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Role of intraoperative navigation in the fixation of the glenoid component in reverse total shoulder arthroplasty: a clinical case-control study

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Background: Fixation of the glenoid baseplate in reverse total shoulder arthroplasty (rTSA) is an important factor in the success of the procedure. There is limited information available regarding the effect of navigation on fixation characteristics. Therefore, the aims of this study were to determine whether computed tomography–based computer navigation improved the glenoid base plate fixation by (1) increasing the length of screw purchase, (2) altering screw angulation, and (3) decreasing central cage perforation in patients undergoing rTSA.

Methods: Patients undergoing rTSAs using navigation (NAV, N = 27) and manual technique (MAN, N = 23) from January 2014 to July 2017 were analyzed in a case-control design. Screw purchase length and central cage perforation were assessed using multiplanar computed tomography.

Results: Median screw purchase length was significantly longer in the NAV group for both anterior (20 mm vs. 15 mm, $P < .01$) and posterior screws (20 mm vs. 13 mm, $P < .01$). In addition, the NAV group displayed significantly lower incidences of inadequate screw purchase (<22 mm) for the anterior (64.7% vs. 95.2%, $P = .03$) and posterior (70.6% vs. 100%, $P = .01$) screws. Significant differences in axial and coronal screw angulation were observed between groups. Similarly, the NAV group displayed significantly reduced incidence of central cage perforation (17.7% vs. 52.4%, $P = .04$).

Conclusion: The use of computer-assisted navigated rTSA contributes to significant alterations in screw purchase length, screw angulation, and central cage perforation of the glenoid baseplate compared with non-navigated methods.

Level of evidence: Level III; Retrospective Cohort Design; Treatment Study

Keywords: Reverse total shoulder arthroplasty; computer navigation; glenoid component; computer tomography; glenoid fixation; augmented baseplate

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Reverse total shoulder arthroplasty (rTSA) successfully restores function to shoulders impaired by a range of conditions[27] and displays a lower cumulative percent revision at 5 years for osteoarthritis (4.3%) than anatomic TSA (8.1%).[1] Although aseptic loosening comprises 1.1% to 5% of

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postoperative complications for rTSA,[26,33] it accounts for 18.2% of revisions in the Australian Orthopaedic Association's National Joint Replacement Registry (AOANJRR). Appropriate placement of the glenoid baseplate and secure fixation in adequate bone stock is important for rTSA success.[4] Inadequate fixation may lead to bone resorption and increased risk of complete fixation failure.[19] Appropriate fixation is determined by a complex interaction of component design, bone volume and quality, and screw purchase.[15] Contemporary rTSA designs with screw fixation contain a cage that is important for load sharing during functional activity, and needs to be seated within the glenoid vault to provide initial stability.[5] Failure typically occurs by screw pullout nearest to the point of load application, and is moderated by bone density and screw number.[4] Appropriate placement of the screws is an important factor in rTSA fixation,[31] and the considerable between-patient variability in available bone within the narrow and curved glenoid vault must be taken into account.[4] Screw placement and orientation is also affected by surrounding structures, with the subscapularis, suprascapular nerve, and artery at risk of trauma.[12,20] Previous studies have attempted to provide recommendations regarding screw placement based on direct measurements of sawbones,[14] cadaveric specimens with fixed and variable angle base plates,[23] and computed tomography (CT)-rendered virtual models using variable angle screws.[6] However, the minimum screw purchase length (SPL) remains undefined[12] and the length achieved may be shorter *in vivo* compared with cadaveric measurements.[14,21] Nevertheless, generally screws should be oriented within the glenoid vault of the scapula. The use of image-based planning and navigation may assist in optimizing placement to prevent cage perforation and maximizing SPL. However, the data regarding the effects of navigation on these outcomes are restricted to a single case report of a rTSA for rotator cuff arthropathy using intraoperative CT to guide central cage positioning[9] and 1 study that observed a reduction in the incidence of central cage perforation with navigation, but did not completely eliminate screw misplacement.[32] A single study comparing conventional and CT-based navigated simulated procedures with 5 surgeons found improvements in end points and angulation of 3 screws, but not for the inferior screw.[31] The efficacy of navigated rTSA (NAV) remains preliminary with respect to glenoid component fixation. The accuracy of screw and central cage placement needs to be quantified *in vivo* and compared with non-navigated techniques. To address these gaps in the current knowledge, the aims of this study were to determine whether CT-based computer navigation improved the glenoid base plate fixation by (1) increasing the length of screw purchase, (2) altering screw angulation, and (3) decreasing central cage perforation in patients undergoing rTSA.

Figure 1 Glenoid baseplate for reverse total shoulder arthroplasty, illustrating the screw holes and central cage (Equinoxe; Exactech). Image adapted from Exactech.[7]

Materials and methods

Study design and recruitment

This is a retrospective observational case-control study performed in a clinical setting on a sample of convenience. Two series of rTSA performed by the senior author (MDH) were compared as described in a companion paper.[22] Patients electing to undergo primary rTSA for the treatment of osteoarthritis or rotator cuff arthropathy from January 2014 to July 2017 were recruited to a clinical registry. A consecutive series of cases undergoing NAV (N = 27) was compared with a series of conventional rTSAs (controls) implanted with a manual technique (MAN) (N = 23). Patients undergoing rTSA after January 2017 were included in the NAV group, except for patients with intraoperative complications (eg, coracoid fracture), insufficient bone stock for tracker fixation, or unavailable surgical plans. Patients provided written informed consent for the use of their clinical data for research purposes before data collection.

Surgical technique

The surgical techniques for these series are described in detail in a companion paper.[22] All arthroplasties for both groups implanted a reverse total shoulder prosthesis (Equinoxe, Exactech, Naples, FL, USA) that is a lateralizing system with variable-angle screw fixation. The glenoid baseplate has 6 screw holes available for 4 screws to achieve initial fixation (Fig. 1), as well as a central cage to achieve additional bone purchase. The superior hole in combination with the 3 inferior holes was used for these primary cases. A few cases were fixed with 3 screws when accommodation of the fourth screw was not possible, or 5 screws when an adequate hold was in doubt. The compression screws available with the implant system ranged from 18 to 46 mm in length (4 mm increments) with 4.5 mm diameter. The screw holes can accommodate up to 30° of angular variability; however, the central cage of the glenoid plate limits the variation to 20° for converging anterior, posterior, and superior screws.[7] In the conventional group (MAN),

the inferior screw was manually directed toward the inferior/lateral scapular pillar, and the superior screw to the base of the coracoid, as per the manufacturer's recommendations[7] and the 3-column concept of fixation proposed by Humphrey et al.[14] The anterior screw was directed posteriorly toward the scapular spine and the posterior screw aimed anteriorly and inferiorly toward the scapular pillar to prevent intersection with the suprascapular nerve as per Humphrey et al.[14] Full details of the preoperative planning and intraoperative application of the navigation system are provided in a companion paper,[22] but a summary is provided here for clarity and ease of reference. Patients undergoing NAV underwent a preoperative CT as previously described, which was processed by the manufacturer and provided to the surgeon for planning purposes within the navigation software (ExactechGPS v1.1; BlueOrtho, Gières, France; and Exactech). Intraoperatively, a navigation workstation which is a CT-based, image-guided, and surgeon-controlled system provided patient-specific real-time surgical guidance during surgery. During screw fixation, a CT image with a visual overlay of orientation was provided to the surgeon, illustrating the bone quality within the variable angulation available for each screw. The operating surgeon then selected the trajectory that maximized SPL within the 3-column concept.

Measurements

Each patient underwent a postoperative CT at least 6 weeks after the operation, without injectable contrast, from an imaging facility of their choice with a standardized protocol provided by the investigators. The scan was of the entire scapula in the axial plane, with the patient in a supine position and the arm in an adducted position to the side of the trunk. The tube current was set to ≥120 kVp with image reconstruction using a convolution bone kernel at a field of view of 154-410 mm and a standard image matrix size of 512 × 512 pixels, yielding between 200 and 450 images. The interslice distance was kept between 0.3 and 1 mm. Patient studies were transferred electronically from the Picture Archiving and Communication System (PACS) of the radiology provider for local analysis with a free-available DICOM viewer (RadiAnt DICOM Viewer, v4.0.3; Meixant, Poznan, Poland). Initial fixation of the glenoid component was assessed by perforation of the central cage, SPL, and screw orientation in coronal and axial planes. The scans were examined simultaneously on true axial, coronal, and sagittal sections with respect to the scapular axis. Central cage perforation was defined as a breach in the scapular wall in any plane. The SPL was measured as the distance between the backside of the base plate and the point of first breach on the scapular neck. Absolute intraosseous length was considered and the length beyond partial cortical penetration, including double penetration, was excluded. To measure the screw angles, the cage axis and screw axis were determined at the center of cage and screw. Cage axis was then superimposed on the screw axis and angle between these 2 axes was measured. Parameters were measured thrice by one author in the same session (PSN) and an average was taken. Values were rounded up to the nearest millimeter before recording into a spreadsheet for further analysis.

Statistical analysis

A STROBE (strengthening the reporting of observational studies in epidemiology) flow diagram was compiled to track patient recruitment and data analysis.[30] Patient age at surgery was assessed for normality (Anderson-Darling test) and compared between groups using an unpaired 2-sample *t*-test (Mann-Whitney *U* test). Fisher's exact test was used to compare gender distribution between groups. Central cage perforation was defined as a binary outcome (present/not present) and the incidence compared between groups by Fisher's exact test. Screw purchase length and angulation was assessed for normality and compared between groups for each screw using unpaired, 2-sample *t*-tests. Screw purchase length was also analyzed using a clinically acceptable minimum length as an anchor (22 mm, as determined by our clinical experience) and the incidence of SPL within this threshold compared between groups with a Fisher's exact test. Equality of variance was compared between groups for SPL and angulation using multiple comparisons tests. Statistical analyses were performed in Minitab (v18; Minitab Inc., State College, PA, USA) and alpha set for all tests at 5%.

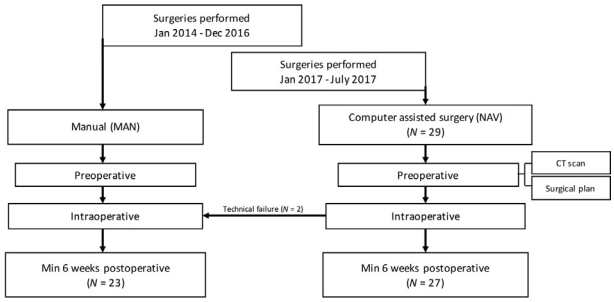

Figure 2 A STROBE[30] diagram illustrating patient recruitment and data analysis. *STROBE*, Strengthening the reporting of observational studies in epidemiology.

Results

Two groups were extracted from the clinical research registry, as illustrated in Fig. 2.

No significant differences were observed between the NAV (72; interquartile range, 64-76) and MAN (73; interquartile range, 67-78) groups for age at surgery ($P = .14$), or proportion of females (52.2% vs. 47.8%, $P = 1.0$). Median SPL was significantly longer in the NAV group for both anterior (20 mm vs. 15 mm, $P < .01$) and posterior screws (20 mm vs. 13 mm, $P < .01$), but not for the superior ($P = .58$) or inferior screws ($P = .95$) (Fig. 3). Significant differences were observed between groups for incidence of inadequate screw purchase (<22 mm) for the anterior and superior screws (Table I).

Axial screw angulation was significantly more posterior in the NAV group on average for the anterior (2° vs. −10° $P < .01$) and inferior (−6° vs. 0°, $P = .01$) screws compared with MAN, but no differences were observed between groups for the superior or posterior screws (Fig. 4). Coronal screw angulation was significantly inferiorized for the superior screw of the NAV group, compared with the MAN results (−2° vs. 3°, $P < .01$) (Fig. 5) and superiorized for the posterior screw, compared with the MAN group (2° vs

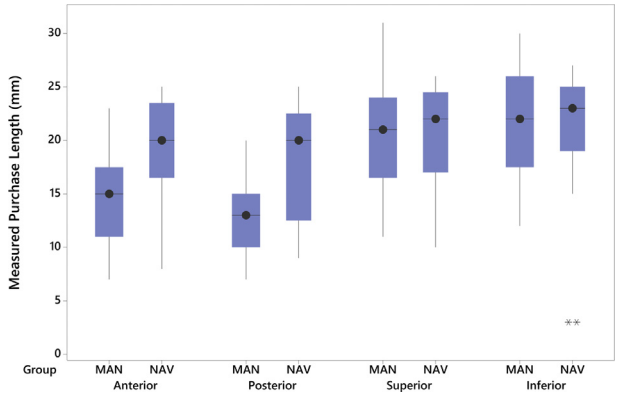

Figure 3 Between-group comparison for measured screw purchase length. Medians with 95% confidence intervals and interquartile range box. *MAN*, manual; *NAV*, navigated rTSA. * denotes outlier.

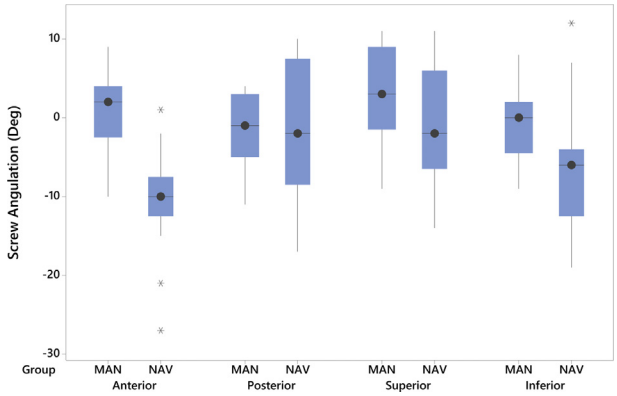

Figure 4 Between-group comparison for measured screw angulation. Medians with 95% confidence intervals and interquartile range box. *MAN*, manual; *NAV*, navigated rTSA. * denotes outliers.

$-4°$, $P = .03$) (Fig. 5). No between-group differences were observed for the anterior ($P = .36$) or inferior screws ($P = .38$). The NAV group displayed a significantly reduced incidence of central cage perforation (17.7%) compared with the MAN group (52.4%) ($P = .04$).

Discussion

The aims of this study were to determine whether CT-based computer navigation improved the glenoid base plate fixation by (1) increasing the length of screw purchase, (2) altering screw angulation, and (3) decreasing central cage perforation in patients undergoing rTSA. The NAV group displayed a significant improvement in average SPL compared with the MAN group by at least 6 mm for the anterior and posterior screws. In addition, screw angulation was significantly more posterior for the anterior and inferior screws in the NAV group, whereas the superior screw was more inferiorly directed and the posterior screw more superiorly directed. The NAV group also displayed a significantly reduced incidence of central cage perforation compared with the MAN group.

Restricting micromotion between the base plate and the underlying bone to below 150 μm is considered ideal for encouraging bony ingrowth.[2,16,24] Inadequate fixation may lead to bone resorption and complete fixation failure.[19] Therefore, strong initial fixation of the glenoid component may be essential for the long-term survival of the rTSA, because aseptic loosening is associated with 18% of revisions in the Australian Orthopaedic Association's National Joint Replacement Registry.[1] The central cage of common rTSA base plate designs provides a portion of the initial stability (12% to 28%),[17] and the present results demonstrated that image-based navigation can accurately seat the cage such that it is wholly contained within the glenoid vault without perforation in >80% of cases. Screw insertion angulation and length provides the majority of initial glenoid fixation in rTSA,[13] particularly the inferior screw.[4] Previous recommendations on screw positioning with respect to purchase length may be problematic in the context of the present findings. The majority of studies to date have relied on cadaver, sawbone, or foam analogues and appear to consistently overestimate SPL when compared with *in vivo* studies (Fig. 6). Our results agree with those of Moon et al,[21] who reported considerably smaller SPL in clinical cases compared with cadaver specimens using radiographic assessment. Our results confirm that the

Table I Incidence (%) of "inadequate" screw purchase length (<22 mm) compared between groups

	NAV	MAN	*P* value
Anterior	64.7	95.2	.03
Posterior	70.6	100	.01
Superior	47.1	57.1	.74
Inferior	35.3	38.1	1.0

NAV, navigation; *MAN*, manual.

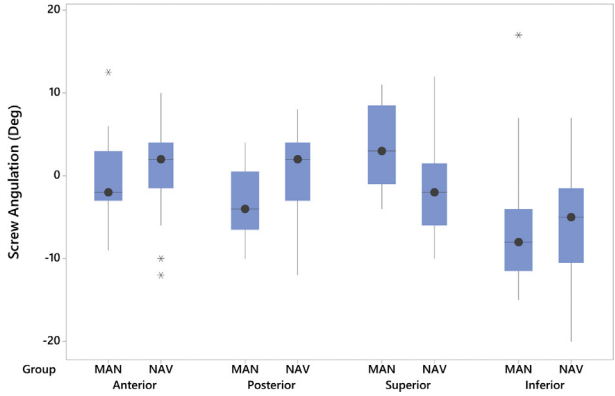

Figure 5 Between-group comparison for screw angulation in the coronal plane (Superior-Inferior). Medians with 95% confidence intervals and interquartile range box. *MAN*, manual; *NAV*, navigated rTSA. * denotes outlier.

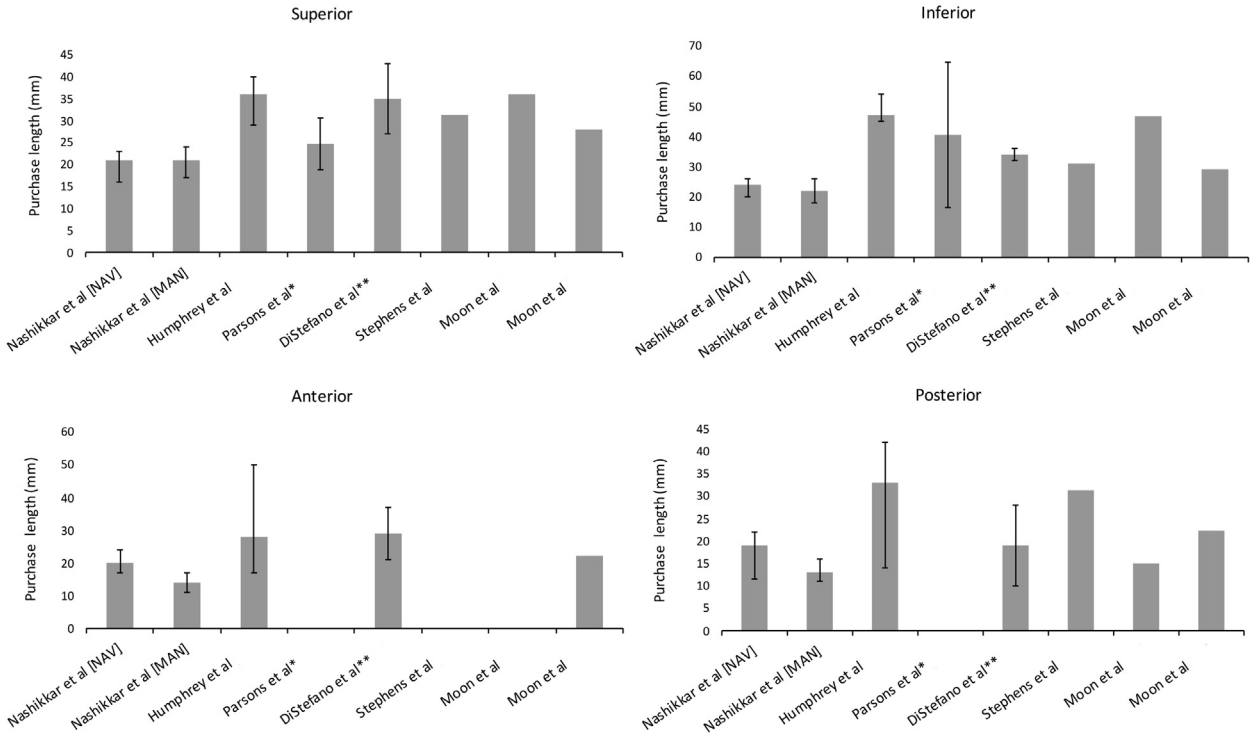

Figure 6 Screw purchase length compared between studies. Methods (from left): clinical + computed tomography (CT) (CAS); clinical + CT (MAN); sawbone + direct measurement;[14] cadaver + direct measurement;[23] cadaver + three-dimensional (3D) reconstruction;[6] cadaver + 3D reconstruction;[28] cadaver + x-ray;[21] clinical + x-ray.[21] *MAN*, manual; *NAV*, navigated rTSA. *Divergent angle locking; **screw contained in ''safe position.''

achieved SPL clinically is a fraction of the lengths achieved in vitro. These findings may have important implications for biomechanical assessments of fixation in rTSA using in vitro or in silico simulations.[4,11,20] The smaller SPL relative to the in vitro literature observed in this clinical series may be due to the presence of soft tissue restraints, limited visibility of the scapula during insertion, as well as base plate design and positioning.[3,25,29] Nevertheless, the use of image-based navigation allowed for direct visualization of screw placement and enabled significant increases in SPL for anterior and posterior screws.

Malpositioned screws may be harmful to surrounding soft tissues, such as the axillary (inferior screw) or suprascapular (superior screw) nerve, blood vessels, or rotator cuff muscles[32] and may cause polyethylene indentation and wear.[10,18] Accurate fixation is crucial in cases of small glenoid bone stock and abnormal scapular morphology, and navigated drilling under image guidance in nearby risky areas prevented multiple drill entries to get longer purchase. Scapula bone quality is often heterogeneous with a wide variation across short distances, and navigation enabled identification of regions with the best bone stock intraoperatively. In this investigation, SPL of the inferior screw was not affected by the use of computer navigation, but was angled more posteriorly compared with the MAN group. Inferior screws were directed posteroinferiorly toward the lateral wall of scapula in NAV cases, which has higher bone density[6] compared with the inferocentral aspect, where the majority of inferior screws were directed in the MAN group. This may be due to the between-patient variability of the scapular pillar, which is the recommended target for the inferior screw,[14] and glenoid abnormalities, which restrict peripheral screw placement,[8] are more frequently observed to affect the posterior aspect of the glenoid. This may explain the significantly higher between-patient variability in angulation for the posterior screw in both axial and coronal planes in the NAV group. In addition, average SPL was increased, and the screw angled more superiorly on average compared with the MAN group. The superior screw was angled more inferiorly on average in the NAV group, whereas the average SPL was not affected, navigation did significantly reduce the incidence of ''inadequate'' SPL. These results demonstrate the relationship between angulation and SPL in the context of nearby neurovascular and musculotendinous structures. Future work should examine the relationship between these alterations in fixation and biomechanical data, as well as patient outcomes.

This study presents new information regarding the application of image-based computer navigation to fixation in rTSA; however, the results should be interpreted in the context of the limitations. First, although this is one of the

largest series of computer-assisted rTSA to date, the statistical findings indicate that some comparisons may remain underpowered. Although the significant findings reported are valid, nonsignificant findings between groups should be interpreted with caution and future works should use the information presented here to design adequately powered comparisons. Secondly, this is a nonrandomized case-control study and a detailed comparison of glenoid and scapula anatomy was not performed, which may impact on screw placement. Nevertheless, the cases were consecutively recorded in a practice registry within a 3-year timespan. The criteria for surgery did not change in this time, and it is unlikely that glenoid morphology changed significantly. However, an anatomical comparison between groups would be a useful follow-up to the present findings to confirm the relationship between bone density distributions or other anatomical characteristics and screw placement. Lastly, this is the first study to our knowledge to use 3-dimensional clinical CT to measure SPL in rTSA. This modality has demonstrated validity and reliability in a range of applications for implant positioning assessment; however, the reliability of the technique described here requires further investigation. In addition, potential drawbacks of the use of navigation include fracture of the tracker mounting site and loosening of the trackers. As reported in our companion paper,[22] the incidence of coracoid fracture and tracker loosening are low (2 of 35 cases), but nevertheless highlight the importance of considering bone quality when choosing the most appropriate surgical approach.

Conclusion

Computer-assisted rTSA with image-based guidance enables real-time visualization and improves glenoid base plate fixation by decreasing the incidence of central cage perforation, increasing the average length of screw purchase and decreasing the incidence of inadequate screw purchase. Navigation also led to significant changes in angulation in the axial and coronal planes, with the posterior screw in particular displaying significantly higher between-patient variability in angulation. Further analysis is required to determine the biomechanical implications of fixation differences relative to conventional techniques, and ultimately the effect on patient clinical outcomes.

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