Injury, Int. J. Care Injured 49 (2018) 2252–2263

Contents lists available at ScienceDirect

Injury

journal homepage: www.elsevier.com/locate/injury

Revisiting the Schatzker classification of tibial plateau fractures

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ARTICLE INFO

Keywords:
Tibial plateau fracture
Classification
Tomography
Decision making

ABSTRACT

Tibial plateau fractures have a broad spectrum of presentations, depending on the mechanism and energy of the trauma. Many classification systems are currently available to describe these injuries. In 1974, Schatzker proposed a classification based on a two-dimensional representation of the fracture. His classification with the six-principles types became one of the most utilized classification systems for tibial plateau fractures. More than four decades after this original publication, we are revisiting each fracture type in the light of information made available by computed tomography, which today comprises a standard tool in assessing articular fractures. The classification we are proposing relies on the fact that the tibial plateau has two anatomical columns, lateral and medial. We are introducing a virtual equator which splits the articular surface in the coronal plane. The equator divides each column into two quadrants, the anterior (A) and the posterior (P). Unicondylar fracture types (I to IV) have now additional modifiers A (anterior) and P (posterior) to describe the exact spatial location of the primary fracture plane. Bicondylar fracture types (V and VI) have the modifiers (A and P) of the main fracture plane for each column, and lateral (L) and medial (M) to denote the column. We are introducing the concept of the main fracture plane. Recognition of the exact location of the principal fracture plane is essential for preoperative planning of patient positioning, surgical approach and for determining where to apply the hardware to achieve stable fixation. The new three-dimensional classification is based on the template of the original Schatzker classification. It covers the mechanism of the injury, the energy of the trauma, the morphologic characteristics of the fracture and its location in three dimensions.

Introduction

Tibial plateau fractures are articular injuries which have a broad spectrum of clinical presentations and are frequently associated with long term complications [1,2]. In recent years these challenging fractures have become a topic of great interest not only regarding their classification but also fixation methods and expected outcomes [3–10].

The complete understanding of the personality of these fractures is the key element in the decision-making process when choosing the best possible treatment [11]. At least 38 classification systems have been used to describe tibial plateau fractures [12]. In 1974, Schatzker published his classification of fractures of the tibial plateau and described six principle types [13] (Fig. 1).

The Schatzker classification was based on a two-dimensional representation of the fracture. The fracture types in his classification were organized according to their essence; namely, age of the patient, the bone quality, the morphologic architecture of the fracture, and the energy of the trauma. The types I to III are fractures of the lateral tibial plateau. *Type I* is a cleavage fracture type of the lateral column. It is more common in younger people, who have a denser cancellous bone which resists impaction. Frequently, this fracture is oriented in the sagittal plane and may be addressed by anatomical reduction and absolute stability of the joint surface with lag screws. In cases where a long split is identified an anterolateral buttress plate should be used in addition. *Type II* is a split wedge fracture of the lateral column associated with depression. It has the same mechanism of injury as Type I, axial and valgus shearing and loading forces but in older patients, who have a less dense metaphyseal bone, the articular surface fails and impaction and depression of the articular surface results. Type II fractures are managed by open reduction and internal fixation. The aim is to restore the articular surface and the

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https://doi.org/10.1016/j.injury.2018.11.010
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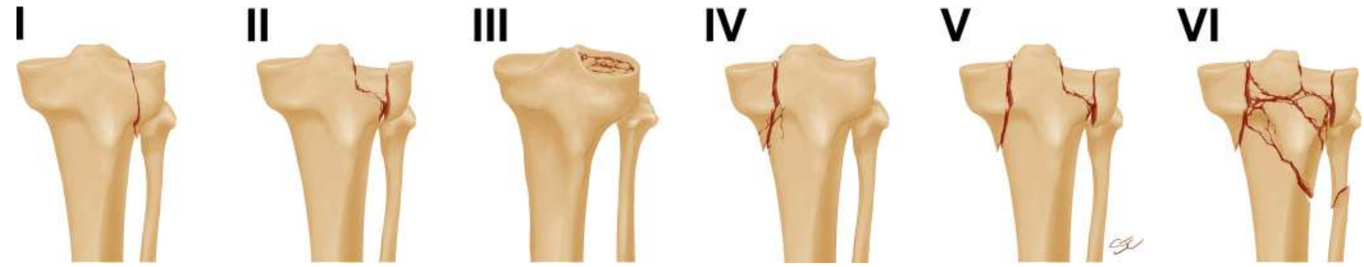

Fig. 1. The six principle tibial plateau fracture types as described by Schatzker. Type I, split wedge of the lateral tibial plateau; Type II, split wedge depression of the lateral tibial plateau; Type III, pure depression of the lateral tibial plateau; Type IV: split wedge of the medial tibial plateau; Type V: bicondylar tibial plateau fracture, where there is continuity between the epiphysis and the diaphysis; Type VI: bicondylar fracture with complete dissociation between the epiphysis and the diaphysis.

mechanical axis of the lower extremity. In the *Type III* the metaphyseal containing cortex remains intact. It is a pure joint depression and most of the time the joint is stable. If, however, the joint depression consists also of impaction and depression of the plateau rim the joint becomes unstable. Regarding surgical treatment, in case the depression is completely contained by the cortex, the joint is normally not opened, the distal metaphyseal cortex is windowed, and a bone tamp is inserted and directed upwards to tap the depressed fragments back in the place. If the rim is involved it must be reduced and mechanically supported. Types IV to VI are high energy injuries associated with knee joint instability ranging from a subluxation to dislocation. *Type IV* is the isolated fracture of the medial column of the tibial plateau. The mechanism of injury is a varus shearing force. As the medial tibial plateau is denser than the lateral one, a higher force is required to fracture it thus the energy of trauma for a type IV is normally high. A type IV is most often a fracture dislocation of the knee, with potential for neurovascular complications. Bicondylar tibial plateau fractures, *types V and VI*, are also high energy injuries. The essence of a *Type V* fracture is the preservation of continuity of the shaft with some part of the overlying metaphysis and joint. The preserved portion is usually its middle. This differentiates the Type V bicondylar fracture from the *Type VI* which is also bicondylar, but in type VI the continuity of the metaphysis is disrupted, and the articular surface loses contact with the diaphysis. The types IV, V and VI because of the high energy required to produce them are usually associated with significant compromise of the soft tissues envelope.

For Schatzker, the indication for surgery was joint instability and not the degree of depression, which was a criterion for surgery in other publications. Schatzker recommended that if a surgeon was in doubt whether the joint was stable or not, an examination under anesthesia was indicated. In 1979, Schatzker et al. published their experience with the management of 94 tibial plateau fractures [14]. Since then, the six basic types have been validated and accepted universally as fulfilling the criteria of a useful and practical classification [15,16].

The AO classification system for long bone fractures was introduced later and was based on an alphanumeric representation. The tibial plateau fractures were described as partial articular, when compromising one of the tibial condyles, and complete articular, when compromising both tibial condyles [17]. The Orthopedic Trauma Association and the AO Foundation published a unified classification system for long bone fractures with the goal of establishing an internationally standardized method of communication for those involved with documentation and research on fractures and dislocations [18]. Tibial plateau fractures were described as the types 41B, to describe unicondylar fractures, and 41C, to describe bicondylar fractures.

The first available classification systems for tibial plateau fractures placed a great of emphasis on the antero-posterior radiograph and relied on the sagittally oriented fracture patterns [13,17–19]. Until the 1970's, plain X-rays and biplane tomography were the only available imaging modalities to study the architecture of a fracture. Computed assisted tomography (CAT) was a later development. Before the advent of the CAT scan many of the fractures in the coronal plane, often the result of high velocity trauma, were not recognized. Therefore, the knowledge of the prevalence of some tibial plateau fractures oriented in the coronal plane was very low.

The aim of this article is to revisit the Schatzker classification, four decades after its description and to examine each fracture type in the light of information made available by CAT scan, which today comprises a standard and essential tool in assessing articular fractures. Further we aim also to incorporate the new information made available by CAT and present the six fracture types of Schatzker with a new notation which allows a three-dimensional representation of the architecture of the fractures. We are proposing to extend the Schatzker classification to encompass the third dimension.

The purpose of a classification system

The purpose of a classification system Audigé et al. listed the criteria that should apply to a classification system; namely, it should lead to an improvement in the understanding, communication, documentation, and decision making about a set of fracture categories [20]. According to Audigé et al., the validation of a classification system involves the objective measurement of quality parameters, such as clinically relevant diagnostic elements, accuracy, and reliability. Accuracy measures how well the described types translate to real cases frequently seen in practice. Reliability measures how repeated utilizations of the classification for a given fracture type is consistent, leading to agreement either by the same observer (intra-observer reliability), or by different ones (inter-observer reliability). A measure has a high reliability if it produces similar results under consistent conditions. Although many classification systems have been published, Schatzker and AO/OTA are the most studied regarding their reliability. In most studies of reliability using only plain radiographs, the reliability of Schatzker and AO/OTA classification systems was rated as fair or moderate [16,21].

The role of tridimensional image studies

The advent of CAT, a tridimensional imaging modality, has set a new standard for the understanding of articular fractures. Brunner et al. demonstrated that computed tomography improves the intra- and inter-observer reliability of Schatzker and AO/OTA classification systems [22]. Two-dimensional computed tomography allows for a better characterization of the main fracture planes as compared to plain radiographs. The superiority of three-dimensional computed tomography reconstructions over two-dimensional computer tomography, however, has not been confirmed [23]. The use of magnetic resonance image (MRI) in the management of tibial plateau has been reported as beneficial for the understanding of associated soft tissues injuries. In fact, all image modalities when used together provide a complete assessment to the extent of the damage [24–27]. The most significant impact and contribution of three-dimensional imaging in the assessment of tibial plateau injuries was the recognition and characterization of fractures in the coronal plane. In 1998, Carlson highlighted the challenge of managing coronal plane oriented fractures and recommended dedicated surgical approaches to access the posterior aspect of the knee joint [28]. In the early 2000's a number of articles raised the importance of a three-dimensional understanding of the tibial plateau fractures, with emphasis on the accuracy of the diagnosis, decision making when determining surgical approaches and fixation methods [29–32]. The incidence of the posteromedial fragment in bicondylar fractures and the importance of proper imaging for an accurate diagnosis and decision making became a relevant topic [30,31].

Luo et al. utilizing computed tomography divided the surface of the tibial plateau into three columns, while emphasizing the relevance of coronal plane oriented fractures [32]. Chang et al. proposed to divide the surface of the tibial plateau into four quadrants aiming to bring further clarity when addressing complex high energy bicondylar fractures [33]. Tridimensional imaging modalities allowed not only for the detection of fracture lines which were frequently not evident in plain radiographs but lead also to the development of new classification systems. Molennars et al. proposed a computed mapping of tibial plateau fractures, identifying the most recurrent fracture patterns [34]. Krause et al. proposed that the tibial plateau should be split into 10 segments, based on computed tomography analysis. These authors presented a three-dimensional, segment-based mapping of the tibial plateau in order to determine specifically the areas of the articular surface compromised by the fracture [35].

The anatomy of the proximal tibia

The proximal epiphysis of the tibia has two axial columns, a medial and a lateral column. Each column supports a corresponding condyle with its horizontally oriented articular surface. The two anatomical columns are completely different in terms of their architecture. The medial one is denser in terms of bone trabeculae and is stronger when subjected to forces. Thus, fractures compromising the medial column of the tibial plateau are in general associated with higher energy.

The proximal tibia articulates with the fibular head. This articulation is located posteriorly to the medial - lateral axis of the tibia. The fibular head is pyramidal in shape and has three anatomical areas, the articular surface for the tibia, the fibular styloid and the lateral tubercle. The lateral tubercle of the fibular head is the site of the attachment of the fibular collateral ligament [36,37]. On the medial side of the knee, the superficial medial collateral ligament has one femoral attachment and two tibial attachments. The femoral attachment is slightly proximal and posterior to the center of the medial femoral epicondyle. The proximal tibial attachment of the superficial medial collateral ligament is at the insertion of the anterior arm of the semimembranosus tendon. Its distal broad attachment is slightly anterior to the posterior tibial crest on the medial aspect of the tibia and is deep to the tendons of the pes anserine and separated from them by a bursa [38]. The deep medial collateral ligament is a thickening of the medial joint capsule and consists of two components, the meniscofemoral and the meniscotibial. The attachments of the collateral ligaments of the knee determine the limits for surgical approaches to the tibial plateau. On the lateral side, an anterolateral approach does not expose properly the posterolateral corner of the tibial plateau without risking the fibular collateral ligament and the insertion of the popliteus tendon. On the medial side, the superficial medial collateral ligament should not be peeled off anteriorly to gain access to the posteromedial corner of the tibia.

The virtual equator of the tibial plateau

In the last two decades, we have seen an increase in the recognition of fractures in the coronal plane of the tibial plateau. Yang et al. in a series of 525 tibial plateau fractures, reported the compromise of the posterior rim of the tibia in 28.8% of the cases [39]. These authors used the Schatzker classification to describe the energy of the trauma and noted the higher prevalence of coronal plane fractures in Schatzker Type VI than Type IV. In the light of the emerging new information regarding the fractures in the coronal plane we decided to revisit the Schatzker classification in order to add the third dimension and see what impact the new information would have on the existing six principle types. Our intent is to keep it simple, universal, but also applicable to the reality of a higher incidence of coronal plane fractures. As the lateral and medial columns of the tibial plateau are clearly defined, we determined anatomical landmarks which could establish a virtual anatomic equator dividing the surface of the tibial plateau into two halves, anterior and posterior. On the lateral side of the knee, the anatomical reference is the lateral tubercle of the fibula, which corresponds to the insertion of the fibular collateral ligament. On the medial side of the joint, the virtual equator intersects the tibial plateau posterior to the attachment of the superficial medial collateral ligament, which also coincides distally with the posterior tibial crest (Fig. 2).

These landmarks may be determined with computed tomography or MRI and are therefore reproducible (Fig. 3).

The virtual equator does not split the tibial plateau into two symmetrical halves, since the posterior one is significantly smaller. Since the tibial plateau has two anatomical columns, the virtual equator splits the proximal tibia into four articular quadrants (Fig. 4).

Each of the four quadrants has peculiar anatomical characteristics and may be accessed through dedicated surgical approaches, while preserving the integrity of the collateral ligaments of the knee and the neurovascular structures around the joint. Crist et al. published our concept of virtual equator in their book chapter dedicated to the management of tibial plateau fractures [40]. Kellam et al. in their review of the AO/OTA Fracture and Dislocation Classification Compendium-2018, also acknowledged the concept described in this manuscript [41].

The three-dimensional classification of tibial plateau fractures

The advent of computed tomography allows for three-dimensional imaging of the proximal tibia together with the characterization of anatomical landmarks which delineate the four anatomical quadrants. This has made it possible to determine the architecture of the fracture and its spatial topography within the tibial plateau. We revisited the Schatzker classification applying the results of three-dimensional imaging.

The six principle fracture types of Schatzker remain the same. We are adding a new set of modifiers "A" (anterior) and "P" (posterior) to denote the quadrants involved in the six principle types. These modifiers are denoted in upper cases. In order to arrive at a three-dimensional localization of the fracture the surgeon must identify the main plane of the fracture and the place where the plane bisects the articular rim of the tibial plateau. Split wedge fractures of the tibial plateau will disrupt the articular rim at two points and will exit the metaphysis distally to the joint, at the apex of the wedge. The points where the wedge bisects the rim

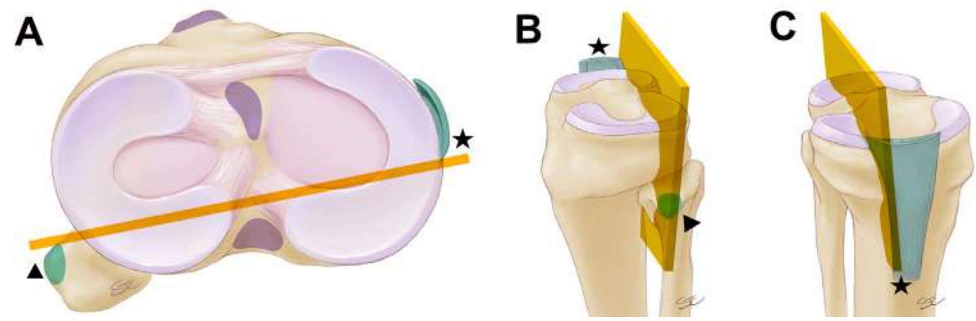

Fig. 2. The virtual equator of the tibial plateau. **a:** Representation of the axial view of the tibial plateau. The fibular collateral ligament (▲) and the superficial medial collateral ligament (★) attachments are represented in green. The virtual equator is represented in yellow and is determined by the lateral tubercle of the fibula, which is the site of insertion of the fibular collateral ligament, and the posterior crest of the tibia, which is the posterior limit of the superficial medial collateral ligament. The equator divides the surface of the tibial plateau into two halves, anterior (A) and posterior (P); **b:** Representation of the lateral view of the upper tibia. The equator is depicted in yellow and is represented in three dimensions, anteriorly to the insertion of the fibular collateral ligament (▲) and posterior to the superficial medial collateral ligament (★) c: Representation of the medial view of the upper tibia. The equator represented in yellow is located posteriorly to the superficial medial collateral ligament (★), at the projection of the posterior tibial crest. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

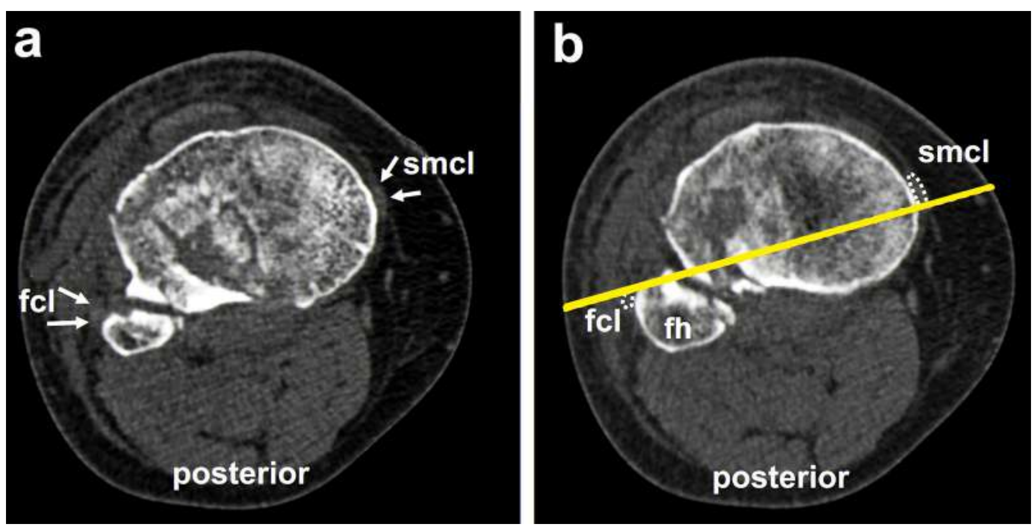

Fig. 3. Computed tomography of a tibial plateau – axial view. **A and B** are axial images of the tibial plateau obtained by computed tomography. The arrows indicate the attachments of the fibular collateral ligament (fcl) and of the superficial medial collateral ligament (smcl); The virtual equator is represented in yellow.

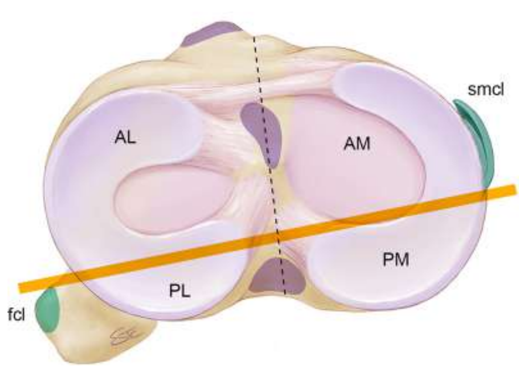

Fig. 4. The anatomical quadrants of the tibial plateau. The virtual equator, represented in yellow, divides the tibial plateau into two halves, anterior and posterior. Since the tibial plateau has two articular surfaces, lateral and medial, the equator delineates four anatomical quadrants. AL: anterolateral; AM: anteromedial; PL: posterolateral; PM: posteromedial. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

are identified by lowercase letters which denote the location or the points in relationship to the virtual equator, namely anterior ("a") or posterior ("p"). The third point where the fracture exits at the metaphyseal area is denoted as "x". This metaphyseal exit point could be anterior (a_x) or posterior (p_x). These three points, being two on the rim and one on the metaphysis, determine the main fracture plane. In case of unicondylar fracture types, the new denotation of the fracture will include the Roman numerals, which describes the lateral column (I to III) or the medial column (IV), and the upper-case letter A (anterior) or P (posterior) (Fig. 5).

Sagittally oriented fractures will typically bisect the rim in two points one being anterior and the other one posterior. Therefore, the rim compromise will have in its description the letters "a" and "p". Coronally oriented fractures, fractures in the frontal plane, will have an orientation mostly parallel to the virtual equator. They may bisect the tibial plateau rim twice anteriorly ("a" and "a") or twice posteriorly ("p" and "p"). For example, the typical posteromedial fragment of a bicondylar tibial plateau fractures normally intersects the rim twice posteriorly. The rim compromise is described as "p" and "p" and the metaphyseal exit point is located posteriorly (p_x) (Fig. 6).

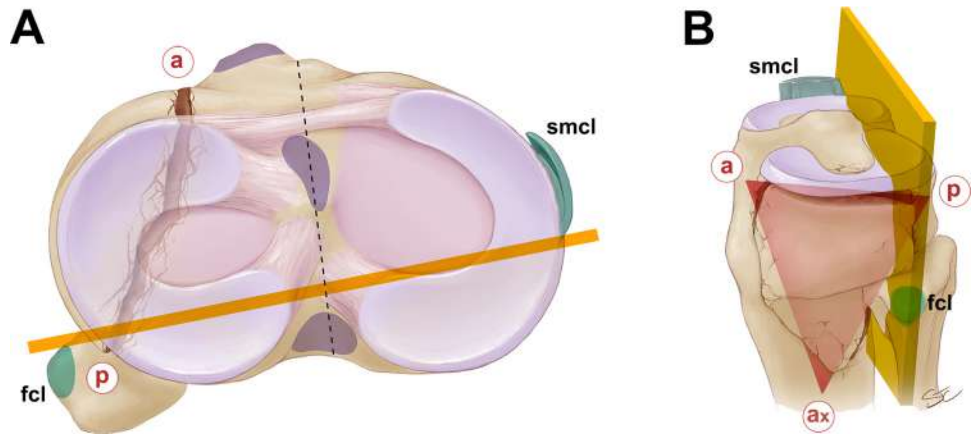

Fig. 5. Anatomical topography of a split wedge fracture. **A:** Axial view of the tibial plateau. The fracture line intersects the rim at two points, one being anterior to the virtual equator "a", and the other one posterior to the equator "p". Fibular collateral ligament (fcl); Superficial medial collateral ligament (smcl); **B:** Lateral view of the proximal tibia. The main fracture plane is determined by three points. The two points where the split wedge bisect the rim and the exit point "x" at the metaphyseal area. In this image, the main fracture plane is represented in red. This case illustrates a simple split wedge of the lateral tibial plateau, which corresponds to a Type I of Schatzker. Since the points at which the fracture plane bisects the rim are located in the anterolateral quadrant of the tibial plateau, according to the new three-dimensional classification we determine this to be a **Type I A**. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

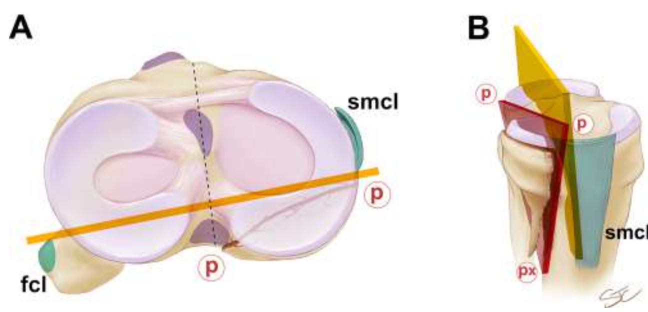

Fig. 6. Characteristics of a frontal plane-oriented fracture. **A:** Axial view of the tibial plateau. The fracture line bisects the rim twice posteriorly, namely "p" and "p"; **B:** Medial view of the proximal tibia. The main fracture plane is denoted by the two points of intersection of the tibial plateau rim ("p" and "p"), and by the exit point at the metaphyseal area ("p_x"). It is represented in red. The superficial medial collateral ligament is depicted on the anteromedial aspect of the tibia. (smcl). This is a Type IV of Schatzker. According to the new three-dimensional classification, the main fracture plane is located at the posteromedial quadrant of the tibial plateau. Therefore, it is named a **Type IV P.** (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

In the decision making the special orientation of the main fracture plane determines where to place the hardware and therefore the surgical approach. Split wedge fractures are inherently unstable under axial load. As a principle, the fracture should be anatomically reduced, and the wedge should be buttressed and thus contained. A buttress plate may be used for this purpose and ideally, it should be placed parallel to the main fracture plane (Fig. 7).

Although the virtual equator is helpful in determining the anterior and posterior halves of the tibial plateau, fracture lines do not necessarily respect anatomical landmarks. It is not rare that in a unicondylar fracture more than one quadrant of the tibial plateau is compromised. In these cases, we have more than one split wedge component and we must ideally determine where each fracture plane is located (Fig. 8).

In case of bicondylar fractures types, one has to pay attention to each column of the tibial plateau, medial and lateral, and determine which quadrants are compromised in each column. The new denotation of the fracture includes the Roman numerals (V or VI), and the spatial location of the main fracture plane noted with an upper-case letter (A and/or P) in each of the two anatomical columns, lateral (L) and medial (M) (Fig. 9).

A split wedge may be separate as an entity or it may also be associated with comminution and depression of the articular surface. The goals in the management of tibial plateau fractures are the restoration of joint stability and this involves the anatomical reduction of the articular surface, the reconstruction of rim stability and the restoration of the mechanical axis of the lower limb [42]. The new nomenclature allows the identification of the most important issue: the discontinuity of the rim integrity and the consequent loss of joint instability. Each fracture type is associated typically with its characteristic joint instability, the result of discontinuity of the tibial plateau rim.

Most of the times, the surgical approach used to reduce the split component of the fracture allows for direct or indirect reduction of the depressed fragments of the articular surface. In a typical ***Type II A***, a split wedge depression of the lateral plateau there is a compromise of the anterolateral quadrant of the tibial plateau. An anterolateral approach allows for the "open book" like lateral retraction of the wedge and direct visualization and reduction of the depressed fragments of the articular surface (Fig. 10).

The Type III of Schatzker is described as a pure depression of the lateral tibial plateau. There is no wedge component which would allow an "open book" type exposure of the depressed fragments.

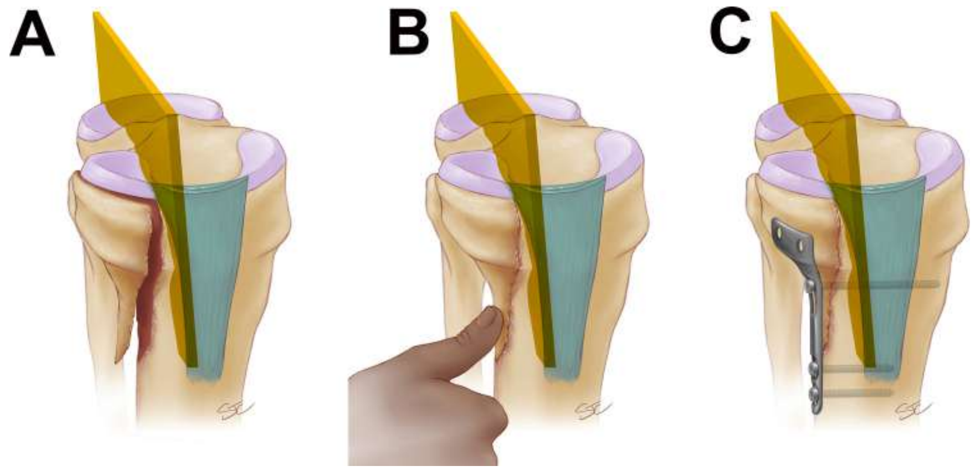

Fig. 7. Clinical application of the three-dimensional anatomical classification of tibial plateau fractures. **A:** Medial view of the proximal tibia. A coronal plane-oriented fracture with compromise the posteromedial quadrant of the tibial plateau is depicted. **B:** The ideal location for a buttress plate coincides with the area where the surgeon would like to apply his thumb to keep the wedge in its place. In this case, the thumb has to be applied on the posteromedial aspect of the tibia, as this is a **Type IV P** fracture; **C:** The best location for a buttress plate is parallel to the main fracture plane. If the surgeon knows where the ideal location for the hardware should be, the decision for the surgical approach becomes logical.

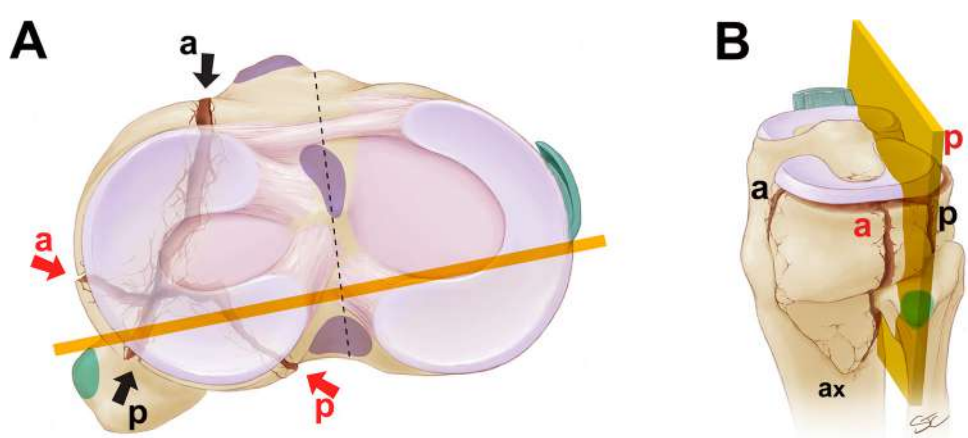

Fig. 8. Illustration of a comminuted lateral tibial plateau fracture. **A** and **B** are a representation of a comminuted lateral tibial plateau fracture: Axial and lateral views of the tibial plateau reveal two main fracture planes. One wedge is described as $\boldsymbol{a/p/a_x}$ (depicted in black) This tells us that the rim in bisected in the sagittal plane once anteriorly and once posteriorly and distally the exit point in the metaphyseal area is anterior to the equator. The quadrant mostly compromised by this wedge is the anterolateral. The second wedge also bisects the rim on two points, but the orientation of its fracture plane is more parallel to the virtual equator and the exit point at the metaphyseal area is posterior to the equator. Its description is $\mathbf{a/p/p_x}$ (depicted in red). The quadrant which is mostly compromised by this second wedge is the posterolateral. Although this is a Type II of Schatzker, the three-dimensional anatomical classification allows for a better understanding about the areas of instability by denoting the places where the articular rim is disrupted. According to the three-dimensional anatomical classification this would be a **Type II A + P** (one wedge anterior and one posterior). The identification of the posterior wedge (a/p/px) is of great importance. To deal only with the anterior wedge would leave the joint unstable posteriorly. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The anatomical classification may be applied considering the location of the depressed area. Most commonly one will identify a ***Type IIIA*** or a ***Type IIIP***, depending on whether the major area of the depression is located anteriorly or posteriorly to the virtual equator. If the rim is intact, a metaphyseal window suffices to permit the reduction of the depressed joint fragments with a punch type of an instrument. Some authors have reported the use of arthroscopy in these cases to control the reduction of the articular surface [43,44]. Pure depression type fractures are normally reduced by means of a bone tamp or punch, which is introduced through a metaphyseal window under guidance of fluoroscopy (Fig. 11).

A situation which requires particular attention is the pure depression fracture which compromises the articular rim. A typical situation happens when axial load is applied with the knee in varus alignment and hyperextension. In this scenario, an association between posterolateral corner ligament injury and anteromedial tibial plateau rim depression may take place. Axial loading applied to the knee positioned in valgus alignment and flexion may result in posterolateral crush of the rim. In cases where the rim has been compromised, besides reducing the depression, the shattered cortex below the rim should be reduced and supported by a horizontally oriented rim plate [45,46]. The horizontal plate is an example of the “hoop plate” principle which provides containment for the reduced crushed cortex. To elevate the crush without supporting the reduced cortex is to invite failure due to loss of reduction since there would be nothing to hold the bone graft supporting the rim in place.

The posterolateral quadrant of the tibial plateau is unique due to its associated anatomical characteristics. Fractures or surgical

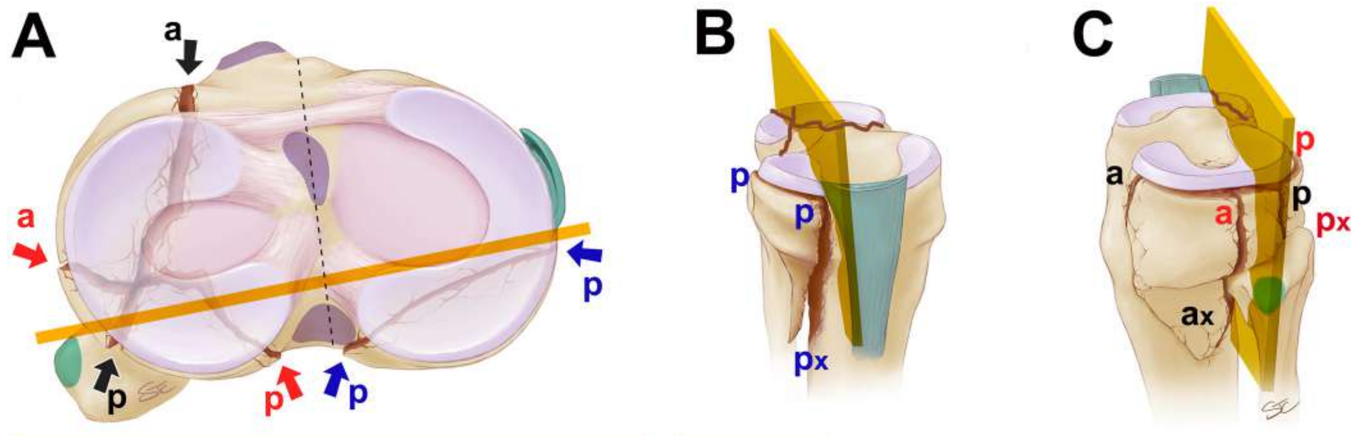

Fig. 9. The application of the three-dimensional anatomical classification in bicondylar tibial plateau fractures. **A:** Axial view of the tibial plateau depicts three main fracture lines. There are two split wedges compromising the lateral tibial plateau and one disrupting the medial tibial plateau. **B:** Medial view of the proximal tibia. The split wedge on the medial side is a type **p/p/p$_x$**. (depicted in blue). Therefore, on the medial side the instability is located on the posteromedial quadrant; **C:** Lateral view of the proximal tibia. One split wedge is described as **a/p/a$_x$** (depicted in black) – which means main compromise of the anterolateral quadrant – and the other one is described as **a/p/p$_x$** (depicted in red) – which translates the instability of the posterolateral quadrant. This is a bicondylar tibial plateau fracture where there is continuity between the epiphyseal area and the diaphyseal area throughout the anterior tibial tubercle. It is a type V of Schatzker. According to the anatomical classification this is a **Type V AL + PL + PM**. The way to apply the anatomical classification to bicondylar tibial plateau fractures consists in the description of the quadrants where the rim has been disrupted, and where the instability is a concern. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

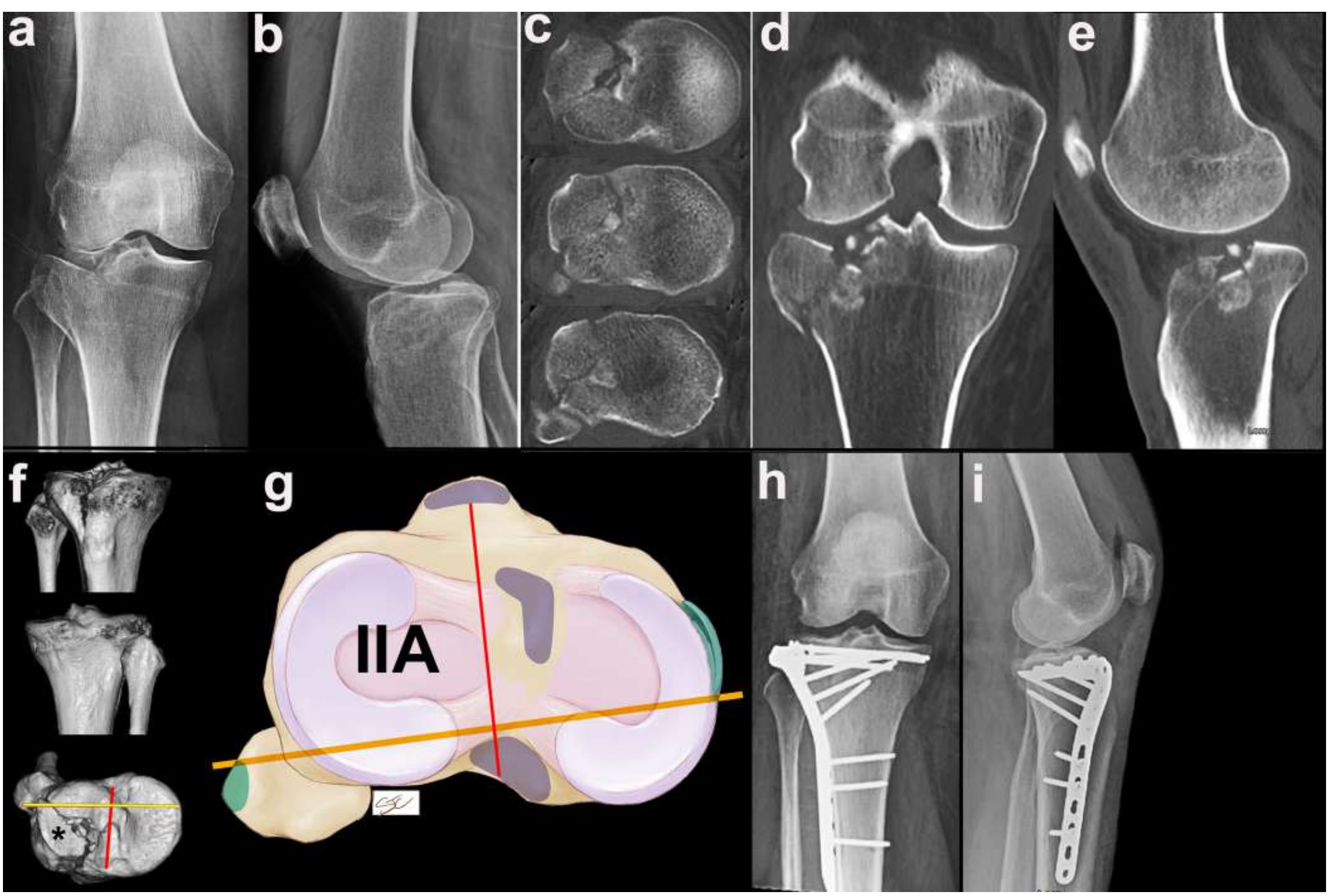

Fig. 10. Illustrative case of a **Type II A** tibial plateau fracture. **a,b**: Plain radiographs in the anteroposterior and lateral projections reveal a split wedge depression fracture type of the lateral tibial plateau; **c-e**: Computed tomography images reformed in the axial, frontal and sagittal planes. The CAT scan allows for precise location of the split and depression components of the fracture.; **f:** Tridimensional reconstruction of the CAT scan allows for a clear understanding of the surface topography of the fracture components; **g:** schematic representation of the axial view of the tibial plateau depicting the anatomical classification of this particular fracture type; **h,i:** Post-operative radiographs in the anteroposterior and lateral projections confirm the restoration of the articular surface, and of the mechanical axis by open reduction and internal fixation. An anterolateral approach and an anterolateral buttress plate were used to manage this **Type II A** fracture.

Fig. 11. Illustrative case of a **Type III P** tibial plateau fracture. **A,B**: Plain radiographs on the anteroposterior and lateral projections reveal a pure depression fracture type in the lateral tibial plateau; **C–E:** Sequence of Magnetic Resonance Imaging depicting a pure depression, in the posterolateral quadrant of the tibial plateau with a significant articular depression. The key is the intact posterior rim better seen in a CT than MRI; F: schematic representation of the axial view of the tibial plateau illustrating a type IIIP without compromise of the articular rim; **G,H:** Intra-operative fluoroscopic views of the anteroposterior and lateral views in which the bone tamp was positioned under the osteochondral fragments, in the metaphyseal area. It was introduced through an anteromedial window towards posterolateral; **I:** Reduction was obtained under fluoroscopic control; **J,K:** Post-operative images reveal a congruent anatomically reduced joint surface. The metaphyseal bone void was filled up with bone graft; the screws illustrate the rafting principle in support of an articular reduction. L: Functional outcomes after 12 weeks. Patient is asymptomatic and has full range of motion comparable with the contra-lateral knee.

approaches in this area may compromise neurovascular structures. We must consider the peroneal nerve and the trifurcation of the popliteal tibial artery. A number of surgical approaches have been described to address fractures located in this quadrant of the tibial plateau [28,32,47–50]. If one uses an extended posteromedial approach to reach the posterolateral wedge one is able to buttress the split wedge but at the expense of a very limited visualization of the articular surface of that quadrant. The trifurcation of the popliteal artery is located approximately 6 cm below the joint line. This means that a direct lateral approach to the posterolateral

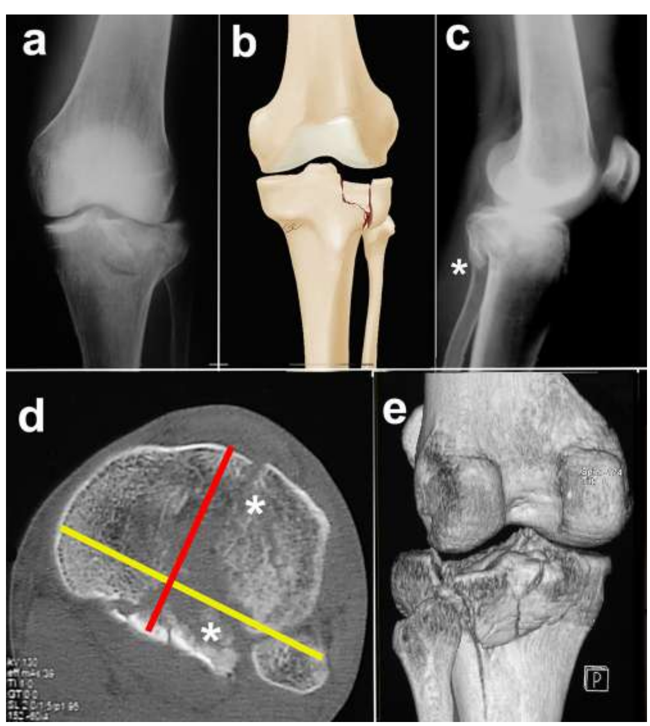

Fig. 12. Illustrative case of a **Type II A + P** tibial plateau fracture. **A.** Radiograph on anteroposterior projection of the left knee. A Schatzker type II is illustrated as depicted schematically in the **C.** If one does not pay attention to the lateral view of the knee, it is easy to miss the posterior location of some of the main fracture components. The asterisk marks the two wedge fragments; **D.** Computed tomography in the axial view with the virtual anatomic equator of the tibial plateau (yellow) drawn in. The rim of the tibial plateau is disrupted (*) anteriorly and posteriorly to the equator.; **E.** Tridimensional surface reformation of computed tomography images shows the major area of instability in this fracture in the posterolateral quadrant, with a significant impaction of the rim. This was the key in the decision making of the best surgical approach. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

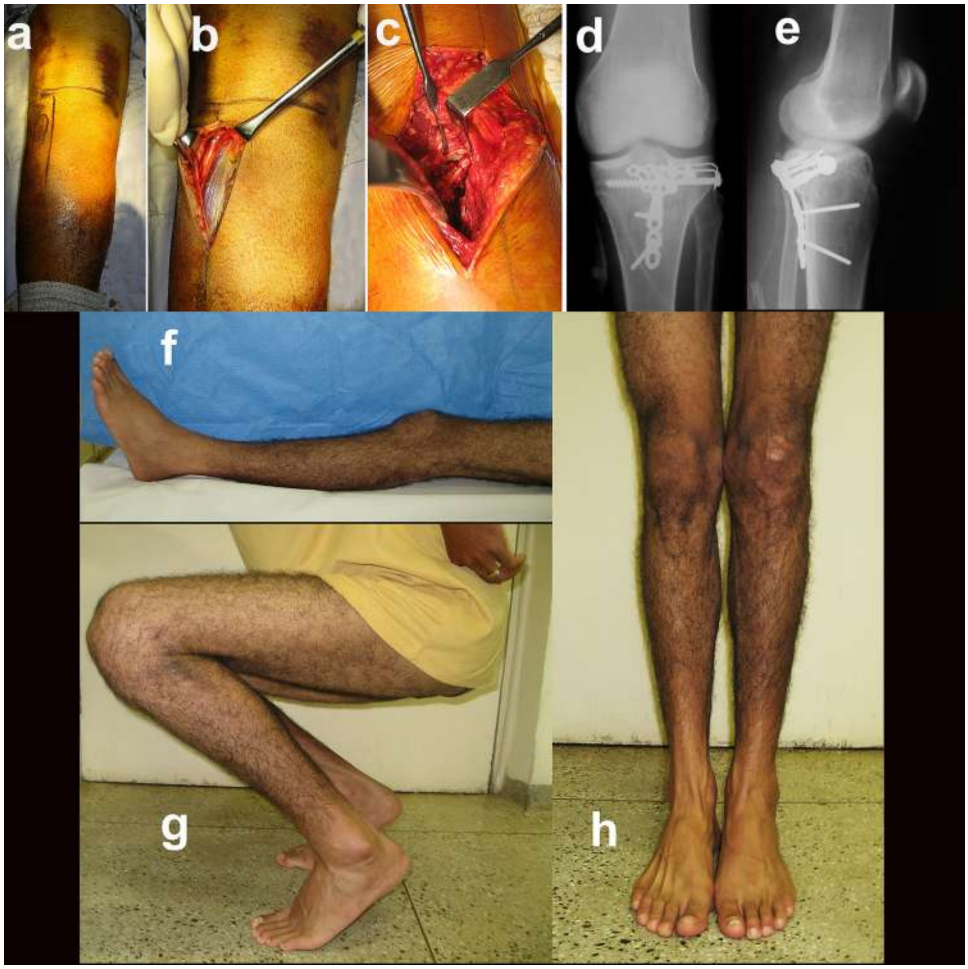

Fig. 13. Continuation of the illustrative case of Fig. 12. **A.** A direct posterolateral approach was chosen. The patient was placed prone on the operative table and anatomical landmarks were identified with a marking pen; **B:** A posterolateral approach was performed, and the peroneal nerve was identified; **C.** The posterolateral rim was exposed, and the lateral meniscus was retracted proximally; **D,E:** Postoperative radiographs, depict the fixation of the posterolateral rim with a buttress plate and of the anterolateral rim with a lag screw and Kirschner wires; **F–H:** final clinical outcomes.

quadrant allows only the use of short buttress plates. Anything longer runs into the vessels. (Figs. 12 and 13)

Terminology of the three-dimensional classification of tibial plateau fractures

The following elements and rules have been introduced with the three-dimensional anatomical classification of tibial plateau fractures:

Virtual equator of the tibial plateau:

Plane determined by joining the insertion of the fibular collateral ligament on the lateral tubercle of the fibular head and the posterior aspect of the insertion of the superficial medial collateral ligament, which is distal to the joint in the metaphyseal area and coincides with the posterior tibial crest.

Tibial plateau condyles:

There are two tibial plateau condyles, the lateral and the medial. Each one contains the corresponding articular surface of the two anatomical columns of the upper tibia. The lateral tibial plateau is designed by a capital “L”. The medial tibial plateau is designed by a capital “M”.

Quadrants:

The virtual equator divides the tibial plateau condyles into two halves. The anterior one is designated by a capital “A”, and the posterior one is designated by a capital “P”. The tibial plateau has two columns, each one supporting its corresponding articular surface. The articular surfaces are separated by the extra-articular tibial spines. Since there are two columns which are split by a virtual equator, this results in the four anatomical quadrants, as follows: AL- anterolateral; AM – anteromedial; PL – posterolateral; PM – posteromedial.

Roman numeral:

Two elements determine the use of a Roman numeral. The fracture pattern – split wedge; split wedge depression; pure depression – and the column which has been compromised – lateral or medial. Types I, II and III refer to the lateral tibial plateau. Type IV refers to the medial tibial plateau. Types V and VI are bicondylar fractures

Unicondylar tibial plateau fractures:

According to the Schatzker classification these are the types I, II, III (lateral types) and IV (medial type). In the three-dimensional anatomical classification, the main fracture plane may be located anterior and/or posterior to the virtual equator line. The way to denote this is by using the Roman numeral first referring to the column which has been fractured, followed by capital "**A**" or capital "**P**", which denote the area of the plateau where the main fracture plane is located. In cases where the anterior and posterior rim areas are both compromised we use the denotation **A + P** as in Fig. 8.

Bicondylar tibial plateau fractures:

The types V and VI do not refer to one of the tibial plateau condyles but to both of them. Therefore, it is important to describe the compromise of each condyle. The letters that refer to each quadrant are written in capital letters. AL: anterolateral; AM: anteromedial; PL: posterolateral; PM: posteromedial. A plus sign is used to describe the additional compromise of another quadrant. As an example, a Type V AL + PM, describes a bicondylar tibial plateau fracture, where there is continuity between the epiphyseal and the diaphyseal segments and where there is a compromise of the tibial plateau, being the compromise of the rim located in the anterolateral and in the posteromedial quadrants.

Wedge and articular rim intersecting points:

The points where the wedge, defined by the principle fracture plane, disrupts the rim are described in lowercase letters. "a" depicts anterior, "p" describes posterior. The point where the fractures exits the metaphyseal bone is also "a" or "p" but to differentiate, it gets the addition of an "x". All letters are written in lower case.

Discussion

In the 1950's the classification systems for tibial plateau fractures spoke of simple types as depression and split [12]. In the 1970's, still based on a two-dimensional imaging and two-dimensional description of fracture, more detailed systems were introduced, speaking also of differences between the lateral and medial plateau [13,17]. Schatzker and later the AO/OTA classification systems, introduced more fracture types [13,17,18]. The more details a classification presents, the higher the likelihood of disagreement in an inter- and intra-observer basis [16,21,22]. The advent of computed tomography allowed for the localization of the fracture in the axial plane, identifying for the first time with precision coronal plane-oriented fractures. Since then tibial plateau fractures have become a topic of great interest not only from the classification point of view but also from the fixation method and expected outcomes.

Luo et al. introduced the three-column concept with particular attention to the compromise of the posterior aspect of the tibial plateau. Luo's system enhanced the awareness about the compromise of the posterior rim of the tibial plateau, but it does not differentiate between the posterolateral and posteromedial aspects of the rim and does not highlight differences between split and depression types of fracture [32]. To address the differences between the posterolateral and the posteromedial quadrants of the tibial plateau, Chang et al. proposed the four quadrants concept, but does not provide the description on the mechanisms of injury and its related fracture patterns causing the compromise of each quadrant [33]. Krause et al. using the axial view of a computed tomography divided the articular surface of the tibial plateau into ten segments but did not offer details about mechanisms of injury related to the compromise of each segment. To our knowledge, the most utilized classification systems published so far are based either on plain radiographs or computed tomography, but not on both of them. Our proposed extension of the Schatzker classification is based on plain radiographs in describing the types and is further complemented by computed tomography to add the third dimension. Plain radiographs allow for the understanding of the mechanism of injury, as originally described in the six principle types by Schatzker [13,14]. Computed tomography gives us a detailed information about the exact location of the main fracture plane in each of the four anatomical quadrants which we have defined in this paper. We recognize the two main patterns of articular fractures which compromise the tibial plateau, namely, the split wedge and the articular depression. In the case of a split, we provide a method to define the main fracture plane by determining the two points where the fracture plane bisects the tibial plateau rim and the point where the fracture exits the metaphyseal bone. To our knowledge we are first to provide the definition of a main fracture plane and how to localize it in each quadrant of the tibial plateau. If one determines the orientation and position in three dimensions of the main fracture plane, it is possible to plan with accuracy the placement of a buttress plate, which should be parallel to this main fracture plane. Once the surgeon knows the location of the fracture and the exact placement of the supporting plate, the surgeon has the necessary and proper guidance of where to perform the surgical approach. The extension of the original classification, when it comes to pure depression, allows for its precise location. If the depression is located centrally, metaphyseal bone windows should be opened granting access to the metaphysis and the compressed bone deep to the subchondral bone plate, which can then be elevated by bone pushers. If the depression involves the rim, the rim should be reconstructed in that particular quadrant, restoring the stability of the joint. This usually means also the use of a horizontal oriented plate. We are introducing a three-dimensional complement to the Schatzker classification, which not only provides the axial, coronal, and saggital morphology of the tibial plateau but also the mechanisms of injury and the exact spatial localization of the main fracture planes. The following chart describes how to apply the new classification system (Fig. 14).

Conclusions

The new system for the three-dimensional classification of tibial plateau fractures is based on the template of the original Schatzker classification, to which we add information obtained from computed tomography. Our goal was to revisit the Schatzker classification four decades after its description and to extend it to include the orientation of the injury in the third dimension. The

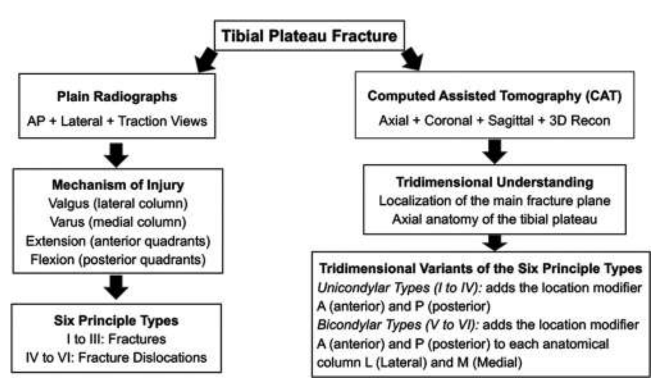

Fig. 14. The mechanics of the tridimensional tibial plateau classification based on the use of plain radiographs and computed tomography scan. Plain radiographs allow for an overall picture of the mechanism and energy of the injury, while computed tomography determines the exact fracture pattern and location in all three planes.

spatial localization of the fracture should help the surgeon when carrying out the pre-operative plan to determine with precision the surgical approach and fixation methods. We acknowledge that our current manuscript has some limitations. First, we are focused on the anatomical description of the bony injury, with no mention of soft tissues envelope. Soft tissues are key elements in the management of the tibial plateau fractures. We assumed that the reader who is familiar with the Schatzker classification understands the differences and the implications or each type when considering the severity of the soft tissue injury and the nuances between the simple fractures – types I to III – and the fracture dislocations – types IV to VI. This study does not make references to the injuries of the tibial spines and of the anterior tubercle, since these are extra-articular structures. We foresee and what is true of all classifications, that some fractures will not be easy to classify, considering their comminution and atypical patterns. We also recognize that by adding more details to the classification we make it more cumbersome and, therefore, more prone to lack of reproducibility. Our goal is to provide a three-dimensional orientation of the fracture and to facilitate the decision making in the most typical types regarding to the surgical approach and fixation method. Future studies, taking into consideration inter- and intra-observers' evaluations, are needed to validate the current classification which places emphasis on the three dimensional localization of the fracture elements and the resultant joint instability. We have introduced some new concepts like the virtual equator, the main fracture plane, the containment of rim support in cases of cortical comminution as well as the importance of rim integrity for the stability of the joint. We have also pointed out that buttress plates must be parallel to the main fracture plane. The advantage of this three dimensional extension of the original Schatzker classification is that it makes use of a widely used and accepted classification system. In addition, it provides a simple method based on computed tomography morphology of the injury to localize the fracture and to provide a simple method of notation of the details of the injury. It also provides clear guides to preoperative planning which should hopefully help to avoid surgical mistakes and improve the outcomes of treatment.

Acknowledgment

The authors would like to thank Stacy Turpin Cheavens, MS, CMI, Certified Medical Illustrator University of Missouri, Department of Orthopedic Surgery for the illustrations in Figs. 1, 2, 4, 5, 6, 7, 8, 9, 10g, 11f and 12b.

Disclosure

None of the authors received payments or services, either directly or indirectly (i.e., via his or her institution), from a third party in support of any aspect of this work. None of the authors, or their institution(s), have had any financial relationship, in the thirty-six months prior to submission of this work, with any entity in the biomedical arena that could be perceived to influence or have the potential to influence what is written in this work. Also, no author has had any other relationships, or has engaged in any other activities, that could be perceived to influence or have the potential to influence what is written in this work.

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