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ORIGINAL ARTICLE

Computed tomography–based prediction of the straight antegrade humeral nail's entry point and exposure of "critical types": truth or fiction?

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Background: Straight antegrade intramedullary nailing of proximal humerus fractures has shown promising clinical results. However, up to 36% of all humeri seem to be "critical types" in terms of the potential violation of the supraspinatus (SSP) tendon footprint by the nail's insertion zone. The aims of this study were to evaluate if a computed tomography (CT) scan could reliably predict the nail's entry point on the humeral head and if it would be possible to preoperatively estimate the individual risk of iatrogenic violation of the SSP tendon footprint by evaluating the uninjured contralateral humerus.
Methods: Twenty matched pairs of human cadaveric shoulders underwent CT scans, and the entry point for an antegrade nail as well as measurements regarding critical distances between the entry point and the rotator cuff were determined. Next, gross anatomic measurements of the same data were performed and compared. Furthermore, specimens were reviewed for critical types.
Results: Overall, 42.5% of all specimens were found to be critical types. The CT measurements exhibited excellent intra-rater and inter-rater reliability (intraclass correlation coefficients >0.90). Similarly, excellent agreement between the CT scan and gross anatomic measurements in contralateral shoulders (intraclass correlation coefficients >0.88) was found.
Conclusion: Assessing the uninjured contralateral side, CT can reliably predict the entry point in antegrade humeral nailing and preoperatively identify critical types of humeral heads at risk of iatrogenic implantation damage to the SSP tendon footprint. This study may help surgeons in the decision-making process

Institutional Review Board approval is not required because the use of anonymized cadaveric specimens is exempt at our institution.
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on which surgical technique should be used without putting the patient at risk for iatrogenic, implant-related damage to the rotator cuff.
Level of evidence: Anatomy Study; Imaging

Keywords: Proximal humerus fracture; fifth anchoring point; proximal anchoring point; straight antegrade humeral nailing; entry point; osteoporotic fracture

Fractures of the proximal humerus are the third most common fractures in patients older than 65 years.[1,12] Distinct treatment algorithms for displaced and unstable fractures remain controversial.[11,16] Various surgical techniques are available, ranging from minimally invasive K-wire or screw fixation, plating, and antegrade intramedullary nailing to hemiarthroplasty or reverse total shoulder arthroplasty. Evidence-based guidelines are still missing. Postoperative complication rates as high as 36% have been reported.[19,22] Varus dislocation, caused by comminution of the medial calcar, is a common failure mode.[13,24] The risks of failure increase exponentially in patients with osteoporosis.[13] In 3- and 4-part fractures, sufficient anchoring in the head fragment seems mandatory to provide stability. One possible solution to this problem is the creation of an additional proximal bony anchoring point provided by the tip of a straight antegrade humeral nail. Designated anchoring points within the humeral head are supplied by head locking screws. If all 4 head locking screw options are used, this additional anchoring point has been described as the "fifth anchoring point" for the MultiLoc nail (DePuy Synthes, West Chester, PA, USA).[21] The highest bone mineral density within the humeral head is located in the cranial, medial, and dorsal regions of the head. In contrast to the curvilinear nail, the tip of the straight nail is designed to anchor at the dense apex of the humerus and is therefore presumed to provide increased stability.[21] Furthermore, in 3-part fractures including a fracture of the greater tuberosity, the curvilinear nail may enter the humeral head within the fracture zone, whereas the straight nail's tip may potentially anchor the humeral head at the solid, not comminuted central and most proximal area. Clinically, straight intramedullary nails have been demonstrated to provide a union rate comparable to that of the curvilinear design, with a much lower incidence of complications.[15] However, because of anatomic variability, there is a risk of violation of the supraspinatus (SSP) tendon footprint even for straight nails, potentially additionally causing iatrogenic impairment of the patient's postoperative range of motion.[5] Diameters of straight nails available on the market range from 9.5 to 12.5 mm at the tip and 7 to 10 mm at the shaft, resulting in a recommended minimal proximal reaming diameter of at least 10 mm. This equates to 5 mm being the smallest possible radius needed for antegrade nailing procedures in the proximal humerus (critical distance [CD]) and 8 mm being the minimum safety distance from the critical point (CP) to avoid iatrogenic damage to the SSP tendon insertion while ensuring proper bone fixation.[5,8] Euler et al therefore defined the "safe type," not exceeding the safety distance, and the "critical type," exceeding the safety distance. They reported up to 36% of all humeri appearing to be critical types in terms of damaging the SSP tendon footprint by the nail's entry point.[5] They emphasized the need for "fastidious" preoperative planning to minimize the risk of iatrogenic violation of the rotator cuff. In order not to iatrogenically put the patient at risk, the individual anatomy may be assessed by using bilateral computed tomography (CT) scans of the shoulders to preoperatively scan for critical types.

However, it remains unclear if CT measurements do reliably reflect the macroscopic anatomy to sufficiently scan for the individual patient's qualification for straight antegrade humeral nailing procedures preoperatively. The aim of this study was to evaluate the feasibility of the individual anatomic prediction of the exact straight nail's entry point on the humeral head using CT scans of the contralateral side. We therefore hypothesized that CT scans are feasible to reliably predict the straight nail's entry point on the humeral head using the contralateral side. Clinically, this information is relevant to plan the surgical approach and furthermore to estimate the individual risk of potential iatrogenic violation of the SSP tendon footprint.

Materials and methods

Study design

Twenty matched pairs (10 male and 10 female) of osteoporotic cadaveric humeri were used for this study (n = 40 specimens). Specimens were chosen to be at least 70 years of age to be preferably osteoporotic, without any prior injuries or surgeries to their shoulders, and matched for gender. Median age was 81 years (range, 73-95); median body mass index was 22.4 (range, 15.4-34.7), and median bone mineral density was 70.8 mg/cm^3 (range, 51.6-88.4). CT scans of all specimens were conducted using an Aquilion Premium CT scanner (Toshiba America Medical Systems, Inc., Tustin, CA, USA). To assess measurement repeatability, all CT-based measurements were performed by 2 investigators. Two weeks after the initial round of measurements, 1 rater performed a second round of CT measurements. Meanwhile, gross anatomic measurements were conducted once and by a single rater. Scans were reconstructed 2-dimensionally in 3 perpendicular planes using IMPAX EE R20 (Agfa HealthCare N.V., Mortsel, Belgium). Using CT scans of paired and uninjured humeral heads, the ideal designated entry point on the humeral head for straight antegrade nailing, the CP (intersection between the sagittal axis of the most cranial extension of the greater tuberosity, the cortical border of the humerus in the anterior-posterior view), the

CD (distance between the CP and the entry point) and lateral distance (entry point to most lateral extension of the greater tuberosity) were evaluated as described by Euler et al[5] (Fig. 1).

Using the same cadavers and following the manufacturer's surgical technique instruction, ideal macroscopic insertion points of the nails were assessed in a second step. After adjustment of the center of the axis of the humeral shaft using 2 perpendicular planes, this center was extrapolated proximally through the humeral head to mark the potential entry point of the straight antegrade nail (Fig. 2). In accordance with the CT method described before, comparable gross measurements were assessed.

To reinforce the reliability of the test method, 4 more measurements on both the CT scans and the gross specimens macroscopically were assessed and compared: ventral (entry point to the anterior

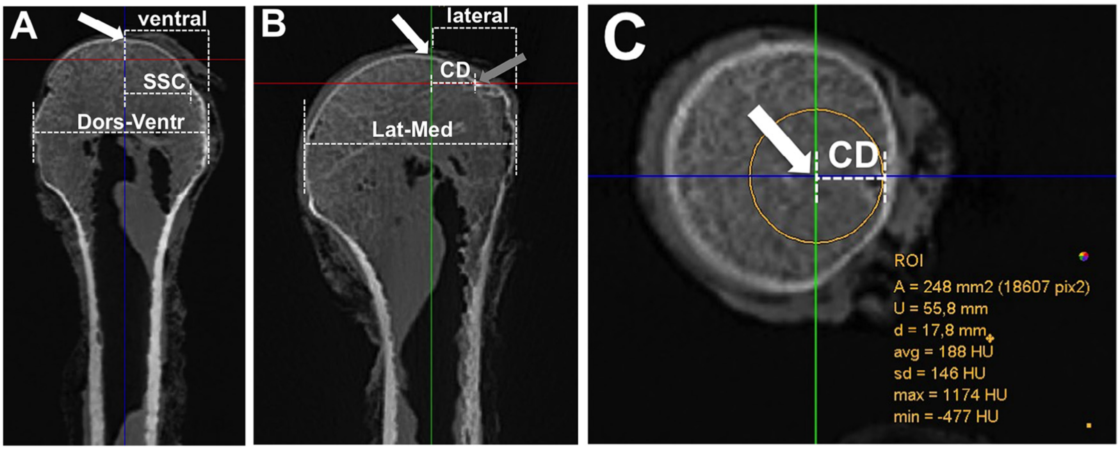

Figure 1 Two-dimensionally reformatted computed tomography scan and illustration of measurements. (**A**) Saggital view: *ventral*, entry point to the anterior end of the lesser tuberosity; *SSC* , entry point to the transition zone of the subscapularis tendon; and *dorsal-ventral* (*Dors-Ventr*), largest possible perpendicular distance between the dorsal joint surface and the most ventral extension of the lesser tuberosity; the *arrow* indicates the entry point. (**B**) Anteroposterior view: *lateral*, entry point to most lateral extension of the greater tuberosity; *CD*, critical distance, distance between the critical point and the entry point; and *lateral-medial* (*Lat-Med*), largest possible perpendicular distance between the medial joint surface and the most lateral extension of the greater tuberosity; the *white arrow* indicates the entry point; the *gray arrow* indicates the critical point. (**C**) Axial view; the *arrow* indicates the entry point.

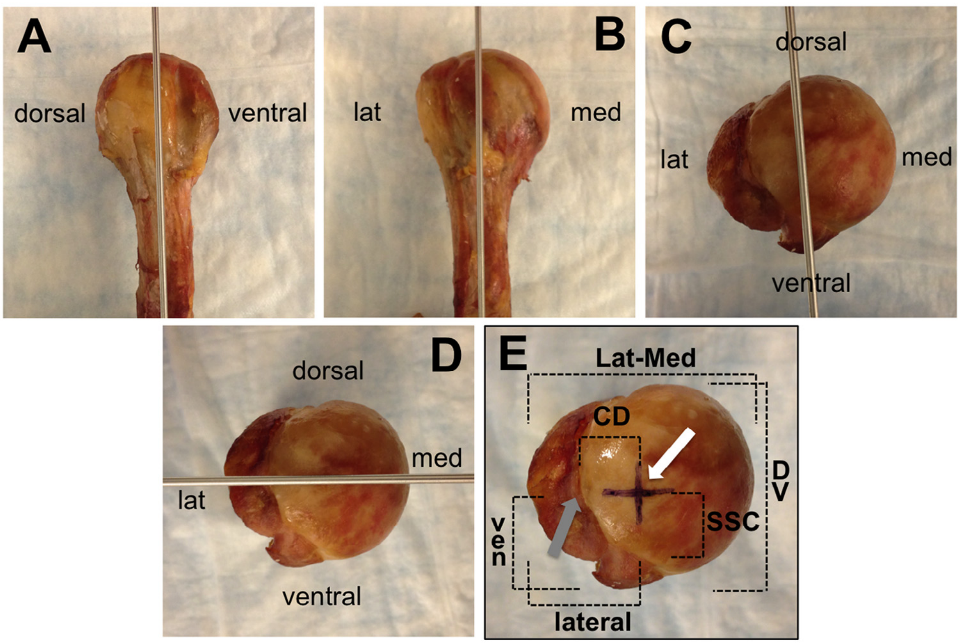

Figure 2 Macroscopic images of specimens. (**A**) Saggital view, metal wire indicating the humeral shaft axis. (**B**) Anteroposterior view, metal wire indicating the humeral shaft axis. (**C** and **D**) Axial views, metal wires indicating the (**C**) ventral-dorsal and (**D**) medial-lateral axes of the humeral head. (**E**) Axial view and illustration of performed gross measurements: lateral-medial (*Lat-Med*), critical distance (*CD*), subscapularis (*SSC*) tendon, ventral (*ven*), lateral, and dorsal-ventral (*DV*); the *white arrow* indicates the entry point; the *gray arrow* indicates the critical point.

end of the lesser tuberosity), subscapularis tendon (entry point to the transition zone of the subscapularis tendon), medial-lateral (largest possible perpendicular distance between the medial joint surface and the most lateral extension of the greater tuberosity), and dorsal-ventral (largest possible perpendicular distance between the dorsal joint surface and the most ventral extension of the lesser tuberosity) (Fig. 2, *E*). Critical types, as determined by calculating CPs and CDs, were also recorded for both CT and gross anatomic methods.

Statistical analysis

To address the purpose of this study, 5 types of measurement agreement were assessed. First, intra-rater and inter-rater reliability was calculated for the CT measurements. Next, agreement was judged between left and right paired specimens for gross anatomic measurements only. Last, agreement between CT and gross anatomic measurements (intermethod) was evaluated in 2 ways: comparisons for each measurement within the same shoulder and comparisons between contralateral shoulders with differing modalities (right CT vs. left gross anatomic measurement, and vice versa).

In all cases, a 2-way random-effects model was used to calculate the single measures, absolute agreement version of the intraclass correlation coefficient (ICC). Nonparametric 95% bootstrap confidence intervals were reported with each ICC calculation. The ICC values were interpreted as follows: ICC < 0.40, poor agreement; 0.4 < ICC < 0.75, fair to good agreement; and ICC > 0.75, excellent agreement.[7]

To assess the measurement reliability in the units of measurement, Bland-Altman 95% limit of agreement analyses were performed.[2] This tool aids in clinical interpretation by determining the average bias and spread of the observed differences between 2 sets of measurements. All statistical analyses were performed with the statistical package R (R Development Core Team, Vienna, Austria) with packages *psy* and *boot*.[4,6,20]

Results

Thorough summary statistics for each measurement can be found in Table I.

Intra-rater and inter-rater reliability metrics for CT measurements are presented in Table II. Both types of agreement were excellent for all 6 measurements, achieving ICC > 0.9 in all cases. Bland-Altman analysis found that absolute observed mean differences (bias) were never larger than 0.5 mm.

The 6 gross anatomic measurements were found to correlate strongly between left and right paired specimens (Table III). Again, all ICC estimates were >0.90, and observed bias was at most 0.2 mm.

Measurement agreement between CT and gross anatomic measurements is presented in Table IV. CT and gross anatomy measurements agreed closely when they were made on the same (ipsilateral) shoulder (ICC >0.95, observed bias ≤0.3 mm). Agreement was slightly lower, and limits of agreement were wider, but ICCs were still excellent in comparing CT with gross anatomic measurements on contralateral shoulders (ICC >0.88, observed bias ≤0.3 mm).

Mean ± standard deviation for the CD measurement was 8.6 ± 2.9 mm when measured on CT. Overall, 42.5% (17/40) of all specimens were found to be critical types at risk for an iatrogenic violation of the SSP tendon. CT and gross anatomic measurements agreed on the categorical classification of critical type (SSP distance <8 mm) in 100% of the 40 shoulders in this study.

Table I Summary statistics for each measurement

	Measurement method	Mean ± SD	Minimum-maximum
Lateral	CT	23.9 ± 3.6	18-33
	Gross-anatomic	24.1 ± 3.7	17.5-33.6
Ventral	CT	26.9 ± 3.9	19.1-35.2
	Gross-anatomic	27.2 ± 3.8	19.5-35.7
SSP	CT	8.6 ± 2.9	3.9-13.2
	Gross-anatomic	8.7 ± 2.9	4.1-13.5
SSC	CT	11.3 ± 3.3	5.2-19.9
	Gross-anatomic	11.4 ± 3.4	5.5-20.8
Medial-lateral	CT	52.3 ± 4.9	44.6-61.2
	Gross-anatomic	52.2 ± 5.1	45.3-62.1
Dorsal-ventral	CT	48.4 ± 5.1	39-57.1
	Gross-anatomic	48.5 ± 5.2	38.9-57

SSP, supraspinatus; *SSC*, subscapularis; *CT*, computed tomography; *SD*, standard deviation.
Lateral: entry point to most lateral extension of the greater tuberosity; *Ventral*: entry point to the anterior end of the lesser tuberosity; *SSC*: entry point to the transition zone of the subscapularis tendon; *Medial-lateral*: largest possible perpendicular distance between the medial joint surface and the most lateral extension of the greater tuberosity; *Dorsal-ventral*: largest possible perpendicular distance between the dorsal joint surface and the most ventral extension of the lesser tuberosity.

Table II Intra-rater and inter-rater reliability metrics for CT measurements

		ICC [95% CI]	Bias (lower, upper)
Intra-rater (CT)	Lateral	0.99 [0.981, 0.995]	0 (−1, 1)
	Ventral	0.94 [0.887, 0.969]	0.4 (−2.1, 3)
	SSP	0.98 [0.964, 0.988]	0 (−1.1, 1.2)
	SSC	0.978 [0.962, 0.989]	−0.2 (−1.5, 1.1)
	Medial-lateral	0.937 [0.904, 0.96]	−1.1 (−4.2, 2)
	Ventral-dorsal	0.988 [0.981, 0.993]	−0.3 (−1.8, 1.1)
Inter-rater (CT)	Lateral	0.962 [0.928, 0.98]	0 (−1.9, 1.8)
	Ventral	0.96 [0.931, 0.978]	−0.2 (−2.4, 1.9)
	SSP	0.987 [0.978, 0.993]	0 (−0.9, 0.9)
	SSC	0.98 [0.962, 0.99]	−0.1 (−1.4, 1.2)
	Medial-lateral	0.924 [0.879, 0.952]	−1.1 (−4.6, 2.4)
	Ventral-dorsal	0.978 [0.96, 0.988]	−0.5 (−2.4, 1.4)

CT, computed tomography; *SSP*, supraspinatus; *SSC*, subscapularis; *ICC*, intraclass correlation coefficient; *CI*, confidence interval.

Table III Bilateral correlation of gross anatomic measurements

		ICC [95% CI]	Bias (lower, upper)
Left-right agreement for gross anatomic measurements	Lateral	0.952 [0.872, 0.985]	−0.2 (−2.5, 2.2)
	Ventral	0.942 [0.877, 0.979]	−0.2 (−2.9, 2.5)
	SSP	0.932 [0.845, 0.972]	−0.2 (−2.4, 1.9)
	SSC	0.929 [0.832, 0.98]	0.2 (−2.4, 2.9)
	Medial-lateral	0.931 [0.693, 0.988]	0 (−3.9, 4)
	Ventral-dorsal	0.917 [0.796, 0.969]	−0.2 (−4.6, 4.2)

SSP, supraspinatus; *SSC*, subscapularis; *ICC*, intraclass correlation coefficient; *CI*, confidence interval.

Table IV Measurement agreement between CT and gross anatomic measurements

		ICC [95% CI]	Bias (lower, upper)
Ipsilateral	Lateral	0.981 [0.955, 0.991]	−0.3 (−1.6, 1)
	Ventral	0.986 [0.963, 0.993]	−0.3 (−1.5, 0.8)
	SSP	0.993 [0.987, 0.995]	−0.1 (−0.8, 0.5)
	SSC	0.992 [0.985, 0.995]	−0.1 (−0.9, 0.7)
	Medial-lateral	0.951 [0.798, 0.991]	0.1 (−3.1, 3.3)
	Ventral-dorsal	0.996 [0.991, 0.998]	−0.1 (−1, 0.8)
Contralateral	Lateral	0.949 [0.888, 0.976]	−0.3 (−2.6, 2)
	Ventral	0.938 [0.883, 0.967]	−0.3 (−3, 2.4)
	SSP	0.932 [0.874, 0.963]	−0.1 (−2.3, 2)
	SSC	0.934 [0.875, 0.968]	−0.1 (−2.6, 2.4)
	Medial-lateral	0.889 [0.707, 0.96]	0.1 (−4.7, 4.9)
	Ventral-dorsal	0.919 [0.841, 0.96]	−0.1 (−4.3, 4.1)

CT, computed tomography; *SSP*, supraspinatus; *SSC*, subscapularis; *ICC*, intraclass correlation coefficient; *CI*, confidence interval.

Discussion

The most important findings of our study were that CT can reliably predict the entry point in antegrade humeral nailing using the contralateral uninjured side. Furthermore, CT can reliably identify critical types of humeral heads at risk of iatrogenic implantation damage to the SSP footprint. Overall, 42.5% (17/40) of the specimens were found to be critical types.

Within the past few decades, CT has gained popularity as a reliable tool in both diagnostics and preoperative planning in trauma and orthopedic surgery. For example, CT scans are routinely used for preoperative planning in most intra-articular fractures of both upper and lower extremities, spinal fractures, and pelvic fractures. For a variety of indications, using the uninjured contralateral side as a template can assist in accurately determining joint configurations and screw placement. The bilateral comparability of humeri has been shown to be reliable, with only minor differences.[3,10] Regarding proximal humerus fractures, Jeong and Jung recently used CT to determine the neck-shaft angle of the proximal humerus in an effort to precisely plan the portal placement in arthroscopically assisted antegrade humeral nailing.[9] Fragment dislocation and malalignment are frequent in acute traumatic proximal humerus fractures. Given this fact, exact anatomic measurements on the index shoulder are oftentimes impossible. Comparing bilateral measurements on CT scans and on the same real specimens anatomically, we found excellent intra-rater and inter-rater agreement for all measurements, achieving ICC >0.9 in all cases. According to our findings, a reliable prediction of entry points and critical types was accurately possible using CT scans of the uninjured contralateral humerus.

To achieve the most solid fixation, several authors strongly recommend implant placement as far medially and cranially in the humeral head as possible.[14,23] In contrast to the traditional bent or curvilinear antegrade humeral nails, straight antegrade humeral nails anchor the humeral head more medially, therefore providing a strong proximal anchoring point. This concept is termed the fifth anchoring point, or additional anchoring point, in accordance with the number of locking screws used within the surgical procedure.[21] However, even this more medial insertion point may put the SSP tendon's footprint at risk to be violated by the reaming process.[5] In a clinical study, Lopiz et al have found "symptoms related to a rotator cuff disease" in 34.6% of all patients after antegrade insertion of a straight humeral nail.[15] Furthermore, the distance to the lateral extension of the humeral head seems to be crucial to ensure solid fixation of the nail within the humeral head. Because of anatomic morphology, humeral heads can be categorized as safe types or critical types that put the patient at risk after straight antegrade humeral nailing.[5] Evaluating 400 specimens, we found a mean CD of 8.51 mm in a prior study, and 38.5% of all humeri were classified critical types. In this study, we found a mean CD of 8.6 mm and a comparable rate of 42.5% critical types.[5]

Because of its potentially increased fixation properties, like the fifth anchoring point, straight antegrade humeral nailing has recently gained popularity. Clinically, Lopiz et al demonstrated that straight antegrade nails yielded union rates comparable to those of curvilinear nails, with a much lower incidence of complications.[15] Postoperative symptoms related to a rotator cuff disease were present in 73% of the bent nail group and in 34.6% of the straight nail group. Reoperation rate was 42% in the bent nail group and 11.5% in the straight nail group.[15] Nolan et al reported on >50% of patients with rotator cuff disease after bent antegrade nail osteosynthesis.[18] In a cadaveric study, Noda et al emphasized the significance of the entry point as a potential cause of loss of reduction at the fracture site after nail insertion.[17]

In reality, anatomic reduction might not always be possible, leading to a different, not exact position of the entry point. For comparability in this cadaveric study, all measurements were standardized on anatomically reduced fractured humeri.

To the best of our knowledge, there is no anatomic or biomechanical study evaluating the insertion point and its related risks for straight antegrade humeral nailing. Our study suggests that CT scans of both the injured and uninjured contralateral side can be a helpful tool in preoperative planning of antegrade humeral nailing. In clinical reality with sometimes relevantly dislocated fracture patterns, an exact planning of the potential entry point seems to be even more important in order not to cause additional iatrogenic damage. As critical types with a potential risk of iatrogenic damage to the SSP footprint are common, we believe that such planning is of importance in an effort to identify patients suitable for antegrade nailing compared with those patients who might be better treated with, for example, a locking plate.

Conclusions

Assessing the uninjured contralateral side, CT can reliably predict the entry point in antegrade humeral nailing and preoperatively identify critical types of humeral heads at risk of iatrogenic implantation damage to the SSP tendon footprint.

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