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Locked Versus Nonlocked Plate Fixation for First Metatarsophalangeal Arthrodesis: A Biomechanical Investigation

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ABSTRACT

Background: **First metatarsophalangeal (MTP) arthrodesis using dorsal plate fixation is a common procedure for painful conditions of the great toe. Locked plates have become increasingly common for arthrodesis procedures in the foot, including the hallux MTP joint. The biomechanical advantages and disadvantages of these plates are currently unknown. The purpose of this study was to compare locked and nonlocked plates used for first MTP fusion for strength and stiffness.** ***Materials and Methods:*** **The first ray of nine matched pairs of fresh-frozen cadaveric feet underwent dissection, preparation with cup-and-cone reamers, and fixation of the MTP joint with a compression screw and either a nonlocked or locked stainless steel dorsal plate. Each specimen was loaded in a cantilever fashion to 90 N at a rate of 3 Hz for a total of 250,000 cycles. The amount of plantar MTP gap was recorded using a calibrated extensometer. Load-to-failure testing was performed for all specimens that endured the entire cyclical loading. Stiffness was calculated from the final load-to-failure test.** ***Results:*** **The locked plate group demonstrated significantly less plantar gapping during fatigue endurance testing from cycle 10,000 through 250,000 ($p < .05$). Mean stiffness was significantly greater in the locked plate group compared with the nonlocked plate group ($p = .02$). There was no significant difference in load to failure between the two groups ($p = .27$).** ***Conclusion:*** **Compared with nonlocked plates, locked hallux MTP arthrodesis plates exhibited significantly less plantar gapping after 10,000 cycles of fatigue endurance testing and significantly greater stiffness in load-to-failure testing.** ***Clinical Relevance:*** **As the use of locked plate technology is becoming increasingly common for applications in the foot, a thorough understanding of the biomechanical characteristics of these implants may help optimize their indications and clinical use.**

Key Words: First Metatarsophalangeal Arthrodesis; Hallux Rigidus; Hallux Valgus; Locked Plate

INTRODUCTION

First metatarsophalangeal (MTP) joint disorders are a frequent presenting problem to the orthopaedic surgeon. The two most common disorders of the first MTP joint are hallux valgus and hallux rigidis.[28] Arthrodesis has been shown to be a successful treatment for these disorders, particularly as a salvage option for failed procedures.[14,28] The primary goal of MTP arthrodesis is pain relief and restoration of function. Although arthrodesis is a common treatment for first MTP pathology, the reported rate of union still varies from 56% to 100%.[11,13,15,18]

Several different techniques have been described for arthrodesis of the first MTP joint. These include compression screws placed axially or obliquely, intramedullary Steinman pins, crossed Kirschner wires (K-wires), cerclage wiring, staples, sutures, external compression clamps, dorsal plates, and various combinations of the preceding techniques.[5,14,18,28] Contemporary literature focuses on rigid internal fixation with screws and plates. Cup-and-cone

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reaming of the joint and fixation with a lag screw and dorsal plate have been shown to produce the greatest stability.[4,6,21] However, even with cup-and-cone preparation and dorsal plating, nonunion rates and hardware failure remain a problem.[1,15]

Most current data on locked plating techniques are in the long-bone fracture literature, where locked plates have been shown to provide superior construct stability in certain distal radius, proximal humerus, and distal femur fractures.[17,22,29] However, there are also reports of higher nonunion rates and hardware failures with locked plating techniques.[24,25,27] With the recent proliferation in locked plates for use in foot fractures and arthrodesis, an understanding of the biomechanical characteristics of these implants may provide important insight into failure rates and help optimize their indications and clinical use. The purpose of this study was to compare locked and nonlocked plates used for first MTP fusion for strength and stiffness. The hypothesis was that the locked plates would provide greater stiffness and strength in biomechanical testing than the nonlocked plates.

MATERIALS AND METHODS

Nine pairs of fresh-frozen below-the-knee extremity cadaveric specimens were obtained. The specimens consisted of five men and four women with an average age of 78 (range, 66 to 97) years (Tables 1 and 2). All specimens were evaluated visually and radiographically to ensure the absence of gross deformity, previous operation, or fracture. Each specimen was wrapped in moist gauze and placed in a -20°C freezer for storage. After thawing, the first ray was dissected from each specimen, preserving ligamentous attachments at the MTP joint. Bone mineral density (BMD) measurements were obtained from each metatarsal base using a Hologic QDR Discovery bone densitometer (Bedford, MA).

The MTP joints of the specimens were dissected and prepared using our standard arthrodesis procedure with a cannulated power cup-and-cone reamer system (Wright Medical Technology, Arlington, TN). A single 0.062-inch K-wire was placed proximally through the center of the metatarsal head over which a reamer was run to expose subchondral bone. The radius of the reamer was sequentially moved down in size until the entire articular surface had been removed. Reaming of the phalanx was performed in a similar fashion to the corresponding size. The two bony surfaces were temporarily stabilized with crossed 1.6-mm Kirschner wires with the hallux in approximately 20° of dorsiflexion and 10° of valgus at the MTP joint confirmed with a goniometer. A single cross-compression 3.5-mm screw (Synthes, West Chester, PA) was placed from distal-medial to proximal-lateral across the joint in the standard lag fashion, with the configuration described in most clinical series.[3,5,6] After computer-generated randomization of the matched pairs, each specimen was then fixed according to treatment group with a seven-hole 2.7-mm dorsal stainless

Table 1: Locked Plate Specimen Data

					Cycle plantar gap (mm)										
Spec.	**Side**	**Age**	**Gen**	**BMD (g/cm2)**	**1**	**10**	**100**	**1,000**	**10,000**	**100,000**	**200,000**	**250,000**	**Completed cycles**	**Failure load (N)**	**Failure Mode**
1	L	70	M	0.546	0.05	0.06	0.06	0.07	0.10	0.11	0.09	0.08	250,000	378.92	Plate bend
2	L	78	M	0.527	0.22	0.23	0.22	0.20	0.19	0.21	0.21	0.21	250,000	476.25	Bone fracture
3	R	97	F	0.407	0.08	0.09	0.09	0.07	*	-	-	-	3,803	N/A	Bone fracture
4	R	88	F	0.355	0.92	1.16	1.18	1.15	1.19	*	-	-	24,018	N/A	Bone fracture
5	R	84	M	0.558	0.05	0.06	0.07	0.08	0.09	0.12	0.11	0.11	250,000	300.25	Bone fracture
6	L	79	M	0.572	0.10	0.11	0.13	0.19	0.21	0.22	0.22	0.21	250,000	468.51	Plate bend
7	R	74	M	0.559	0.24	0.33	0.42	0.59	1.70	2.45	3.11	3.48	250,000	255.69	Bone fracture
8	R	70	F	0.514	0.43	0.71	1.73	2.15	2.10	1.97	1.92	1.95	250,000	136.52	Bone fracture
9	L	66	F	0.581	0.22	0.41	1.08	2.26	3.10	*	-	-	20,813	N/A	Plate bend

NOTE: BMD, bone mineral density; Spec., specimen; Gen, gender; N/A, not applicable; *, bone fracture.

Table 2: Nonlocked Plate Specimen Data

					Cycle plantar gap (mm)									
Spec.	**Side**	**Age**	**Gen**	**BMD (g/cm2)**	**1**	**10**	**100**	**1,000**	**10,000**	**100,000**	**200,000**	**250,000**	**Completed cycles**	**Failure load (N)**	**Failure Mode**
1	R	70	M	0.607	0.31	0.43	0.55	0.73	2.51	2.43	2.37	2.37	250,000	322.58	Plate bend
2	R	78	M	0.501	0.43	0.73	0.77	0.79	0.81	0.94	0.93	0.91	250,000	354.64	Plate bend
3	L	97	F	0.381	1.22	2.55	*	-	-	-	-	-	20	N/A	Bone fracture
4	L	88	F	0.347	0.32	0.44	0.60	0.60	0.60	0.67	0.69	*	238,698	N/A	Bone fracture
5	L	84	M	0.561	1.49	2.78	2.87	2.94	3.01	3.08	3.07	3.09	250,000	264.2	Bone fracture
6	R	79	M	0.575	0.29	0.39	0.52	0.55	0.60	0.68	0.68	0.67	250,000	332.9	Plate bend
7	L	74	M	0.559	0.53	0.98	1.92	2.90	3.27	3.46	3.46	3.46	250,000	347.48	Plate bend
8	L	70	F	0.502	0.32	0.44	0.65	1.44	4.06	*	-	-	11,045	N/A	Plate bend
9	R	66	F	0.573	0.68	1.15	1.93	3.26	3.27	*	-	-	85,024	N/A	Plate bend

NOTE: BMD, bone mineral density; Spec., specimen; Gen, gender; N/A, not applicable; *, bone fracture.

steel LCP T-plate with locking (group 1) or nonlocking (group 2) cortical screws (Synthes, West Chester, PA). Therefore, each cadaver pair was assigned one nonlocking and one locking construct. A total of six screws were used for the plate in each specimen: three in the proximal phalanx and three in the metatarsal (Figure 1). All screws had good bicortical purchase. There were no loose screws.

Each metatarsal base was embedded and secured in 2.5-inch-diameter polyvinyl chloride (PVC) tubing filled with polymethylmethacrylate (PMMA) that was then mounted with a custom fixture on a servohydraulic materials testing machine (858 Bionix, MTS Systems Corporation, Eden Prairie, MN). A perpendicular load was applied to the plantar surface of the proximal phalanx at the level of the distal condyles such that the construct underwent cantilever bending (Figure 1).[6,19,20] Each specimen was loaded in a cyclic sinusoidal fashion between 5 and 90 N at a rate of 3 Hz for a total of 250,000 cycles. This was designed to replicate 6 weeks of postoperative weight bearing in a short leg walking cast.[3,8,23] Using a calibrated extensometer (MTS 632.25F-20, MTS Systems Corporation, Eden Praire, MN) with custom-fabricated attachments, the load and amount of plantar MTP gap were recorded for the first 100 cycles, then every 100th cycle to 1,000 cycles, then every 1,000 cycles until the 250,000 cycle test was completed. Testing was terminated early if the plantar MTP gap reached 5 mm. In the case of premature failure (either 5-mm extensometer displacement or piston displacement of 25 mm), the last 30 cycles of the testing were recorded using a circular buffer. Gap formation was defined as the maximum extensometer displacement during the loading cycle.

Load-to-failure testing was performed for all specimens that endured the entire cyclical loading. The constructs were loaded at a rate of 1 mm/s to failure, defined as a sharp change in the load displacement curve. Stiffness (N/mm) was calculated from the final load-to-failure test using the linear portion of the load-displacement curve. Anteroposterior and lateral radiographs were obtained pre- and posttesting to

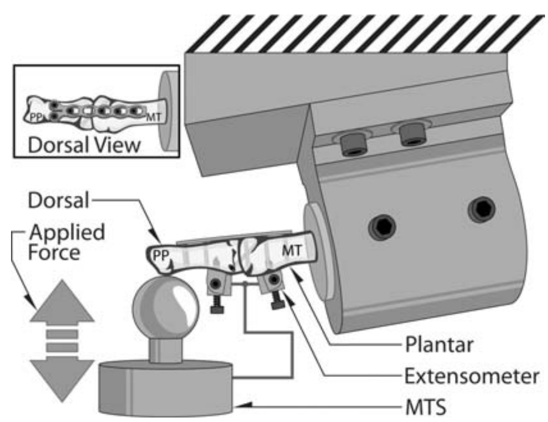

Fig. 1: Illustration of the experimental setup. MTS represents the servohydraulic materials testing machine used for the study. MT, hallux metatarsal; PP, hallux proximal phalanx.

evaluate for mode of failure. Mode of failure (bone fracture, plate bending, screw pullout, screw loosening) was recorded.

Paired t tests were used for group comparisons of: (a) MTP gap displacement during cyclical loading, (b) load to failure, and (c) stiffness. For clarity of results, the amount of maximum plantar MTP gap was compared at cycles 1, 10, 100, 1,000, 10,000, 100,000, 200,000, and 250,000. For fatigue endurance testing, three locked plate specimens and four nonlocked plate specimens failed before reaching 250,000 cycles. Four of the seven premature failures did so by gapping greater than 5 mm at the MTP joint. To preserve statistical power, we carried forward the failure gap measurement (5 mm) for all subsequent cycles of these specimens. Although carrying forward these values artificially inflated the sample size, the result is a more conservative estimate of the difference between the plating techniques. Any specimens that failed because of reaching the piston displacement limit were excluded from further analysis.

RESULTS

Four nonlocked plate specimens failed before reaching 250,000 cycles (cycles 20, 11,045, 85,024, and 238,698) (Table 2) in comparison to three locked plate specimens (cycles 3,803, 20,813, and 24,018) (Table 1). Of the four nonlocked plate specimens that failed early, two reached 5 mm of plantar MTP gap and two sustained fractures through a screw hole in the metatarsal. One of the three locked plate specimens that failed early reached 5 mm of plantar MTP gap and two sustained fractures through a screw hole in the metatarsal. Although there was no statistically significant difference in plantar gapping between the locked plate and nonlocked plate constructs through 1,000 cycles of fatigue endurance testing ($p = .07$), the locked plate group demonstrated significantly less plantar gapping from cycles 10,000 through 250,000 as compared with the nonlocked plate construct (Figure 2). There was no statistically significant difference in ultimate load to failure between the two methods of fixation (locked 375.9 ± 44.1 N, nonlocked 324.4 ± 16.0 N, $p = .27$) (Figure 3). Six of the nine specimens in the locked plate group failed by bone fracture, and six of the nine specimens in the nonlocked group failed by plate bending (Figure 4). Of the six fractures in the locked plate group, all occurred through a proximal screw hole in the metatarsal. Mean stiffness was significantly greater in the locked plate group compared to nonlocked plate group (70.3 ± 11.6 N/mm versus 43.1 ± 5.5 N/mm, respectively; $p = .02$) (Figure 5). There was no statistically significant difference in BMD between the two groups (locked 0.513 ± 0.079 g/cm^2, nonlocked 0.512 ± 0.091 g/cm^2; $p = .44$). However, all specimens with a BMD less than 0.50 g/cm^2 failed before 250,000 cycles. There was a moderate correlation between BMD and failure load ($r = .553$, $p < .05$).

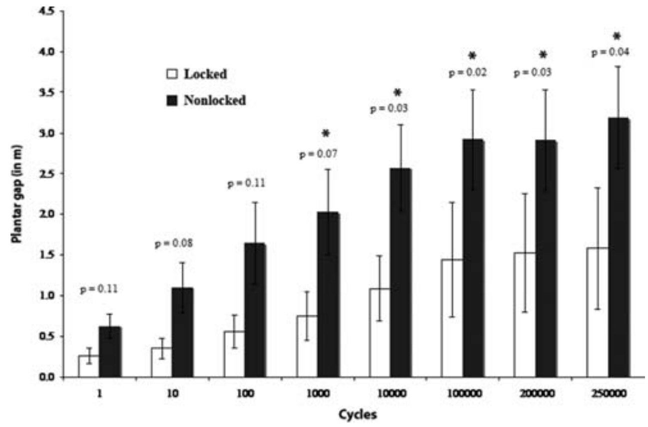

Fig. 2: Amount of plantar gapping (in mm) at MTP joint during fatigue testing (mean ± SE) at interval loading cycles. There was a statistically significant difference between constructs for cycles 10,000 through 250,000 ($p < .05$). *, statistically significant to $p < .05$.

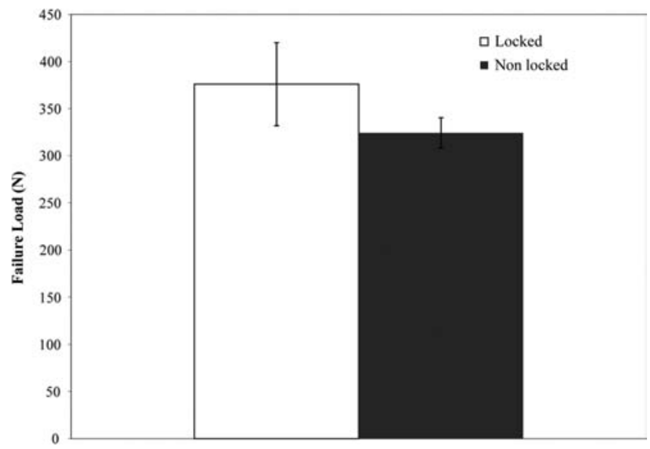

Fig. 3: Load to failure in Newtons (mean ± SE). Difference was not statistically significant ($p = .27$).

DISCUSSION

These results demonstrate that, compared with nonlocked plates, the locked first metatarsophalangeal arthrodesis plates tested in this study exhibited significantly greater stiffness in load-to-failure testing and significantly less plantar gapping after 10,000 cycles of fatigue endurance testing. However, no difference was found in ultimate load to failure between the groups. Fatigue endurance testing to 250,000 cycles was used to replicate 6 weeks of postoperative ambulation in a short leg walking cast.[3,8,23] The duration and high number of cycles were necessary to replicate common postoperative protocols and time to fusion.[7,14]

First MTP arthrodesis is a common procedure with several different fixation techniques described in the literature.[14,18,28] Dorsal plate constructs have become popular because they offer superior strength and potentially higher union rates.[21] The optimal dorsal plate construct would allow adequate interfragmentary compression and bony contact,

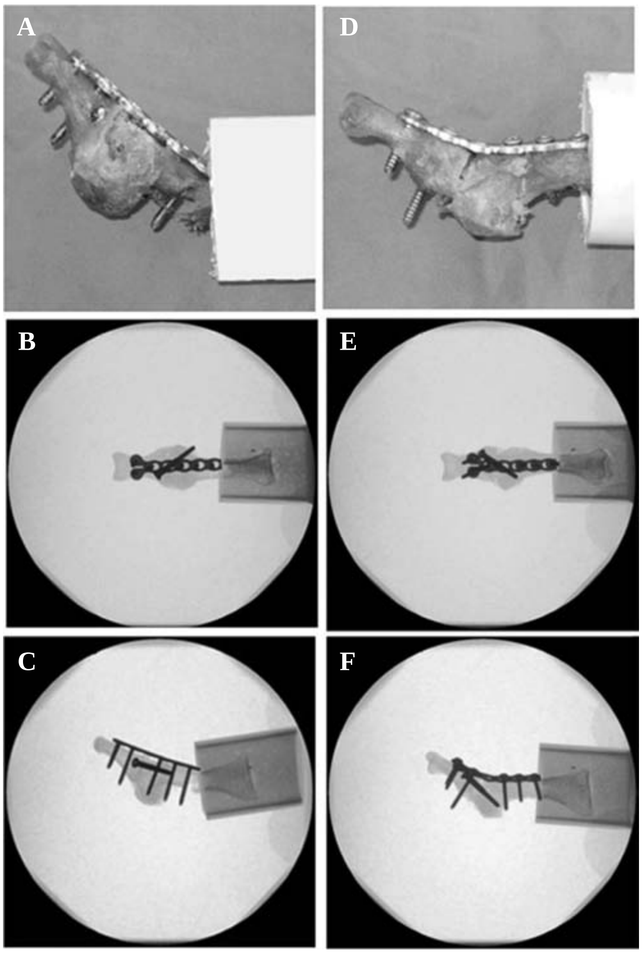

Fig. 4: Photographs and fluoroscopic images illustrating construct failure. Right side with locked plate (**A–C**) and left side with nonlocked plate (**D–F**). The locked plate construct failed by fracture through the proximal screw hole and the nonlocked plate failed by plate bending. The metatarsal is at right in each image and is embedded in PMMA.

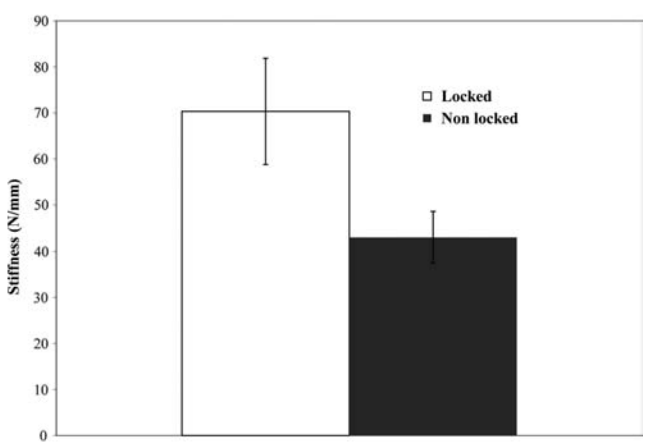

Fig. 5: Construct stiffness (N/mm) (mean ± SE). The difference was statistically significant ($p = .02$).

while providing sufficient stiffness to allow early protected weight bearing without compromising fixation. However, published results of fusion rates with hallux MTP plate arthrodesis still vary.[11,15] Bennett et al[1] evaluated 95 patients treated with a 2.4-mm nonlocked dorsal titanium plate in addition to a compression screw and found a 15% nonunion rate, all with hardware failure. Similarly, Goucher and Coughlin[13] treated 49 consecutive patients with 2.7- and 3.0-mm nonlocked dorsal titanium plates and reported an 8% nonunion rate.

Locked plates are now used broadly for foot arthrodeses, but there are limited clinical data in the orthopaedic literature regarding the constructs. Although the results of this study suggest that locked plates for hallux MTP fusion provide increased stiffness with sagittal plane forces, the precise clinical implications are unknown. No clear conclusion regarding fusion rates can be made from this study alone. Although some would suggest that with superior biomechanical properties locked plates would lead to higher union rates, a recent retrospective study showed a trend toward a higher nonunion rate in patients treated with titanium locked plates compared with stainless steel nonlocked plates for first MTP fusion.[15] That study reported on 73 feet treated with a locked titanium dorsal plate and 107 feet treated with a nonlocked stainless steel plate. Although only a statistical trend ($p = .06$), a 23% nonunion rate was found for the locked plate group compared with an 11% nonunion rate for the nonlocked plate group.[15]

Locked plate technology has gained popularity because of its biomechanical properties.[17,22,25,29] This is particularly true in the treatment of patients with osteopenic or osteoporotic bone and periarticular fractures.[16,26] These potential benefits and a recent surge in locked plate technology available for foot and ankle procedures are the likely impetus for the increased use of locked plates in the foot. Indeed, locked plates have been shown to result in superior union rates for first tarsometatarsal arthrodesis.[9] However, in view of recent findings of a higher nonunion rate using locked plates for hallux MTP fusions,[15] it is possible that locked plates produce an environment that is too stiff to reliably promote bone healing if there is not sufficient compression and bony contact at the time of plate application. Recent studies suggest that locked plate constructs suppress interfragmentary motion to a level that is insufficient to promote healing, especially at the cortex adjacent to the plate.[2,12] It is plausible that although the locked hallux MTP plate was found to provide superior rigidity, the reduction in micromotion when bone contact is insufficient may result in a higher incidence of nonunion. This can be particularly problematic in the hallux MTP joint, where sagittal plane motion predominates and there is little axial or torsional loading during normal gait.[10]

The most common mode of failure in the locked plate group in this study was fracture of the metatarsal adjacent to one of the proximal screws. A three-point cantilever loading configuration was chosen because it best approximates physiologic loading. Very little axial or torsional loading occurs at the MTP joint during physiologic activities. The cantilevered bending loading environment likely produced the greatest bending moment at the most proximal metatarsal screw–bone interface, which may explain the high incidence of failure at this location. A four-point bending configuration would have distributed the moment equally to all screws, but would have been a less physiologic loading environment. The nonlocked plates were more likely to fail because of bending of the plate, most likely a result of reduced overall stiffness.

An inherent limitation to this biomechanical study is that it does not directly evaluate in vivo stability of the constructs. Although the methods replicate 6 weeks of postoperative stress to the hardware, we did not have 6 weeks of concurrent bony healing. Any fusion procedure is a race between bone healing and hardware failure, especially when early weight bearing is allowed. Another limitation is the use of elderly cadaveric specimens. The osteopenia in some of our specimens explains some of the early failures from bone fracture (all with BMD < 0.50 g/cm^2). Caution must be used when applying these data to plates used in patients with bone of greater density and a higher healing potential.

CONCLUSION

The results of this study demonstrate that dorsal locked plates for first MTP arthrodesis had reduced plantar gap formation during cyclic loading and increased stiffness compared with nonlocked plates in an ex vivo biomechanical model. Further clinical studies are needed, however, to determine whether this leads to any difference in ultimate fusion rates. Because the use of locked plate technology is becoming increasingly common for arthrodesis and fracture fixation in the foot, an understanding of the biomechanical characteristics of these implants is paramount to optimizing their indications and clinical use.

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