analysis

239 target areas. Quantitative analysis of the obtained mapping data focused on the location of high-density

240 areas (HDAs) through the articular surface. HDAs were defined as areas where HU fell within the top

241 30% of the total area for both the medial and lateral compartments. The lateral ratio was calculated as the

proportion of the lateral compartment HDA to the total HDA of both compartments. The percentage of HDA in each region was defined as the division of each region HDA by the entire articular surface HDA.²¹ In the femorotibial joint, the medial compartment of the proximal tibia was segmented into 4 subregions of equal width in the coronal direction, labeled M1 to M4 from the medial to lateral sides. Similarly, the lateral compartment was divided into 4 subregions, denoted L1 to L4 from the medial side to the lateral side (Figure 3).

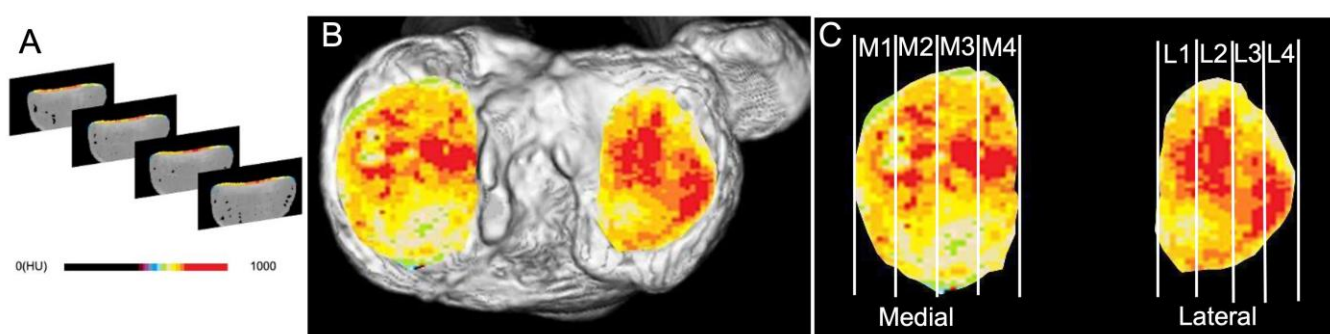


Figure 3. Identification of the subchondral bone regions in the proximal tibia using custom software. (A, B) Subchondral bone density of the selected region was automatically measured at each coordinate point in each 1.0-mm sagittal slice. (C) Images representing the quantitative analysis areas used for bone density mapping in the medial and lateral compartments of the proximal tibia. L1-L4: Subregions of the lateral compartment, divided equally from the medial to the lateral side. M1-M4: Subregions of the medial compartment of the proximal tibia, divided equally divided from the medial to lateral side.

Statistical Analysis

Statistical analyses were executed using JMP Pro (Version 16.0; SAS Institute Inc). The significance threshold was established at a P value of .05. Calculations were made for the means and 95% confidence intervals regarding the postoperative changes in patients with valgus knees. The comparison between control individuals and patients with valgus knees, both before and after surgery, utilized the Student t test, while the evaluation of patients with valgus knees before and after operation used a paired t test.

263 Pearson correlation analysis was conducted to examine the association between the lateral ratio and other
264 variables (age, body mass index [BMI], HKA angle, femorotibial angle, MA, and mL DFA), contrasting
265 controls with preoperative patients. Furthermore, the changes from preoperative to postoperative values
266 (indicated by D) in the medial ratio and other variables were compared using Pearson correlation. These
267 variables were chosen for analysis because of their presumed effect on knee joint biomechanics and
268 subchondral bone density distribution.^{22,56} The reproducibility of the data obtained through our
269 noncommercial software (OsteoDens 4.0) was assessed. Intra and interobserver reliabilities were
270 evaluated using 3 randomly selected knees from both the control group and each OA group. Two observers
271 (M.M., T.O.) independently measured the percentage of HDA in the 6 knees; 48 subregions were
272 measured twice in a blinded fashion at 1-month intervals. The intraclass correlation coefficients (ICCs)
273 for intraobserver reliability were 0.926 (M.M.) and 0.913 (T.O.), while the ICC for interobserver
274 reproducibility was 0.915.

275

276 **RESULTS**

277 **Patient Characteristics and Clinical Outcomes**

278 The participant characteristics are detailed in Table 1. The mean time between surgery and the
279 postoperative radiograph and CT absorptiometry imaging was 13.6 months (range, 11- 19 months). The
280 mean length of clinical follow-up was 28.7 months (range, 14-62 months) after surgery. The mean
281 postoperative Lysholm and JOA scores showed significant improvement at the final follow-up ($p < .001$
282 for each).

283

284 TABLE 1. Patient characteristics and clinical outcomes.

	Control group (n = 18)	Osteotomy group (n = 14)		p value	
		Preoperative	Postoperative	Preoperative vs Control	Preoperative vs Postoperative
Age, y	21.2 (2.9) (range: 15-35)	43.5 (14.9) (range: 22-73)		< 0.001	
Male/Female, n	4/14	3/11		0.191	
Body Mass Index, kg/m ²	23.2 (4.3)	26.6 (5.7)		0.023	
Lysholm score, points		58.7 (19.8)	87.4 (7.0)		< 0.001
JOA score, points		64.9 (14.6)	87.2 (8.5)		< 0.001

Data, except for the sex of the patients, are reported as the mean (standard deviation).

JOA: Japanese Orthopaedic Association

Radiological and CT Osteoabsorptiometry Evaluations

The HKA angle, femorotibial angle, MA, mL DFA, and lateral ratio all exhibited significant differences between the control and preoperative osteotomy groups ($p < 0.001$ for each) (Table 2). Specifically, the mean lateral ratio was 17.7% percentage points higher in the preoperative osteotomy group compared with the control group ($p < 0.001$). Within the osteotomy group, the mean correction angle achieved was 7.2° of varus. Significant alterations were observed in the mean HKA angle, femorotibial angle, MA, and mL DFA ($p < 0.001$ for each). Moreover, the mean lateral ratio significantly decreased from 58.8% to 45.3% ($p < 0.001$). Radiological evaluations after surgery showed no OA progression in the femorotibial joint. When comparing the osteotomy and control groups postoperatively, no significant differences were

found in leg alignment. However, the lateral ratio remained 4.2% percentage points higher in the osteotomy group compared with the control group (p = 0.023).

TABLE 2. Radiological evaluations.

	Control group	Osteotomy group		p value		
		Pre.	Post.	Controls vs. Pre. osteotomy group	Pre. vs post. osteotomy group	Post. osteotomy group vs Controls
Correction angle, degree		n/a	7.2 (1.6)			
HKA angle, degree	- 1.2 (1.5)	6.3 (4.9)	-1.9 (3.0)	< 0.001	< 0.001	0.121
FTA, degree	176.1 (2.5)	168.2 (4.3)	176.6 (3.6)	< 0.001	< 0.001	0.083
MA, %	44.5 (6.6)	74.6 (19.5)	42.1 (11.7)	< 0.001	< 0.001	0.224
mLDFA, degree	88.2 (3.4)	81.7 (4.0)	89.4 (3.7)	< 0.001	< 0.001	0.151
Lateral ratio, %	41.1 (7.5)	58.8 (8.9)	45.3 (9.8)	< 0.001	< 0.001	0.023
FT OA, No. of knees						
Grade 2		5	5			
Grade 3		9	9			

Data, except for femorotibial OA grades, are reported as the mean (standard deviation).

n/a, unavailable; HKA, hip-knee-ankle angle; FTA, lateral femorotibial angle; MA, mechanical axis; mLDFA, mechanical lateral distal femoral angle; OA, osteoarthritis; lateral ratio: ratio of the high-density area (HDA) of the medial compartment to the total HDA of both compartments.

306 The HKA angle and MA demonstrated a significant correlation with the lateral ratio ($p < 0.047$ and $p <$
 307 0.024 , respectively) (Table 3 and Figure 4).

308

309 TABLE 3. Pearson correlation between the lateral ratio and patient data in the control and osteotomy
 310 groups before surgery.

	Control group		Preoperative osteotomy group	
	r Value	p Value	r Value	p Value
Age	-0.174	0.534	0.215	0.459
Body Mass Index	-0.065	0.817	-0.188	0.518
HKA angle	0.630	0.011	0.537	0.047
FTA	0.517	0.090	0.490	0.061
MA	0.673	0.005	0.596	0.024
mLDFA	-0.097	0.730	-0.519	0.056

311 HKA, hip-knee-ankle angle; FTA, lateral femorotibial angle; MA, mechanical axis; mLDFA, mechanical
 312 lateral distal femoral angle; lateral ratio, ratio of the high-density area (HDA) of the medial compartment
 313 to the total HDA of both compartments.

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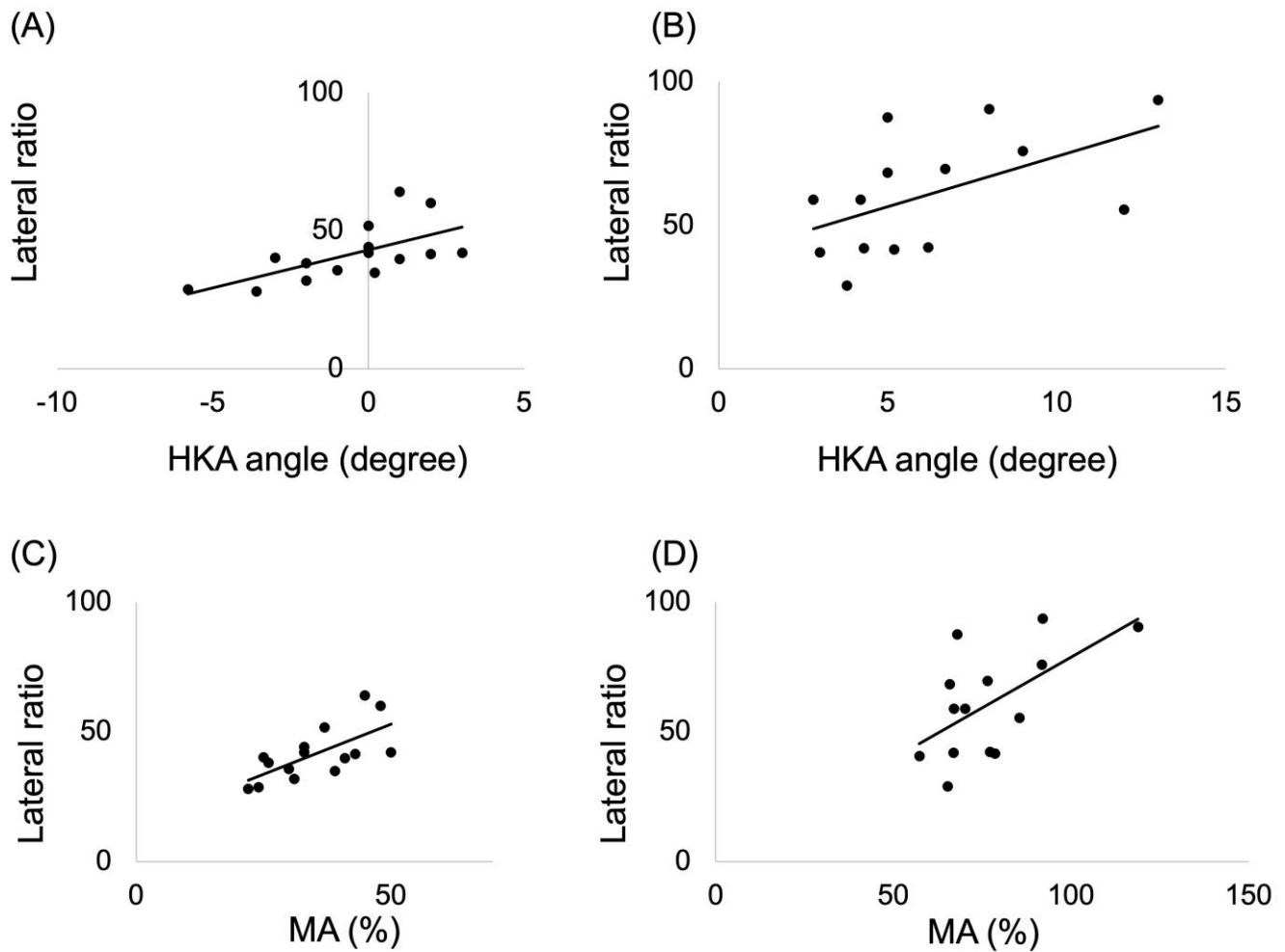


Figure 4. Relationship between the hip-knee-ankle (HKA) angle and the lateral ratio. (A) Control group: Pearson correlation analysis shows a significant positive correlation between the HKA angle and the lateral ratio (Pearson $r = 0.630$; $p=0.011$). (B) Osteotomy group: Pearson correlation analysis shows a significant positive correlation between the HKA angle and the lateral ratio (Pearson $r = 0.537$; $p=0.047$). Relationship between the mechanical axis (MA) and the lateral ratio. (C) Control group: Pearson correlation analysis shows a significant positive correlation between the MA angle and the lateral ratio (Pearson $r = 0.673$; $p < 0.005$). (D) Osteotomy group: Pearson correlation analysis showed a significant positive correlation between the MA and the lateral ratio (Pearson $r = 0.596$; $p=0.024$). Lateral ratio: the ratio of the high-density area (HDA) of the medial compartment in relation to the total HDA of both compartments.

Of the characteristics of osteotomy patients, including age, BMI, and the JOA knee score, none demonstrated a significant correlation with the change in the lateral ratio. However, among the parameters that were altered after MCW-DFVO, the HKA angle, FTA, MA, and mL DFA showed significant correlations with the Δ lateral ratio ($p=0.002$, $p=0.018$, $p=0.003$, and $p=0.002$, respectively) (Table 4).

TABLE 4. Pearson and Partial Correlation Coefficients Between the Change in the Lateral Ratio and Patient Data in Patients With Valgus Knees Before and After DFVO.

	Correlation Coefficient	P Value	Partial Correlation Coefficient
Pre DFVO			
HKA angle	-0.439	0.076	-0.239
FTA	0.443	0.082	0.308
MA	-0.513	0.056	-0.400
mL DFA	0.387	0.171	0.264
Post DFVO			
HKA angle	0.267	0.356	0.184
MA	0.221	0.447	-0.137
FTA	0.232	0.425	0.160
mL DFA	-0.495	0.071	-0.351
Δ Pre- vs post DFVO			
HKA angle	0.742	0.002	0.540
FTA	-0.620	0.018	-0.487
MA	0.734	0.003	0.544
mL DFA	-0.752	0.002	-0.680

333 HKA, hip-knee-ankle angle; FTA, lateral femorotibial angle; MA, mechanical axis; mL DFA, mechanical
 334 lateral distal femoral angle; lateral ratio, ratio of the high-density area (HDA) of the medial compartment
 335 to the total HDA of both compartments.

336
 337 In the subregional %HDA analysis of the proximal tibia, the %HDA in the M2, M3, M4, and L1 regions
 338 of the preoperative osteotomy group were significantly lower than those in the control group ($p = 0.035$,
 339 0.007 , 0.045 , and 0.035 , respectively) (Table 5). Conversely, the %HDA in the L2 and L3 regions of the
 340 preoperative osteotomy group was significantly higher than that in the control group ($p = 0.026$ and 0.003 ,
 341 respectively). Following DFVO, there was a significant increase in the %HDA of the M2, M3, and M4
 342 regions in the tibia ($p = 0.029$, 0.026 , and 0.003 , respectively). Moreover, the %HDA in the L2, L3, and
 343 L4 regions of the tibia significantly decreased post-DFVO ($p = 0.031$, 0.043 , and 0.036 , respectively).

344

345

346 TABLE 5. Subregional analysis of percentage high density area.

Subregion	Controls	Osteotomy group		p value	
		Preoperative	Postoperative	Preoperative vs Controls	Preoperative vs Postoperative
M1	4.8 (1.3)	4.7 (3.4)	5.5 (1.4)	0.291	0.178
M2	16.8 (3.8)	12.5 (4.1)	15.2 (4.8)	0.035	0.029
M3	22.3 (4.5)	15.5 (4.8)	21.5 (5.7)	0.007	0.026
M4	14.8 (5.0)	9.3 (2.8)	12.1 (3.3)	0.045	0.003
L1	11.8 (3.4)	10.3 (4.5)	10.5 (3.3)	0.035	0.239
L2	12.7 (2.7)	19.3 (5.8)	14.1 (6.4)	0.026	0.031
L3	10.6 (3.0)	19.4 (6.6)	13.9 (6.3)	0.003	0.043
L4	5.9 (2.6)	9.6 (4.3)	6.8 (3.1)	0.055	0.036

Data are reported as the mean (standard deviation). HDA, high-density area (i.e., 30% of the highest area in Hounsfield units out of the sum of the medial and lateral compartments). M1-M4: subregions of the medial compartment of the proximal tibia divided equally from the medial to the lateral side. L1-L4: Subregions of the lateral compartment divided equally from the medial to the lateral side.

DISCUSSION

The main findings of the present study were that, first, the mean lateral ratio was significantly greater in the preoperative OA group compared with the control group. Second, after MCW-DFVO, the mean lateral ratio significantly decreased from 58.8% to 45.3%. Third, the alteration in the lateral ratio of the post MCW-DFVO showed a significant relationship with changes in the HKA angle and the mL DFA. The critical insights from this study underscore that using CT osteoabsorptiometry enabled the investigation of in vivo stress distribution patterns of subchondral bone density on the proximal tibial articular surface both before and after DFVO. It was evident that the lateral ratio, significantly elevated in patients with valgus knees, substantially decreased after DFVO. Furthermore, both the HKA angle and MA showed significant correlations with the lateral ratio among controls and patients with valgus knees. The alignment correction degree (Δ HKA, Δ mL DFA, and Δ MA) after DFVO was strongly associated with changes in the lateral ratio. Additionally, DFVO markedly reduced the percentages of HDA of L2, L3, and L4 while increasing the percentages of HDA of M2, M3, and M4. These findings highlight that DFVO notably alters the stress distribution from the lateral to the medial compartment of the proximal tibial articular surface toward the medial compartment.

Referencing previous biomechanical studies,^{50,68} DFVO is known to decrease pressure in the lateral compartment. Wylie et al⁶⁸ reported a progressive unloading of the lateral compartment with increased DFVO correction angles in cadaveric knees. Conversely, high tibial osteotomy (HTO) for valgus knees increases the abduction moment and a lateral shift in the dynamic knee joint loading.^{10,62,63,65} Iwasaki et al²¹ observed that HTO shifted the HDA distribution from the medial to the lateral compartment using the

372 same CT osteoabsorptiometry method, indicating stress relief on the medial compartment of the proximal
373 tibial articular surface in knees with varus OA by moving stress toward the lateral compartment. Van
374 Egmond et al⁶⁰ analyzed and compared changes in gait kinetics and kinematics and clinical outcomes after
375 varus osteotomy in OA knees and valgus leg alignments with healthy participants, noting a postoperative
376 mean correction of 10° toward an HKA angle of 1° of varus and an increased adduction moment
377 similar to that of healthy controls throughout the entire stance phase. This implies that varus osteotomy,
378 which exerts an effect opposite to that of valgus osteotomy, shifts the dynamic knee joint load medially.
379 This study confirms that MCW-DFVO significantly transitions the in vivo stress distribution patterns of
380 the femorotibial joint by shifting it from the lateral compartment to the medial compartment, supporting
381 the findings of previous biomechanical studies.^{50,60,68}

382 Previous studies involving CT osteoabsorptiometry have shown that the distribution pattern of
383 subchondral bone density mirrors the resultant stress distribution on a joint surface under actual load
384 conditions.^{21,24,33,35,42,46} This study found that the lateral ratio was higher in patients with valgus knee OA
385 compared with healthy individuals and decreased after MCW-DFVO. Additionally, the HKA angle and
386 MA correlated significantly with the lateral ratio in both healthy individuals and patients with valgus knees.
387 The strong correlation between Δ HKA angle, Δ MA, Δ mLDFA and change in lateral ratio ($r = 0.742$, r
388 $= 0.734$, and $r = -0.752$, respectively) underscores the significant effect of leg alignment changes on the
389 stress distribution pattern across the proximal tibial articular surface.

390 Comparisons between the patients postoperatively and controls revealed similar alignments, yet the
391 lateral ratio remained higher in postoperative patients. This discrepancy could stem from the influence of
392 OA on the subchondral bone density in patients with knee OA and valgus deformity.^{22,45} Alternatively, it
393 may indicate that the subchondral bone density distribution approximately 1 year after MCW-DFVO is
394 not yet the final distribution. Further research is required to ascertain when the final subchondral bone
395 density distribution is established.

Subregional analysis of HDA distribution patterns before and after MCW-DFVO showed decreased percentages of HDA in L2 to L4 postoperatively, whereas M2 to M4 regions saw increased percentages of HDA. This suggests a reduction in stress in most regions of the lateral compartment and an increase in stress across most regions of the medial compartment after MCW-DFVO. Short-term clinical scores significantly improved after MCW-DFVO. While the optimal varus correction angle for the knee remains under debate,^{15,51} the goal of the correction angle for valgus HTO has been thoroughly investigated and established.^{18,69} Recommendations suggest that favorable clinical outcomes after DFVO are achieved within an MA alignment of 36% to 43%.^{17,52,58} Dewilde et al¹¹ observed a trend toward more failures in undercorrected DFVO for valgus deformity. This study aimed for a target alignment of an MA of 42% and an HKA angle of -2° to minimize the risk of medial OA. Schroter et al⁵⁴ highlighted adverse outcomes after overcorrection in patients who underwent MCW-DFVO. While future studies are needed to explore the effect on long-term clinical outcomes, surgeons should be wary of medial compartment OA progression risks after MCW-DFVO because of the increased mechanical stress, especially if OA changes have already occurred. This study corroborates the reliability of CT osteoabsorptiometry as a method for evaluating stress distribution, aligning with previous findings on lateral compartment loading ratios. If a longer-term follow-up of these patients was undertaken, further investigations into the distribution pattern of subchondral bone density could provide insights into optimal leg alignment for patients undergoing MCW-DFVO

There are several limitations in this study. First, limitations include not directly measuring knee stresses in the knee but inferring them through subchondral bone density distribution via the CT osteoabsorptiometry method.^{36,37} The absolute stress value at each analysis point remains undetermined, indicating that the stress distribution assessed may not reflect the actual stress at the analysis points. Second, there is a wide age range of participants (22-73 years), which might influence the outcomes given the age-related differences in bone quality. In addition, age differences between the osteotomy and control groups were notable. There was a significant difference in age between the osteotomy and control groups

(mean difference, 22.3 years). This study reveals that age did not correlate with the lateral ratio in the osteotomy and control groups. However, leg alignment was found to be correlated with the lateral ratio in both groups. This indicates that age might influence the distribution of subchondral bone density as strongly as valgus alignment. Third, the study included only 14 knees (and 18 controls), which may not be sufficient to generalize the results. The small sample size, because of the inclusion of only patients who underwent MCW-DFVO and the exclusion of those with meniscal injuries, may have biased the results toward patients with positive outcomes. Inclusion and exclusion criteria were deemed necessary to accurately evaluate the sole influence of MCW-DFVO on subchondral bone density distribution. Fourth, postoperative evaluations were performed within a relatively short time frame (mean, 28.7 months; range, 14-62 months), which may not capture the long-term effects of stress distribution changes in the knee. In addition, there are insufficient data on long-term clinical outcomes (>2 years), which are crucial to assess the lasting efficacy of the surgical intervention. Fifth, the time between surgery and follow-up is a wide range (14-62 months). On the other hand, the mean time between surgery and the postoperative radiograph and CT absorptiometry imaging was 13.6 months (range, 11-19 months). Therefore, the HDA results may not have reached a final steady state. Sixth, the evaluation occurred after metal component removal. The stress-shielding effect of the locking plate has been demonstrated by finite element analysis,²⁷ although its effect on the articular surface is unclear. Moreover, regardless of the stress-shielding effect of the MCW-DFVO plate, this study revealed that the distribution of subchondral bone density differed significantly before and 1 year after MCW-DFVO. Despite these limitations, this study, showing that MCW-DFVO shifts HDA distribution from the lateral to the medial compartment, suggested that knee joint stress distribution reduces stress on the lateral compartment in valgus knees, and leg alignment is crucial in altering subchondral bone density distribution.

In conclusion, the present study demonstrated that the mean lateral ratio was significantly greater in the preoperative OA group compared with the control group. MCW-DFVO resulted in a redistribution of HDA from the lateral to the medial compartment of the proximal tibial articular surface. The extent of

alignment correction after MCW-DFVO was closely linked to the shifts in HDA distribution, reflecting changes in stress distribution. However, clinical follow-up is short and may not reflect the medium- and long-term effects of load redistribution

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