Predictors of humeral head ischemia after intracapsular fracture of the proximal humerus

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The purpose of this study was to evaluate predictors of fracture-induced humeral head ischemia. Between February 1998 and December 2001, 100 intracapsular fractures of the proximal humerus, treated by open surgery, were included in a prospective surgical evaluation protocol (mean age, 60 years; minimum, 21 years; maximum, 88 years; 45 men; 57 right shoulders). Fracture morphology was assessed following a structured questionnaire and based on radiographic and intraoperative findings. Perfusion was assessed intraoperatively by observation of backflow after a borehole was drilled into the central part of the head in all shoulders and by intraosseous laser Doppler flowmetry in 46. Good predictors of ischemia were the length of the metaphyseal head extension (accuracy, 0.84 for calcar segments <8 mm), the integrity of the medial hinge (accuracy, 0.79 for disrupted hinge), and the basic fracture pattern (accuracy, 0.7 for combined types 2, 9, 10, 11, and 12). Moderate and poor predictors of ischemia were fractures consisting of four fragments (accuracy, 0.67), angular displacement of the head (accuracy, 0.62 for angulations over 45°), the amount of displacement of the tuberosities (accuracy, 0.61 for displacement over 10 mm), glenohumeral dislocation (accuracy, 0.49), head-split components (accuracy, 0.49), and fractures consisting of three fragments (accuracy, 0.38). When the above criteria (anatomic neck, short calcar, disrupted hinge) were combined, positive predictive values of up to 97% could be obtained. The most relevant predictors of ischemia were the length of the dorsomedial metaphyseal extension, the integrity of the medial hinge, and the basic fracture type determined with the binary description system. (J Shoulder Elbow Surg 2004;13: 427–33.)

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1058-2746/2004/$30.00
doi:10.1016/j.jse.2004.01.034

Perfusion of the humeral head is, among other arguments, an important consideration when deciding on the treatment of complex intraarticular fractures of the proximal humerus. Therefore, it was our intention to search for tools to predict humeral head perfusion. It was believed that evaluation of fracture planes would probably provide some guidance. It was also hypothesized that when a metaphyseal extension remained attached to the head, a degree of residual perfusion provided by the posterior circumflex humeral vessels could be anticipated. The purpose of this study was to verify this hypothesis—that is, to evaluate the impact of fracture morphology including the position and the size of the metaphyseal head extensions on humeral head perfusion.

MATERIALS AND METHODS

Between February 1998 and December 2001, 116 consecutive patients with an intracapsular fracture of the proximal humerus on presentation were included in a prospective surgical evaluation protocol. (The term "intracapsular" is derived from Kocher's original description and states that there is at least a fracture component that lies proximal to the surgical neck; it is a general term comprising all potentially critical fractures of the proximal humerus.) Only fractures less than 10 days old and requiring open surgery were included. Sixteen fractures were excluded because of insufficient or missing radiographic documentation. The remaining 100 fractures in 98 patients (mean age, 60 years; minimum, 21 years; maximum, 88 years; 45 men; 57 right shoulders) were available for this study.

Evaluation and description of fracture

Evaluation included a description of the fracture morphology following a structured questionnaire (Table I). The fracture planes were assessed by use of a previously presented binary description system (Figure 1),[8] which was based on the original drawings of Codman.[2] The system describes five basic fracture planes that can be identified by answering the following questions:

1. Is there a fracture between the greater tuberosity and the head?
2. Is there a fracture between the greater tuberosity and the shaft?
3. Is there a fracture between the lesser tuberosity and the head?
4. Is there a fracture between the lesser tuberosity and the shaft?

Table I Structured questionnaire (binary fracture description)

Questions relating to basic fracture pattern
1. Is there a fracture between the greater tuberosity and the head? (Y/N)
2. Is there a fracture between the greater tuberosity and the shaft? (Y/N)
3. Is there a fracture between the lesser tuberosity and the head? (Y/N)
4. Is there a fracture between the lesser tuberosity and the shaft? (Y/N)
5. Are there a fracture between the lesser tuberosity and the greater tuberosity? (Y/N)
Accessory questions
6. How long is the posteromedial metaphyseal head extension? (mm)
7. How large is the displacement of the shaft with respect to the head? (*displacement measured between posteromedial edge of the head and posteromedial shaft fracture line*) (mm)
Medial or lateral displacement of the shaft?
8. How large is the displacement of the tuberosities with respect to the head? (*displacement measured at transition zone between the tuberosity and the cartilaginous fracture line*) (mm)
9. Amount of angular displacement of the head? (*under consideration of the 3-dimensional position*) (°)
Varus or valgus?
10. Is there a glenohumeral dislocation? (Y/N)
Anterior or posterior?
11. Is there a head impression fracture? (Y/N)
Anterior or posterior?
12. Is there a head-split component? (*>20% of head involvement*) (Y/N)
With two intraarticular fracture planes? (Y/N)
With one intraarticular fracture plane? (Y/N)

When questions could not be answered with certitude based on standard radiographs, additional imaging (magnetic resonance or computed tomography) was demanded.

5. Is there a fracture between the lesser tuberosity and the greater tuberosity?

This results in 12 basic fracture patterns. There are 6 possible fractures dividing the humerus into two fragments, 5 possible fractures dividing the humerus into three fragments, and a single fracture pattern dividing the humerus into four fragments (Figure 1). In addition, the following accessory criteria were determined (Figures 2, 3, and 4): length of the posteromedial metaphyseal head extension, displacement of the shaft with respect to the head (the maximal displacement was measured between the posteromedial edge of the head and the posteromedial shaft fracture line), whether the shaft is displaced medially or laterally, displacement of the tuberosities (maximum displacement of either the greater or the lesser tuberosity), amount of angular displacement of the head, varus or valgus, whether there is a glenohumeral dislocation (anterior or posterior), whether there is a head impression fracture (anterior or posterior), and whether there is a head-split component (>20% of head involvement) with one or two intraarticular fracture planes.

Assessment of the fracture was based on true anteroposterior and axillary views and on additional magnetic resonance and/or computed tomography scans as required. Additional imaging was required when one or more of the above criteria could not be determined.

Reliability of fracture description

Interobserver and intraobserver reliability had been previously assessed.[8] Reliability has been shown to depend above all on the training status of the observer. To avoid discrepancies resulting from a different training status, categorization by a single expert observer (R.H.) was chosen for this study. The distribution of the encountered basic fracture patterns is depicted in Figure 5.

Evaluation of perfusion

Humeral head perfusion was evaluated intraoperatively by observation of backflow after the head was drilled with a 2.5-mm drill bit in its central part. When there was uncertainty, up to 3 drill holes were applied. Only a clear backflow, while suction was applied to the base of the head to avoid falsification by capillarity, was considered proof of positive perfusion. Perfusion was also assessed by laser Doppler flowmetry in 46 of 100 shoulders. Fifty-four shoulders were not measured by laser Doppler flowmetry because the equipment was not available in the emergency operating room. A 3.5-mm laser Doppler probe was introduced into the cancellous bone through the previous drill hole. A pulsatile, electrocardiographic synchronous signal was considered as proof of positive perfusion. Laser Doppler had been previously validated at our institution.[13] A high-power laser Doppler source (20 mW, emitting a wavelength of 780 nm) was used in combination with a standard flowmeter (DRT4; Moor Instruments, Axminster, England). The signals were continuously recorded in real time and stored for later analysis on a 1.0 DRT4 Windows computer software program. The time constant was set at 0.1 second, and the display rate was set at 20 per second to enable the visualization of pulsatile signals.

In order to force a yes/no answer, uncertain borehole observations were corrected by use of the following path: (1) a pulsatile laser Doppler signal, when available, was considered proof of head perfusion, regardless of the borehole observation; (2) a nonpulsatile laser Doppler signal was considered proof of head ischemia, regardless of the

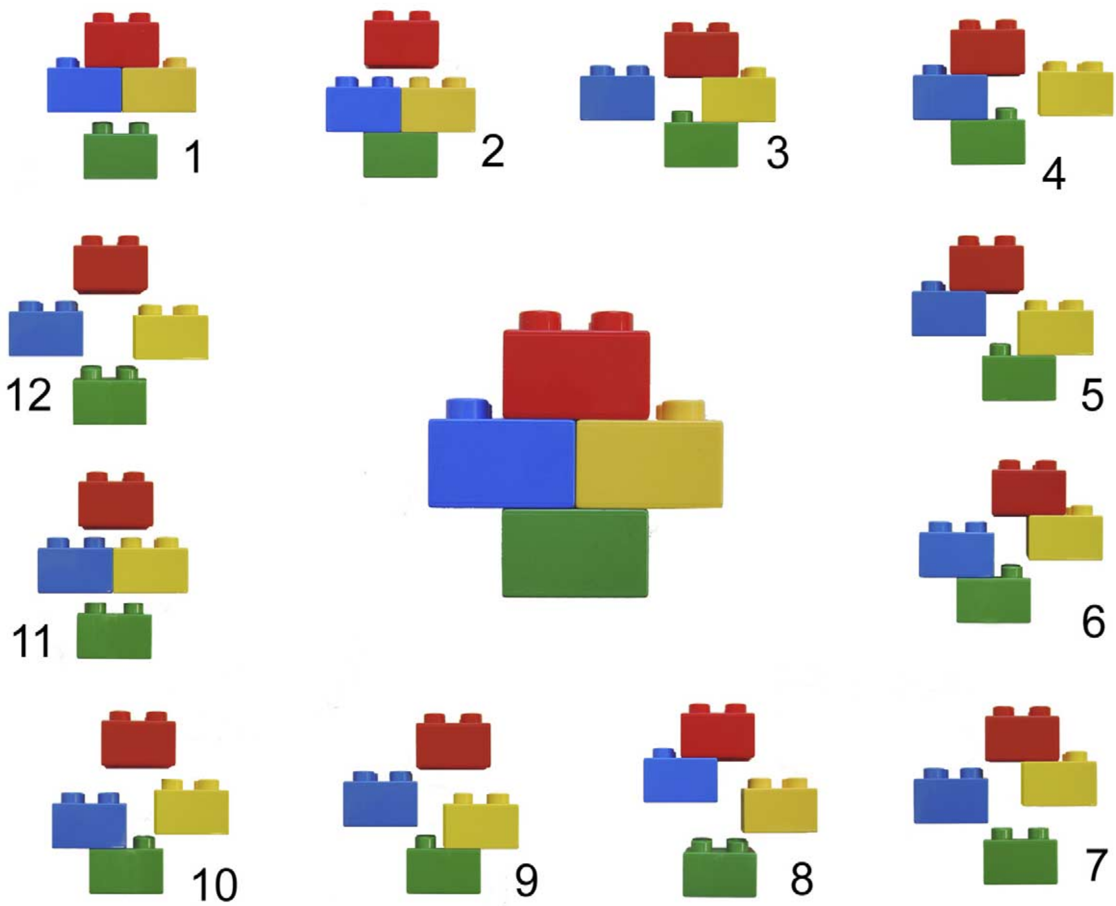

Figure 1 Binary (LEGO) description system. Combining the 5 basic fracture planes results in 12 basic fracture patterns. Basic fracture planes lie between the greater tuberosity and the head, the greater tuberosity and the shaft, the lesser tuberosity and the head, the lesser tuberosity and the shaft, and the lesser tuberosity and the greater tuberosity. There are 6 possible fractures dividing the humerus into two fragments, 5 possible fractures dividing the humerus into three fragments, and a single fracture dividing the humerus into four fragments.

Figure 2 First additional criterion: length of the medial metaphyseal head extension. The longer the extension, the more likely the head is perfused.

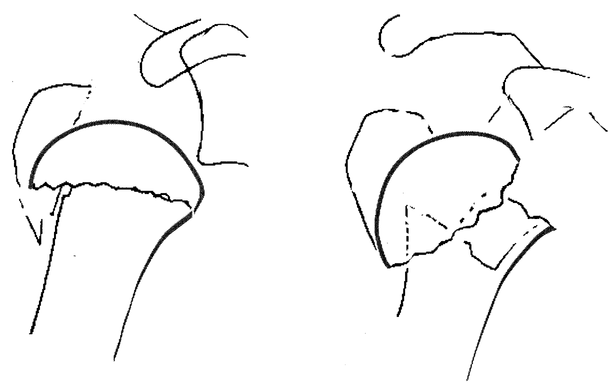

Figure 3 Second additional criterion: integrity of the medial hinge. Integrity of the hinge is a predictor of both ischemia and practical feasibility of reduction.

borehole observation; and (3) partial head perfusion (eg, positive signal in the distal portion of the head and negative signal in the proximal portion of the head) was considered equal to total head perfusion.

The mean time from injury to assessment of perfusion was 4 days (range, 0-10 days). Before surgery, informed consent was obtained from patients or their relatives.

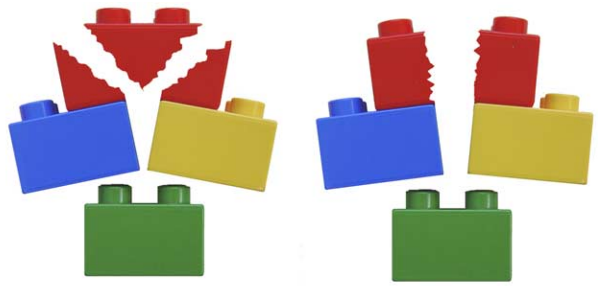

Figure 4 Third additional criterion: head-split components. There are classic head-split geometries (*left*) and special head-split geometries where both fragments remain perfused (*right*).

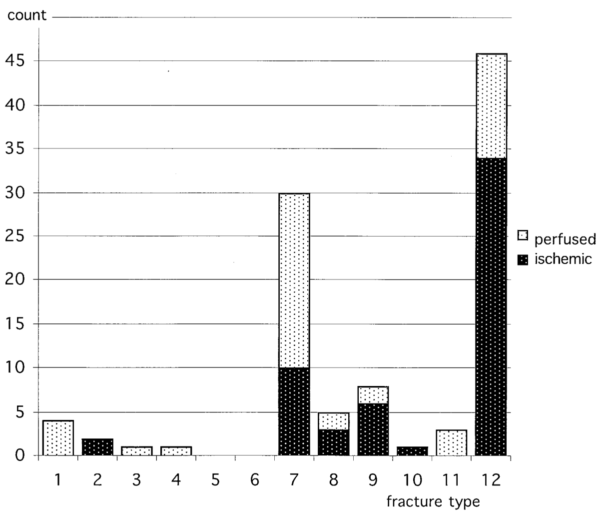

Figure 5 Distribution of the 12 basic fracture patterns in 100 shoulders and relative frequencies of head ischemia. It should be noted that this is a selected series of patients (referred for special treatment) containing a disproportionately large number of complex fractures.

Statistical evaluation

Nonparametric statistical evaluation (Mann-Whitney unpaired 2-group test) and contingency tables (χ^2 values) were used for calculation of *P* values. *P* values of less than .05 were considered significant.

The sensitivity (True positive [Tp]/Tp + False negative [Fn]), specificity (True negative [Tn]/Tn + False positive [Fp]), accuracy (Tp + Tn/Total), positive predictive value (Tp/Tp + Fp), and negative predictive value (Tn/Tn + Fn) were calculated for each criterion.

Definitions

An intracapsular fracture was defined as a fracture with at least one fracture plane communicating with the articular cavity. An intracapsular fracture may or may not run through the articular cartilage.

For a metaphyseal head extension (also called calcar segment), part of the metaphysis remains attached to the head (Figure 2). The metaphyseal extension was most often located posteromedially.

The binary fracture description system[8] was derived from the original drawings of Codman.[2] It was based on the analysis of fracture planes and not on the number of fragments. It comprised 12 different basic fracture patterns (Figure 1). Fractures were described with numbers from 1 to 12. There were 6 possible fracture combinations dividing the humerus into two parts, 5 possible fractures dividing the humerus into three parts, and a single fracture type dividing the humerus into four parts. With the use of a model composed of LEGO toy bricks (Lego Company, Billund, Denmark), the concept can be easily explained (Figure 1). Additional qualifiers related to the length of the medial metaphyseal head extension, the integrity of the medial hinge, head-split components, and glenohumeral dislocation. These features were postulated to affect the integrity of the posterior circumflex vascular system directly.

The medial hinge was defined as the pivot point of the head at the level of the posteromedial fracture line.

RESULTS

Borehole bleeding and a pulsatile laser Doppler signal correlated in 40 of 46 patients. In 4 patients there was a pulsatile Laser signal but the observed bleeding was minimal (defined as uncertain). In 1 patient there was a pulsatile signal but no bleeding was visible, and in another patient there was uncertain bleeding whereas the laser signal was not pulsatile. In 3 cases there was a pulsatile signal in the distal half of the head but no signal could be measured in the proximal half, indicating partial head ischemia. According to the outlined definitions, 55 heads were considered ischemic and 45 were considered perfused. Ischemia was observed in fractures with two, three, and four fragments but only in binary types 2, 7, 8, 9, 10, and 12. Ischemia occurred in the single type 2 fracture, in 10 of 30 type 7 fractures, in 3 of 5 type 8 fractures, in 6 of 9 type 9 fractures, in the single type 10 fracture, and in 34 of 46 type 12 fractures.

The mean length of the posteromedial metaphyseal extension (calcar) was 2 mm (SD, 0.36 mm; minimum, 0 mm; maximum, 8 mm) in ischemic heads and 13 mm (SD, 2 mm; minimum, 0 mm; maximum, 50 mm; 2 outliers without medial fracture line) in perfused heads. The difference was significant ($P < .0001$). The posteromedial metaphyseal extension was shorter than 8 mm in all ischemic heads and in 16 of 45 perfused heads (χ^2 $P < .0001$)(Figure 6).

The mean displacement of the shaft with respect to the head was 13 mm (SD, 15 mm; minimum, 0 mm; maximum, 70 mm) in ischemic heads and 4 mm (SD, 10 mm; minimum, 0 mm; maximum, 55 mm) in perfused heads ($P < .0001$). Medial displacement of the shaft with respect to the humeral head occurred in 25 of 55 ischemic heads and in 3 of 45 perfused heads (χ^2 $P < .0001$). Lateral displacement of the

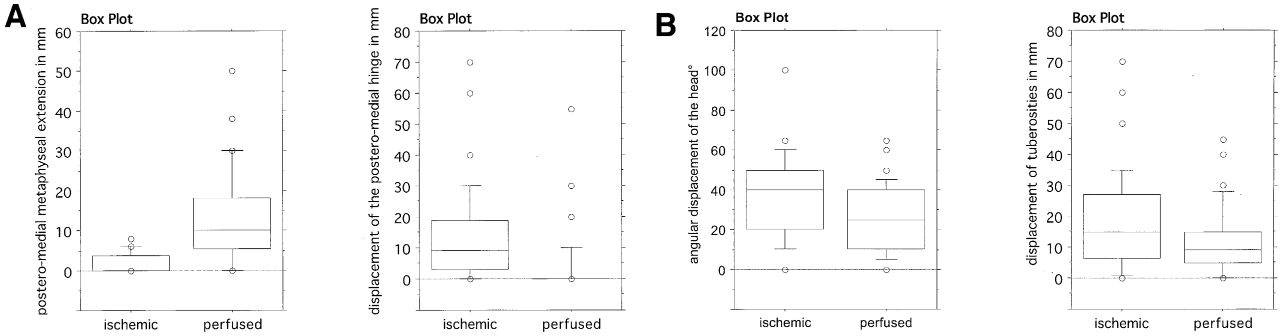

Figure 6 A, Length of the medial metaphyseal head extension and medial hinge displacement. **B**, Head angulation and displacement of the tuberosities. Box plots indicate the median value, twenty-fifth and seventy-fifth percentiles, and fifth and ninety-fifth percentiles. The *circles* indicate outliers. Compared with ischemic heads, perfused heads had a significantly longer metaphyseal extension. To determine the clinically relevant cutoff values, we should look for the intersection of the Gaussian curves and not arbitrarily determine a value.

shaft with respect to the humeral head occurred in 18 of 55 ischemic heads and in 6 of 45 perfused heads (χ^2 P = .02).

The medial hinge was considered disrupted if there was a displacement of the shaft in any direction greater than 2 mm, because the intersection of the two Gaussian curves occurred approximately between 2 and 3 mm. Disruption of the medial hinge occurred in 43 of 55 ischemic heads and in 9 of 45 perfused heads (χ^2 $P < .0001$). The integrity of the medial hinge was of vascular relevance only if the metaphyseal head extension was shorter than 8 mm.

The mean angular displacement of the head was 36° (SD, 21°; range, 0°-100°) in ischemic heads and 26° (SD, 18°; range, 0-65°) in perfused heads. The difference was not significant (P = .072). Angular displacement of the head in excess of 45° occurred in 23 of 55 ischemic heads and in 6 of 45 perfused heads (χ^2 P = .0018).

The mean displacement of the tuberosities was 19 mm (SD, 17 mm; range, 0-70 mm) in ischemic heads and 11 mm (SD, 10 mm; range, 0-45 mm) in perfused heads (P = .0188). Displacement of the tuberosities greater than 1 cm occurred in 38 of 55 ischemic heads and in 22 of 45 perfused heads (χ^2 P = .04).

Glenohumeral dislocation occurred in 12 of 55 ischemic heads and in 8 of 45 perfused heads. The difference was not significant (χ^2 P = .61).

Head-split components occurred in 11 of 55 ischemic heads and in 7 of 45 perfused heads (χ^2 P = .56). There was no significant difference between ischemic and perfused heads when comparing age (χ^2 P = .48), sex (χ^2 P = .11), or side (χ^2 P = .1).

Good predictors of ischemia were the length of the metaphyseal head extension (accuracy, 0.84 for calcar segments <8 mm), the integrity of the medial hinge (accuracy, 0.79 for disrupted hinge), and the basic fracture pattern (accuracy, 0.7 for combined types 2, 9, 10, 11, and 12).

Moderate and poor predictors of ischemia were fractures consisting of four fragments (accuracy, 0.67), angular displacement of the head (accuracy, 0.62 for angulations over 45°), the amount of displacement of the tuberosities (accuracy, 0.61 for displacement over 10 mm), glenohumeral dislocation (accuracy, 0.49), head-split components (accuracy, 0.49), and fractures consisting of three fragments (accuracy, 0.38).

When the above criteria (anatomic neck, short calcar, disrupted hinge) were combined, positive predictive values of up to 97% could be obtained (Table II).

DISCUSSION

To manage complex fractures of the proximal humerus adequately, it appears important to collect reliable information on the geometry of the fracture as well as on the viability of the various fragments.

Most contemporary fracture classifications are based on the original drawings of Codman,[2] in which a four-part concept is depicted. Sadly, his miniature drawings have found little attention. They depict the various theoretical patterns that can be obtained by combining five basic fracture planes.

Classification systems such as that of Neer[12] are biased with uncertainty because several fracture plane combinations were simply not considered and because diagnostic subgroups were not sharply discernible (overlapping of the various criteria). Codman's concept, on the contrary, defined clear-cut diagnostic subgroups.

We have slightly modified Codman's concept, because we believe that the tuberosities are to be seen as an intercalated segment between the head and the shaft rather than protuberances sitting on the metaphysis. This results in 12 rather than 14 possible basic fracture patterns. These patterns can be determined

Table II Results

Ischemia-predicting criterion	Sensitivity	Specificity	Accuracy	Positive predictive value	Negative predictive value
Basic fracture type					
7, 8, 9, 10, and 11 (3 fragments)	0.36	0.40	0.38	0.43	0.34
12 (4 fragments)	0.62	0.73	0.67	0.74	0.61
2, 9, 10, 11, and 12 (anatomic neck)	0.76	0.62	0.7	0.71	0.68
Accessory criteria					
Short calcar segment (<8 mm)	1	0.64	0.84	0.77	1
Disrupted medial hinge (>2 mm dislocation)	0.78	0.8	0.79	0.83	0.75
Displacement of head (>45° inclination)	0.42	0.87	0.62	0.79	0.55
Displacement of tuberosities (>10 mm)	0.69	0.51	0.61	0.63	0.58
Glenohumeral dislocation	0.22	0.82	0.49	0.6	0.46
Head-split component	0.2	0.84	0.49	0.61	0.46
Combined criteria					
Anatomic neck fracture and calcar <8 mm	0.76	0.82	0.79	0.84	0.74
Anatomic neck fracture and calcar <8 mm and disrupted hinge	0.58	0.98	0.76	0.97	0.66

with precision, thus minimizing errors resulting from subjective appraisal. The description is based on 5 questions concerning the basic fracture planes that can be answered with yes or no. The method was, therefore, called the binary description system. Additional descriptors, such as the length of the posteromedial metaphyseal extension, the integrity of the medial hinge, glenohumeral dislocation, and so on, are added to the basic fracture type as required. The binary description system, including additional descriptors, is comprehensive and easy to teach and learn. It has proved efficient because it provided clear-cut diagnostic subgroups. The residual difficulty, as with all classifications systems, remains in actually recognizing the fracture lines. This requires adequate radiographs (anteroposterior and axillary view) and an experienced eye. Additional imaging including computed tomography and/or magnetic resonance scans is necessary only when conventional radiographs do not provide clear answers.

Perfusion of the head fragment is an essential, though not the only, element for decision making. Despite an ischemic head, a head-preserving treatment is an option when revascularization can be expected and/or when a 2-staged management protocol is required for local or systemic reasons (first stage, osteosynthesis; second stage, hemiarthroplasty should avascular necrosis not be tolerated). At our institution, head-preserving surgery is mainly indicated when the bone quality is good enough to ensure a stable osteosynthesis, in order to warrant healing (especially of the tuberosities) in an anatomic position.

This study showed that specific fracture plane combinations were associated with impaired head perfusion and that additional elements, such as the length of the posteromedial metaphyseal head extension and the integrity of the medial hinge, were the key elements for occurrence of vascular disruption. Interestingly, the degree of displacement of the fragments was less important. This was in contrast to what had been suggested previously.[12] Although fracture types with an anatomic neck component (types 2, 9, 10, 11, and 12) were at great vascular risk, 17 of 59 heads with an anatomic neck component were still perfused. Perfused heads had a significantly ($P <$ .0001) longer medial metaphyseal extension than ischemic heads. None of the ischemic heads had a medial metaphyseal extension longer than 8 mm. Of the 17 perfused heads in fractures comprising the anatomic neck, 3 had no or minimal medial extension visible on standard radiographs. Magnetic resonance images taken preoperatively had shown a short (5-8 mm) posterior metaphyseal extension with a capsular reflection in continuity with the head. Fracture type 7, the classic three-fragment fracture, had an ischemic head only when the medial metaphyseal extension was below 8 mm and the lesser tuberosity that remained attached to the head was small (50% or less of its size). In this case only the tendinous insertion of the subscapularis remained attached to the head, and no major vascular channels remained for irrigation of the humeral head.

Disruption of the medial hinge was a critical factor for fractures with medial metaphyseal extensions below 8 mm. Displacement-induced stripping of the periosteum (and vessels)[14] might distinguish between perfusion and ischemia in this specific subgroup. Overall, 78% of the ischemic heads but only 20% of the perfused heads had a disrupted medial hinge. Medial displacement of the shaft with respect to the humeral head was significantly more critical than lateral displacement. Unrelated to the vascular status, the integrity of the medial hinge is also an important aid in fracture reduction and stabilization. It determines the potential difficulty of reduction and internal fixation.

Besides the disruption of the medial hinge, all other directions of fracture displacement, including glenohumeral dislocation, did not strongly correlate to the vascular status. These findings confirm the results of Trupka et al,[15] who were astonished that fracture-dislocation was not associated with an increased incidence of avascular necrosis of the humeral head.

Residual perfusion of the head seems to rely on the medial and posteromedial metaphyseal extension that might remain attached to the head. Although the vascular anatomy of this region has been well described,[6,7,10] too much emphasis was put on the dominance of the anterior circumflex vessels. It might well be that, in the nonfractured humerus, the arcuate artery is dominant for head perfusion.[1,7] In the fractured humerus this cannot be the case, as this vessel is generally interrupted even in the most simple fracture patterns. Anatomic findings[1,3,4] and clinical observations[5,9,14–16] seem to confirm that perfusion derived from the posterior circumflex vessels alone may be sufficient for head survival. It might well be that, in patients with constitutionally highly dominant anterior vessels, only a posteroinferior part of the head remains perfused initially (as observed in some of our laser Doppler cases). The ischemic cranial part might be revascularized when adequate contact with bleeding cancellous bone and a stable mechanical environment are provided. A process of revascularization and creeping substitution has been postulated even for the fully ischemic head.[11] The authors support such findings, having observed and confirmed by laser Doppler that several patients with initial total ischemia proceeded to partial and full revascularization of the humeral head.

The strength of the study is the uniformity of data acquisition. The limitation is the single observer's appreciation of the fracture pattern and of the perfusion. This may lack broad objectivity. It must be considered that it is practically impossible to measure intraobserver reliability for the assessment of humeral head perfusion. Because of the emergency setting in which these fractures are treated, it would not be feasible to call in prospectively and routinely an independent and experienced colleague to give his or her intraoperative opinion on the perfusion. It is also difficult to assess the sensitivity and specificity of the different methods of measurement of perfusion, as there is no proven standard against which these methods can be tested. Not even the long-term outcome after internal fixation can be used as an indirect indicator for initial perfusion, as we have observed full-substance revascularization in several cases of initially proven head ischemia (head on the side table outside the patient). We believe that the presented information is of both scientific and practical value. It focuses attention on specific and practically relevant elements that can be incorporated into the clinical assessment of these fractures.

In conclusion, the most relevant predictors of ischemia were the length of the dorsomedial metaphyseal extension, the integrity of the medial hinge, and the basic fracture type determined with the binary description system.

We would like to thank the LEGO Company, Denmark, for allowing us to use their bricks for didactic purposes.

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