

1.1 Introduction

1 AO Foundation Mission Statement

The **AO Foundation** is a medically guided nonprofit organization led by an international group of surgeons specialized in the treatment of trauma and disorders of the musculoskeletal system. It was founded in 1958 as a study group by 13 visionary Swiss surgeons and transformed into a foundation in 1984.

The **vision** of the AO Foundation is excellence in the surgical management of trauma and disorders of the musculoskeletal system.

The **mission** is to foster and expand the AO network of healthcare professionals in education, research, development, and clinical investigation to achieve more effective patient care worldwide.

To adapt to the specific needs of each anatomical region as well as differences in human and animal surgery. AO has established autonomous speciality areas for trauma, spine, craniomaxillofacial, and veterinary surgery. All AO specialties continually redefine the state of the art in their field, maintaining activities in research, development, clinical investigation, and education.

In addition, AO has set up an entity to educate operating room personnel (ORP) and achieve the best possible interaction between specialties and between surgeons and ORP.

2 Research and development within AO Foundation

One of the goals of the AO Foundation is to promote research and development within the scope of the AO Foundation's activities.

Research within the AO Foundation is conducted and promoted through different channels.

- The AO Research Institute Davos (ARI) is dedicated to basic and applied research and development in the area of trauma, disorders of the skeletal systems, and related topics. The institute employs specialists in surgery, biology, materials, science, veterinary medicine, dentistry, biomechanics, and biomedical engineering, among others. Defined research groups specialize in trauma-related topics (more information at: www.aofoundation.org).
- Research grants are available in the clinical priority programs (CPPs). The CPPs are specialty-based research programs which promote research in fields of major interest to each specialty. The principal topic of the craniomaxillofacial CPP is currently "Imaging and Planning in Surgery" (www.aofoundation.org). This program is led by a program committee which reports to the AOCMF Research and Development Commission. It issued its first open calls for grant applications in 2009. Details of these calls and of the studies being funded can be found on the AOCMF website.
- The AO Research Fund (AORF) has since 1983 issued open calls twice a year for start up grants, especially to support young researchers. These grants cover the broad areas of interest of the AO. They will continue to be available from the successor to the AORF, the AO Research and Review Commission (AORRC), on the same basis but will be funded by the AO Academic Council.

- Between 2005 and 2009, the AO Research Fund also issued open calls twice a year for larger focus grants. These were specifically in the focus fields of the specialties and designed to be applied by experienced researchers. Since 2010, these grants are now available from the specialty research and development commissions.
- The AO Exploratory Research Board (AOERB), on which all specialties and the ARI are represented, has the principal responsibility for oversight and funding of basic research in the AO Foundation. Currently much of that is focused on the reconstruction of large bone defects. The AOERB also approves and provides project funding for collaborative research centers worldwide which work with the AO and its researchers on specific research goals.
- Development work can also be done at the ARI. Increasingly, this is collaborative with outside researchers. However, most product development today is done in close cooperation with industrial partners. Usually every marketable product goes into the TK System (see chapter 1.1.3) and is subject to intensive clinical trials before it is released for marketing through the respective industrial partner.

The research and development environment within AOCMF may change while this book is on the market. For current information search the AO website at: www.aofoundation.org.

3 TK system CMF

The AO Foundation has a long history of close collaboration with industrial partners. Surgeon control over the design of implants and instruments was and still is one of the fundamental principles of the AO. Within the AO Foundation, the responsibility for the development and clinical testing of new devices is the TK ("Technische Kommission" or technical commission). The German abbreviation "TK" was kept even after the AO Foundation became a global organization.

The TK is an organization of committees consisting of surgeons, product development staff, and engineers. In the specialty of craniomaxillofacial surgery, there is an overall Technical Commission with various Expert Groups (EGs) in which approximately 40 surgeons work with the engineers on solutions for clinical problems.

From the beginning, the aim of the TK was to ensure that all implants and instruments that were manufactured according to AO standards have a proven record of safety, simplicity, and universality in application. There are three EGs working with the AO industrial partners on the development of new instruments, implants, and techniques in CMF surgery. Ad-hoc committees such as task forces or working groups focussing on new technologies, ie, computer assisted surgery and biomaterials, were also established to support the efforts of the TK and EGs where necessary.

Without prior approval of the TK, almost no Synthes implant or instrument becomes available to the surgical community. However, there is more to the TK System than the decision on the final product approval. All EGs work in close collaboration with the engineers from the first idea to clinical use, and all instruments and implants go through several stages of evaluation with the independent medical members of the EGs making the final decision whether or not the respective project is pursued. Special care is taken to ensure that Expert Groups evolve in line with changing requirements and react promptly to the needs of the medical community. Thus, new research insights are considered, new possibilities for development are evaluated, and new needs and trends are studied.

Further tasks of the Expert and Working Groups are to evaluate devices and methods identified by surgeons or any other interested party and to define and approve a clinical evaluation process. They also monitor the clinical success of approved devices and methods once they have been on the market for a while.

Each group within the TK System consists of five medical members as well as engineers, researchers, and other representatives of the AO industrial partners. Despite defined membership terms, the TK System is anything but a closed circle and remains open to ideas from the outside. Everybody is invited to participate and present his or her ideas to the TK Chairman (see TK innovation form available on the Web: http://courses.aocmf.org/files/editor/documents/TK_Idea_Form_CMF_2009.pdf).

4 Education

Worldwide education is probably the most important mission of the AO Foundation with regard to improving health-care. Educational activities were traditionally coordinated through AO International (AOI), and then later through AO Education (AOE) in a supra-specialty manner. Today education is organized by the four specialties (AOTrauma, AOSpine, AOCMF, and AOVET) and is delivered through different educational channels:

- Face-to-face education through courses, workshops, seminars, and symposia
- Printed media, such as journals (ie, Journal of Craniomaxillofacial Trauma and Reconstruction) and books
- Audiovisual media (eg, videos and DVDs)
- Internet
- Fellowships: The AO Fellowship program offers fellowships to both surgeons and operating room personnel in designated approved AOCMF Fellowship Centers. Interested surgeons and ORP can apply for fellowships on the AO Foundation website (www.aofoundation.org/fellowships).

5 Clinical investigation and documentation

5.1 AOCID mission and strategy

AO Clinical Investigation and Documentation (AOCID) conducts multicenter clinical studies to document safety, effectiveness, and outcome of fracture treatment, thus promoting the application of evidence-based surgery. Its worldwide activities are increasing steadily.

AOCID's strategy is to promote the science of applied clinical research. Applied clinical research involves both doing and using clinical research. AOCID directs and assists surgeons in the conduct of clinical studies. It assists surgeons to search and critically appraise the available literature to answer clinical questions (**Tab 1.1.5-1**).

5.2 Doing clinical research

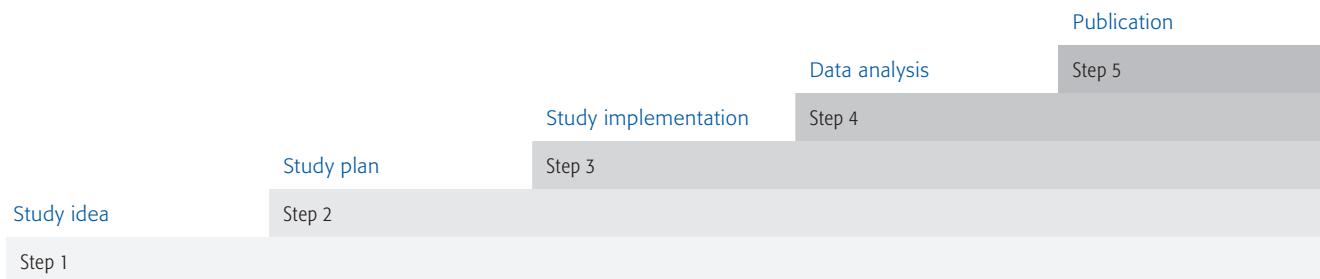
Design and conduct of a clinical trial can be a daunting task. The key to designing and conducting research successfully is being creative and careful. Researchers must correctly articulate the study question, choose the correct study design, and ensure that data are extracted, recorded, managed, and analyzed carefully. The accuracy of the results is dependent on internal and external validity. Internal validity refers to the effects obtained in a study due to the intervention under evaluation. Internal validity is attained through sound study methods. If there are alternative explanations for the data (eg, selection bias), the study may not have internal validity. External validity refers to whether the results can be generalized outside of the specific participants and situations of the study. Careful selection of study subjects ensures that study findings are generalizable.

Five major steps are involved in successfully conducting a clinical study that possesses both internal and external validity:

1. Developing a study idea
2. Careful crafting of a study plan
3. Ensuring that detailed standard operating procedures are followed during study implementation
4. Performing careful data analysis
5. Publishing the results with careful thought and attention (**Tab 1.1.5-2**).

DOING Clinical research	USING Clinical research
<ul style="list-style-type: none">• How to design and conduct clinical trials.	<ul style="list-style-type: none">• How to search the literature to answer a clinical question.• How to critically appraise a medico-scientific article.

Tab 1.1.5-1 AOCID is committed to doing and using clinical research.



Tab 1.1.5-2 The five major steps in successfully conducting a clinical study.

5.3 Using clinical research

The study and understanding of basic mechanisms of injury and healing alone are not sufficient guides for clinical practice. In addition, clinical experience, while valuable, may be misleading in solving clinical problems. There is a growing agreement in the field of surgery that surgeons need to move beyond physiological principles and clinical experience toward evidence-based medicine and its rigorous evaluations of the consequences of clinical actions. Knowing how to use clinical literature (ie, literature search, literature review, and critical appraisal) is imperative in ensuring that surgeons are providing optimal patient care. Surgeons need to focus on a specific clinical question, know where to look for pertinent articles that address the question, and select only the information that is likely to provide results with the best evidence. The final skill of critical appraisal allows surgeons to weigh the evidence against published conclusions.

5.4 Summary

AOCID is dedicated to assist clinicians in achieving success in clinical research. AOCID provides useful services and tools for surgeons to evaluate their devices and interventions. Detailed information on AOCID and its services is available online at: www.aofoundation.org/cid

6 AO classification of craniomaxillofacial fractures

6.1 General concept and objectives of a fracture classification

In biosciences and medicine classifications are omnipresent. Almost every advent of new technologies and novel diagnostic or therapeutic regimens is publicized together with the urge to rethink former systematization and conceptions. This is reflected in headlines and titles containing vocabulary such as grouping, coding, rating, grading, scaling, scoring, typifying, which is indicative for a classifying process. Fractures of the human skeleton come in many variations rendering it difficult to identify appropriate parameters and to assign a clinical series of unique cases into a fixed number of possible categories.

Today the least common denominator for a formal fracture classification is the description of the fracture topography and its morphology based on the analysis of diagnostic x-rays or CT imaging.

There are multiple other variables and factors to fully portray a patient and his injury such as etiology, severity of the trauma, bone quantity and quality, associated soft-tissue damage, functional impairment, age, physical or psychic comorbidities, and social integration. In theory it may seem reasonable to include all conceivable variables and patient

details into a fracture classification; however, this would lead to a diversification into small subcategories, which would be unmanageable in routine clinical use.

What really matters in the treatment of an individual patient is firstly, usefulness for and ease of communication, and secondly, the therapeutic relevance of classifying. For this reason the hierarchy of categories and groups in a fracture classification system should best correlate to the injury severity and/or the difficulty of treatment. A set of agreed rules and definitions is mandatory to identify the groups within an ascending order of injury severity.

A classification model should be minimalistic. Thus, preselection of pertinent parameters by virtue of a rigorous methodological validation concept is crucial. An inherent problem in the development of a concise fracture classification model is to delineate the cut-off criteria between groups from the very onset to predict treatment outcomes.

In the first development stages, a fracture classification proposal should exclusively refer to the biological substratum (nature) of an injury, such as anatomical location, fragmentation, and so on. Necessary modifications are to follow in an iterative process of exploratory trial phases in pilot and agreement studies (**Fig 1.1.6-1**). Only after successful validation, the outcome of differential treatment procedures and the potential risk for complications can be analyzed prospectively in evidenced-based studies.

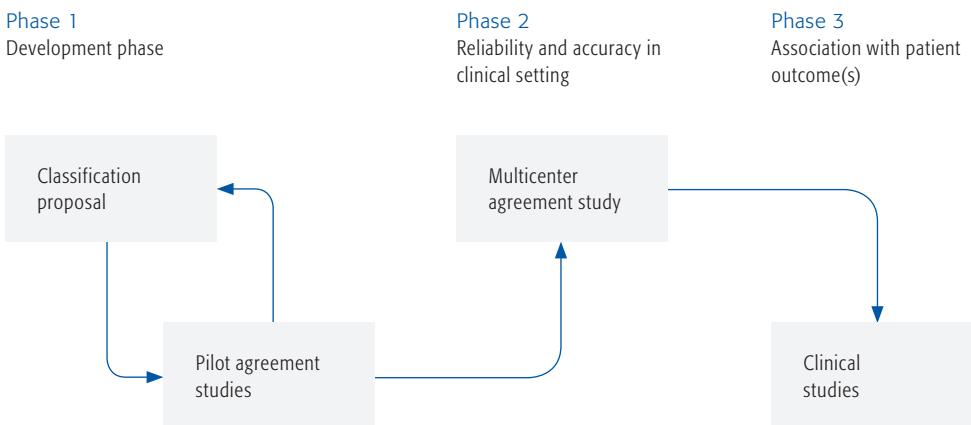


Fig 1.1.6-1 Methodological development and validation along a 3-phase pathway (Audigé et al 2005). The classification proposal and the pilot agreement study are looped repetitively until acceptable reproducibility and consensus are reached.

Empirical information gained from specific treatment paths should not be implemented in the initial version of a fracture classification. Such treatment-based criteria result in bias rather than yielding a rational base for the prospective evaluation of any targeted therapy.

Apart from providing guidelines for individual patient care, a fracture classification serves further purposes. A consistent and reproducible classification provides a universal language and coding that facilitates communication and collaboration. Coding and indexing are prerequisites for using present-day information and computing media for web-based exchange and storage of records on fractures in trauma databases. It enables large-scale documentation, inter-institutional comparisons, quality surveillance of clinical outcomes, the adoption of benchmarking methods in order to possibly optimize the surgical procedures, and last but not least, economic analysis.

In 1986 the AO Foundation officially adopted "The Comprehensive Classification of Fractures of the Long Bones" developed by Maurice Müller and his group as a groundwork for its activities in documentation.

This forerunner of today's AO classification endeavors has introduced a standardized alphanumeric code to indicate the affected bone, the fracture type, and its morphological complexity. Topographic identification analogous to this initial coding is still in use, eg, in the CMF region: 91 for mandible, 92 for midface, 93 for skull base, and 94 for cranial vault.

The fracture codes (or classes) were assembled according to the so-called AO tripartition concept, which was a ranking scale for fracture severity into 27 different degrees with a hierarchical tree-like architecture.

For many years the idea was to apply the tripartition concept universally to all fracture locations in the human skeleton. Interestingly enough, the AO classification manuals have ever since relied on wide-scope diagrammatic representations.

Still a visually based, more or less non-verbal, self-explaining, and intuitive coding procedure is regarded as essential to developing a user-friendly, internationally accepted fracture classification scheme and its successful implementation in the routine workflow of clinicians.

6.2 A brief history of CMF classifications

To date central midface fractures with a potential impact on the occlusion are referred to worldwide by the name of Le Fort. The simple distinction of three Le Fort type fractures is considered as a prototype of a classification system for facial fractures. The experimental cadaver studies of the French physician and pathologist René Le Fort (1901) dating back to the very beginning of the 20th century led to an understanding of the honeycomb construction of the midfacial skeleton and, in turn, of the major lines of weakness. This bony architecture explains why the fractures may follow a predictable course that can be divided into a limited number of well-defined patterns.

Over more than a century a multitude of classifications were created to detail site-specific fracture entities for craniofacial fractures:

- Midface (Guérin 1866, Le Fort 1901, Wassmund 1927, Donat et al 1998)
- Zygoma, zygomaticomaxillary complex fractures (Zingg et al 1992)
- Orbito-zygomatic and orbitoethmoid region (Jackson 1989)
- Nasoorbitoethmoid (NOE) region (Markowitz et al 1991)
- Orbit (Hammer 1995, Carinici 2006, Jacquieré et al 2007)
- Medial orbital wall (Nolasco and Mathog 1995)
- Palate (Chen et al 2008)
- Midface in conjunction with skull base (Buitrago-Téllez et al 1992, 2002, Bächli et al 2009)
- Anterior skull base (Madhusdan et al 2006)
- Temporal bone (Rafferty et al 2006)
- Mandible (Spiessl 1989, Roth et al 2005, Buitrago-Téllez et al 2007)
- Condylar process of the mandible (Spiessl, Schroll 1972, Loukota et al 2005)
- Panfacial injuries and avulsions (Clark et al 1995)

Various attempts were made to build up fracture severity scores for the CMF region by Cooter and David 1989, Joos et al 1999, Bagheri et al 2006, Zhang et al 2006, based on categorical (ordered or ordinal) scales.

6.3 Evolution of a modern AO craniomaxillofacial fracture classification

Several years ago the AO Foundation started to create an up-to-date classification of craniofacial injuries. The project was launched by the work of Buitrago-Téllez, who initially designed a CT-based diagnostic algorithm for craniomaxillofacial fractures to establish a hierarchical classification of increasing severity. The elementary concept was to split craniofacial fracture patterns analogous to the AO tripartition system. The innovation of this first generation CMF classification was the incorporation of accompanying anterior and lateral skull base fractures and fracture line courses deviating from the Le Fort levels. In 2008, a classification model for the mandible differentiating vertical mandibular compartments and a horizontal subdivision of the body and para-symphyseal region was conjoined.

Persistent inconsistencies in interobserver reliability of this first generation CMF system as well as a second generation model accomplished in several classification sessions by the members of an international group of CMF traumatologists did not comply with the upcoming methodological standards.

The complexity of the models enabling a comprehensive mapping of each and every conceivable fracture line and possible combinations was revealed as the main reason for the limited performance of the classification proposals.

The plausible solution was a paradigm shift moving to a streamlined classification model considered as practical, clinically meaningful, and scientifically sound.

In order to keep up with the request for simplification, the road map for the development of the current third generation CMF AO classification takes the following aspects into account:

- To address trauma of: mandible (91), midfacial skeleton (92), skull base (93), and cranial vault (94)
- To use imaging information as common basis for all levels and modules: (91–94: CT scans/supplementary MRIs, 91 alternatively: Panorex, conventional x-rays in two planes)
- To include topographical description of fracture location
- To integrate the Le Fort Classification in the midfacial skeleton (92)
- To describe fracture morphology
- To incorporate a rigorous methodological pathway (interobserver reliability, validity)
- Stepwise development of the system in three levels with progression of accuracy and clinical significance:
 - Level 1: Elementary system for gross fracture location (mandible, midface, skull base, cranial vault)
 - Level 2: Basic system for refined fracture location in the CMF skeleton (outlining the topographic boundaries of the anatomical regions within the fundamental units of the CMF skeleton as a basis for an accurate localization)
 - Level 3: Focused modular system assessing fracture morphology (ie, fragmentation and displacement)
 - Levels 1 and 2 serve as anatomical localizers, while level 3 describes the fracture morphology in an array of modules representing anatomical regions and sub-regions.
- To build up a hierarchical classification system that allows grading of fracture severity
- To provide a rational basis for prospective (functional and patient reported) treatment outcome studies, from which algorithms for clinical decision making can be derived

Anatomical units of the craniofacial skeleton yield the templates (**Figs 1.1.6-2-3**) on which the overall system is gradually built up in a series of modules. A module is representing circumscribed anatomical regions, either in concert (eg, mandibular body, parasympyseal region and angle) or alone (eg, condylar process). Each of the modules is developed in a step-by-step manner to define different levels of precision related to the necessities of documentation and varying scopes of clinical application. Such a staged approach with pilot testing of the items ensures the elimination of all ambiguities and verifies the reliability and appropriateness before any progression to the next level is permitted.

The final proposal for levels 1 to 3 for the entire craniofacial skeleton have been recently completed by the CMF Classification Group. This is considered as a sign that the current development process of a modular CMF fracture classification is on the right track, though the long and arduous way to generate measures reflecting the fracture severity is yet to come.

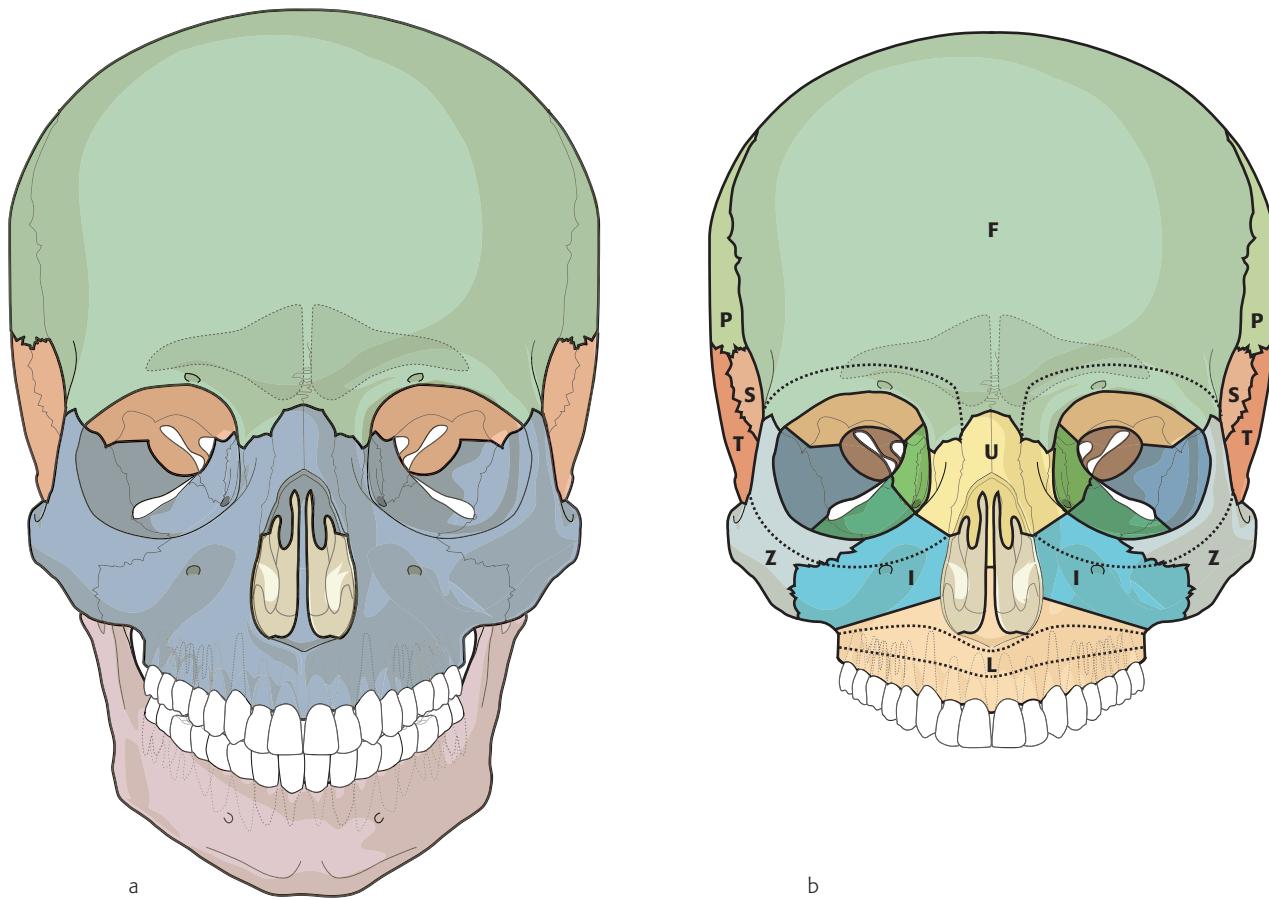


Fig 1.1.6-2a-b Third generation AOCMF classification.

a Level 1: Mandible, midface, skull base, and cranial vault.

b Level 2: Classification proposal: skull frontal view. Differentiation of anatomical regions: zygoma (Z), upper central midface (U), intermediate central midface (I), lower central midface (L), frontal (F), parietal (P), sphenoidal (S), temporal (T).

In the level 2 classification the mandibular body is subdivided by vertical lines into horizontally oriented subdivisions (**Fig 1.1.6-3**). Neither the dental state nor the vertical bone height or any degree of atrophy is an explicit item at level 2. Nonetheless, it is necessary to acknowledge the dentition since the tooth roots are used to provide baseline markings to divide the mandible into regions. Therefore, a full set of permanent teeth is plotted in the level 2 graphic charts of the mandible. Four transition zones were interposed between the mandibular regions to procure corridors in the approximate width of the canine or the third molar for the unequivocal allocation of fracture courses running at the borderline or passing obliquely across the boundaries of adjacent regions.

It is not pure nostalgia that the level 2 midface fracture classification module integrates the classic Le Fort fracture pattern. The Le Fort scheme is popular in the medical community and should not be replaced because it ideally fits into the present-day requirements for a fracture classification. It is easily intelligible, relies on visual programs, and precludes language or semantic problems. The level 2 midface fracture classification delineates the Le Fort levels (except the zygoma) with the help of three horizontal partitions

stacked one above the other alongside the pillars of the central midface (**Fig 1.1.6-2a–b**): lower central midface (LCM), intermediate central midface (ICM), and upper central midface (UCM).

Obvious deficiencies of the Le Fort classification are offset: fracture pattern scenarios beyond the monotonous low-energy impact skeletal disruptions produced in his experiments (ie, direct blows with a wooden club or banging of the head against the round edge of the autopsy table) with comminution, inclusion of multiple midfacial units, extension into the adjacent cranial base and vault, or involvement of the mandible in terms of pancraniofacial fractures are taken into account by the all-inclusive cartography.

Each area-specific classification module will be explained in detail and illustrated with case examples in particular instructional brochures and in a special issue of the Craniomaxillofacial Trauma and Reconstruction journal. To facilitate fracture classification and coding in routine clinical settings, software has been released and can be downloaded, ie, the AO Comprehensive Injury Automatic Classifier (AO COIAC), (<http://www.aofoundation.org/aocoiac>).

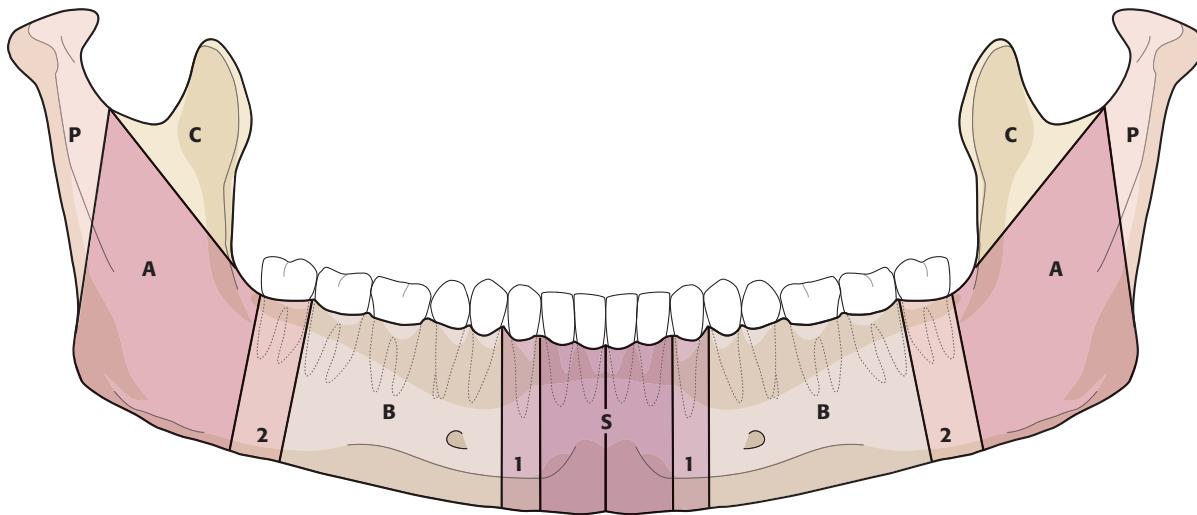


Fig 1.1.6-3 3rd generation AOCMF level 2 classification proposal: Panoramic view of the mandible.

Body regions = 1 (anterior transitional zones)

Ramus regions = 2 (posterior transitional zones)

Condylar process (P), coronoid (C), angle/ramus (A), body (B), symphysis/parasymphysis (S).

6.4 Future perspectives

It takes time to gain expertise in fracture classifications and the current versions certainly will not represent the end of the development process.

Although the existing level 2 CMF classification software provides an almost non-verbal visual logic allowing for effortless documentation, it seems overly ambitious to generate an intuitive software user interface to characterize the fracture morphology at the next level. Level 3 has to deal with an enormous number of variables (injuries of teeth and parodontium, bone atrophy, number and spatial distribution of fracture lines), which can be hardly displayed in the form of symbols, icons or thumb nails, that can be check-marked by simple pointing and clicking.

Another unsolved issue is the aggravating time constraints of clinicians. Image fusion of CT scans and classification charts followed by automatic analysis might be a technical answer to the problem. Technological advances will not only enhance the precision of evaluation and diagnosis but will continuously detect imperfections unknown to previous classification endeavors.

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1.2 Bone

1 Origin of skull bones

During embryogenesis two different mechanisms of bone formation take place in the skull. In the dermatocranum (exocranum) the ossification occurs by direct mineral deposition into the organic matrix of mesenchymal or connective tissue, resulting in a process called membranous bone formation, which is the major ossification process in the skull. Frontal, parietal and nasal bones, maxilla, zygoma, and the mandible are all formed by this mechanism. Endochondral bone formation is the mechanism in the chondrocranium (endocranum). Here a cartilaginous template is formed, which becomes mineralized and then replaced by bone. In the skull the cartilaginous origin of bone is confined to the skull base, occipital bone, nasal septum, and internal components of the nose. Further growth in membranous as well as in bone of endochondral origin occurs by the membranous mechanism. Thus, barely any bone of cartilaginous origin can be detected after completion of all modeling and remodeling processes which take place during growth. Although there seem to be differences in the phenotype of bone cells from sites of different origin, repair processes follow the same membranous patterns, regardless of the embryological origin of the bone.

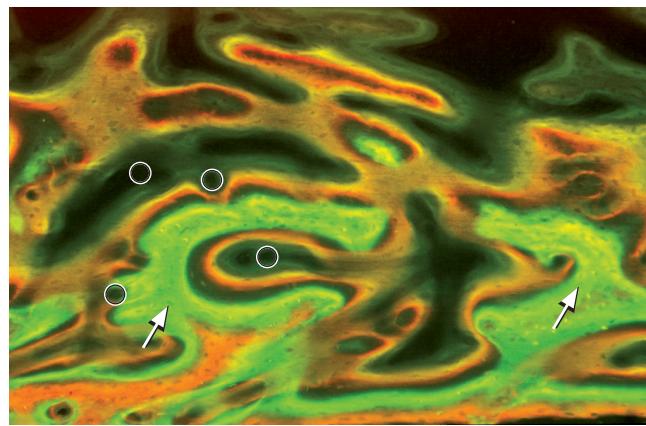


Fig 1.2-1 Bone tissue first formed as a woven bone scaffold, later reinforced by lamellar bone deposition. Green is the original woven bone; red indicates newly deposited woven bone; yellow indicates osteoid; arrows indicate osteocytes; and circles indicate blood vessels.

2 Structure

Depending on functional demands, bone appears as a light weight construct, **cancellous bone**, or in a compact form, **cortical bone**. This appearance is not directly related to microscopic composition and origin of the bone tissue. The mandible mainly consists of compact bone, with cancellous portions in the condyle, angle, and body. The cranial vault is a tri-layered construct with an internal and an external table made of compact bone, separated by the cancellous diploe region. The bones of the midface mainly consist of thin compact layers, supported by a more stable bony frame, while the bones of the skull base have a more compact appearance.

Bone as a tissue is first formed as a relatively loose material, woven bone, in a process which proceeds relatively fast. Later it is reinforced by additional bone deposition into the meshes of this loose network and on its surfaces (**Fig 1.2-1**). This latter type of bone, lamellar bone, is formed more slowly, layer by layer, at a speed of about 1 to 2 mm per day. As a result, this bone is more organized and more compact. Once bone is formed, it undergoes continuous modeling and remodeling to adapt to functional demands (**Fig 1.2-2**).

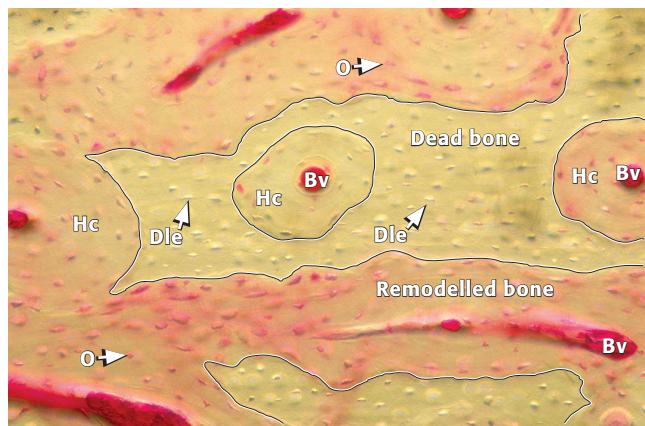


Fig 1.2-2 Bone undergoes continuous remodeling to adapt to functional demands.

O: living bone osteocytes stained pink within lacunae

Dle: dead bone lacunae, empty

Bv: blood vessels (red)

Hc: Haversian canal

Osteoclasts are responsible for these structural changes (**Fig 1.2-3**), which are large multinuclear cells, which locally decalcify and remove bone. Osteoblasts (**Fig 1.2-4**) are responsible for the synthesis of the organic matrix and the mineralization of new bone. Osteoclasts are derived from the hematopoietic system, where monocytes and macrophages are considered to be precursors. Osteoblasts have a local origin from osteoprogenitors and mesenchymal precursor cells. During bone deposition, single osteoblasts are buried in the new bone. They become osteocytes, which are connected to each other by thin cell processes, cana-

liculi (**Fig 1.2-5**). Through this fine canalicular network a rapid exchange of calcium ions becomes possible. Occasionally this exchange becomes visible as osteocytic osteolysis or periosteocytic mineralization. To keep the net bone mass constant, the function of osteoclasts and osteoblasts has to be well balanced. A disturbed balance can be observed under pathological conditions. If osteoclast function dominates over osteoblastic bone formation, a net bone loss will result (osteoporosis). A higher bone density results when osteoclast function is disturbed, as for instance in osteopetrosis or by the influence of therapeutic agents (osteoclast inhibitors).

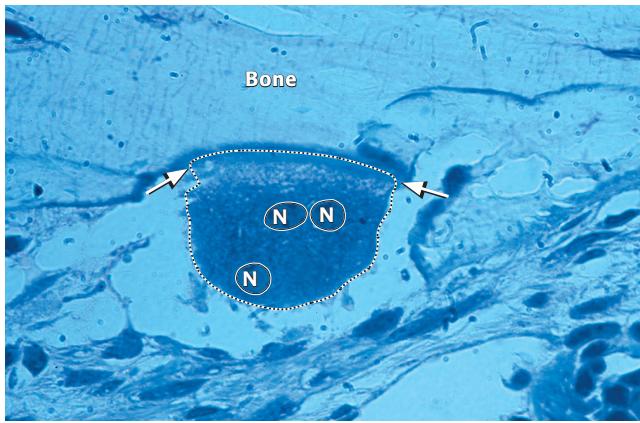


Fig 1.2-3 Osteoclasts, large multinuclear cells, are able to decalcify bone and then remove the organic matrix. At its periphery (zone between arrows) the osteoclasts are intimately attached to the bone surface, creating a subcellular zone between bone and base of osteoclast. Within this hyperacidic resorption compartment (pH 4,5), demineralization takes place. N indicates nuclei.

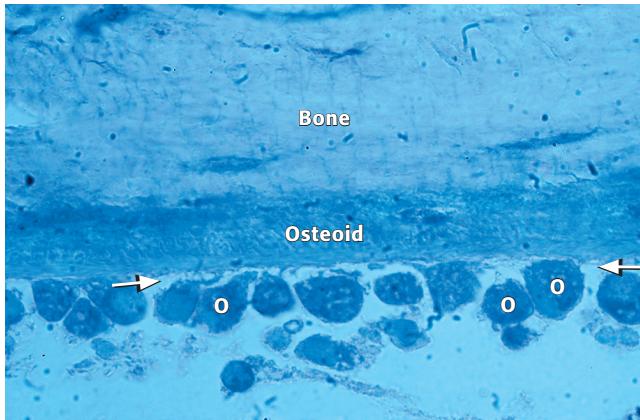


Fig 1.2-4 Osteoblasts (O) are responsible for formation and mineralization of new bone. In between arrows, mineralization front.

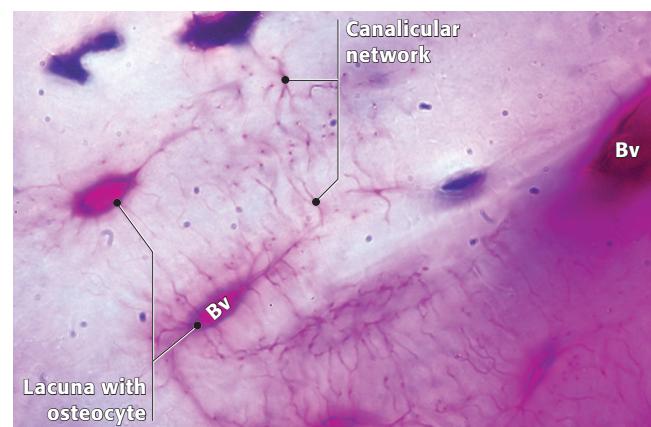


Fig 1.2-5 Nutrition of bone occurs through a fine canalicular network connecting osteocytes. Bv indicates blood vessels.

3 Chemical composition

Bone is composed of an organic matrix loaded with inorganic substances. The sum of the inorganic components amounts to approximately 65% of the total mass. Bone tissue is the most important reservoir of calcium ions which allows rapid release in the case of high demand, or rapid storage in the case of high supply. This is especially important for maintaining the serum level of calcium strictly within narrow boundaries. Hydroxyapatite $[Ca_{10}(PO_4)_6(OH)_2]$, together with other calcium and phosphorus salts, is the major inorganic constituent. Besides the calcium, bone salts contain relevant amounts of magnesium, potassium, chlorine, iron, and carbonate. The organic component of bone consists of about 90% collagen, primarily type I. The remaining 10% are non-collagenous proteins and lipids. These proteins include 23% osteonectin, 15% osteocalcin, 9% sialoprotein, 9% phosphoproteins, 5% α_2 -HS-glycoproteins, 4% proteoglycans, 3% albumin, and further proteins in minor amounts. In recent years, a whole group of bone proteins have been identified which have important functions in bone turnover and bone repair when they are released.

4 Mechanical properties

Bone as a material is a composite, comparable to technical materials like steel-reinforced concrete or fiber-reinforced polymer. Primarily the collagen fibers are responsible for taking over tensile forces, while the mineral phase absorbs compressive forces. The microstructure determines the mechanical characteristics of the materials. It has been demonstrated that fibers show specific orientation depending on the specific loading situation. This results in anisotropic material characteristics which means that the properties are different in different directions. Similar to technical materials, fiber length influences the mechanical properties. An intense remodeling, which interrupts existing structures, leads to a change in material properties. This is probably less important for compressive forces, but it might play a role in tension or shear forces.

Bone is rather brittle; it only tolerates an elongation of 2% before it breaks. The “material” bone has an ultimate strength of about 1 MPa, whereby tensile strength only amounts to two-thirds of compressive strength. This explains why bone

usually fails on the tension side first when it is bent. The mechanical properties of dead bone are not dramatically different to those of living bone, but a continuous remodeling is necessary to avoid accumulation of microtrauma injuries which finally may result in a fatigue fracture.

Bone as an organ has design characteristics that are adapted to the local mechanical requirements. The design normally includes ample reserve for peak loads. Depending on the local demands, bone appears as beams, compact or hollow, or as a light weight construct, as cancellous bone. The mechanical properties of cancellous bone depend on the amount of material, orientation, thickness, and connectivity of trabeculae. The strength of cancellous bone thus covers a wide range but is typically less than one tenth of cortical bone.

5 Mechanical glossary

Technical terminology is encountered when dealing with skeletal biomechanics related to fracture treatment. A small selection is explained here in a simplistic way, and more details can be found in corresponding textbooks. When a force (Newton, N) acts on a body it produces an internal stress (σ , force per unit area, N/m²). A moment is force acting with a lever arm, its unit being Newton times meters (Nm). Under such a force a body is deformed. The deformation ratio, change of length per original length is called strain ($\epsilon = \delta L/L$). It is unitless, and describes the change of the original dimension as a percentage. The relationship between a force and the resulting deformation is called stiffness. The lower the stiffness is the higher is the deformation. A load may consist of up to three vectors of force and three components of moment. It can be static or dynamic, and it can be produced by tension, compression, bending, torsion, or shear, or by a combination thereof. Strength describes the load a body can bear, and it is usually given as ultimate strength, the maximum that the body can bear. The word “stability” is frequently used in context with fracture fixation. This term is technically not well defined. It is used to describe a certain degree of fixation considered adequate to permit undisturbed fracture healing in a specific situation. Thereby the personality of the patient, the type of fracture, the expected loading situation, soft-tissue conditions, expected healing time, and many other parameters are all important in the clinical situation.

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1.3.1 Biomechanics of the craniomaxillofacial skeleton

1 Introduction

The craniomaxillofacial skeleton provides a frame for the protection of soft organs including the eyes and the brain. In addition, it contains important functional entities such as airway and the masticatory apparatus. The bones of the facial skeleton, the skull, and the skull base form a bony, structurally stable frame, on which muscles insert at defined locations that allow suspension and controlled movements of muscles and skin.

The hemispherical design and the layered structure of the cranial vault make it especially suited to protect the brain against direct impact. The cellular structure in the midface, reinforced by the orbitozygomatic frame, is able to function as a shock-absorbing structure, absorbing energy as fractures occur.

The mandible acts mechanically like a curved beam in the axial plane and is supported by the major muscles that insert in the area of the angle and the ascending ramus, and by joints at each end. This curved structure has a pair of sup-

port slings, one on each side, called the pterygo-masseteric sling. Consistent with the natural laws of physics, all curved beams or supports will develop regions of strain in compression or tension relative to a load location. A midline mandible load will generate tension opposite the load (along the lower surface) and compression at the bite location when viewed in the coronal plane. A posterior load will develop a similar pattern at the bite position viewed in the sagittal plane, with a relative reversal of strain at the contralateral position. It remains inconsistent with the laws of physics to define the alveolar surface as a tension zone for all bite force scenarios. This description continues to be used erroneously in reference literature in conflict with basic science.

During mastication the mandible moves relative to the rest of the skull. Forces act at the attachment sites of the masticatory musculature and in the occlusal plane at the bite location. These latter bite forces are transmitted via the teeth to the alveolar bone and from there to the structures of mandible and maxilla. The maxilla is connected by six main vertical trajectories to the orbitozygomatic frame, which is then connected to the neurocranium (**Fig 1.3.1-1**).

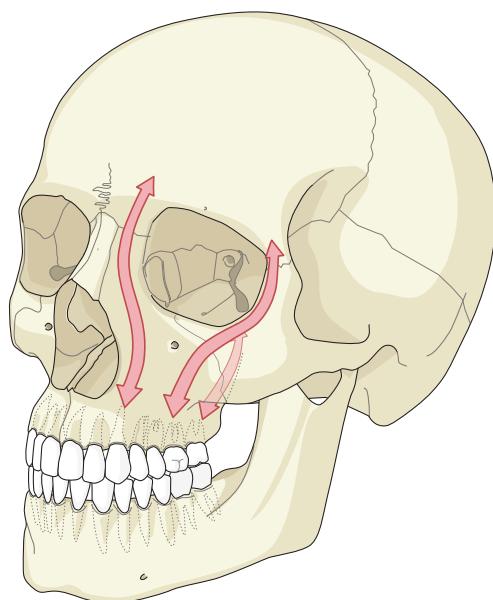


Fig 1.3.1-1 The vertical buttresses of the facial skeleton (nasomaxillary, zygomaticomaxillary, and pterygomaxillary).

1.3.1 Biomechanics of the craniomaxillofacial skeleton

Loading of the occlusal plane may reach high force values. Maximum bite forces in an average population are found in an order of magnitude of 200 to 300 N in the incisor area, 300 to 500 N in the premolar region, and 500 to 700 N in the molar area. The values found during normal mastication are usually much smaller, amounting only to a fraction of the maximum biting forces. These regular masticatory forces cause micro-deformations of the facial bones as a result of strain conditions, but functional forces never cause any fractures in a healthy skeleton.

At the time of deformation of the facial bones, pressure-, tension-, shearing- and neutral zones are observed. During the complex and physiological masticatory loadings the areas for the various forces change rapidly over time and according to the individual loading situation.

Similar deformations are observed when external forces act on the facial bones, however, with strain conditions that may exceed load carrying capabilities of the structures. In this case the areas of tension, compression, or shearing depend on the vector of the external forces (Figs 1.3.1-2a–b, 1.3.1-3a–b).

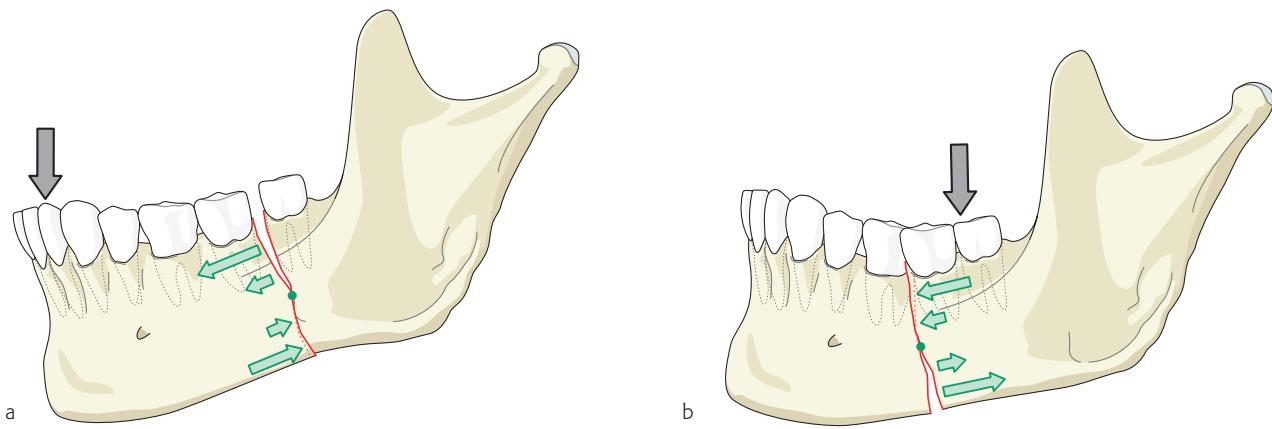


Fig 1.3.1-2a–b

- a External force anteriorly with resulting tension forces superiorly and compression forces inferiorly within the mandible.
- b External force posteriorly with resulting tension forces inferiorly and compression forces superiorly within the mandible.

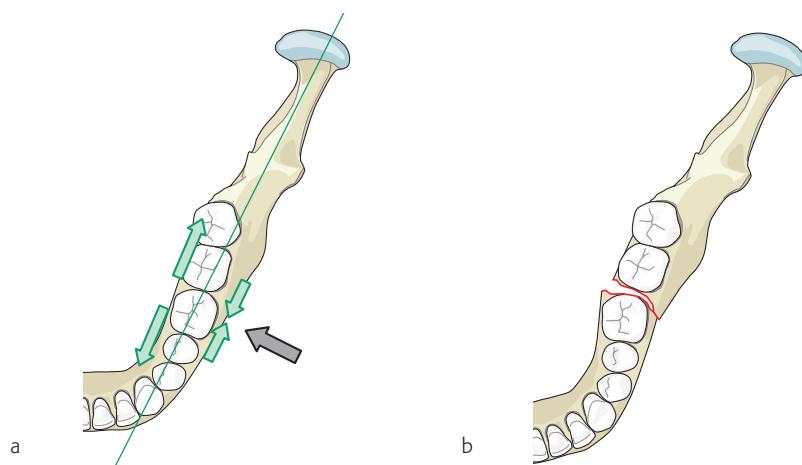


Fig 1.3.1-3a–b

- a As a result of lateral forces acting against the mandible the compression zone is lateral and the tension area is medial.
- b Fracture dislocation as a result of forces acting from the lateral aspect against the mandible.

The biomechanical behavior of the mandible has been studied using finite element analysis (FEA). These studies confirm that areas of compressive, tensile, shear, and neutral forces dynamically change with the load vector and the absolute amount of load (**Fig 1.3.1-4a–c**).

An osteosynthesis must be performed with devices of the appropriate size and placed in such a way that the physiological forces are distributed in a manner consistent with the normal patterns of strain.

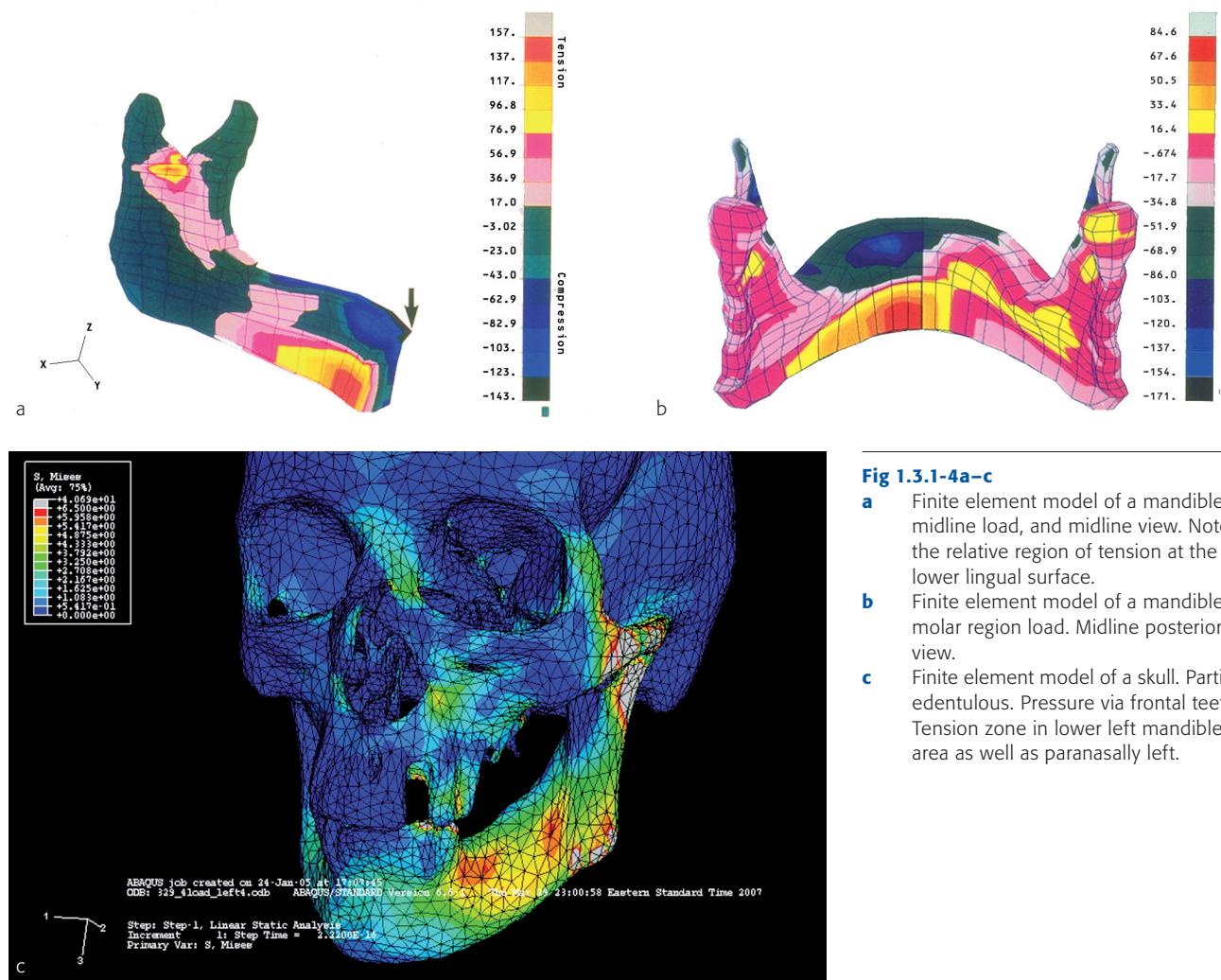


Fig 1.3.1-4a–c

- a** Finite element model of a mandible, midline load, and midline view. Note the relative region of tension at the lower lingual surface.
- b** Finite element model of a mandible, molar region load. Midline posterior view.
- c** Finite element model of a skull. Partially edentulous. Pressure via frontal teeth. Tension zone in lower left mandible area as well as paranasally left.

1.3.1 Biomechanics of the craniomaxillofacial skeleton

The mandible consists mainly of solid bone. The midface includes both, shell-like thin bones and stronger vertical and horizontal buttresses surrounding the orbits, the nasal cavity, and the paranasal sinuses.

Located within this complex compartmental system are several buttresses which can tolerate higher forces (**Fig 1.3.1-5**).

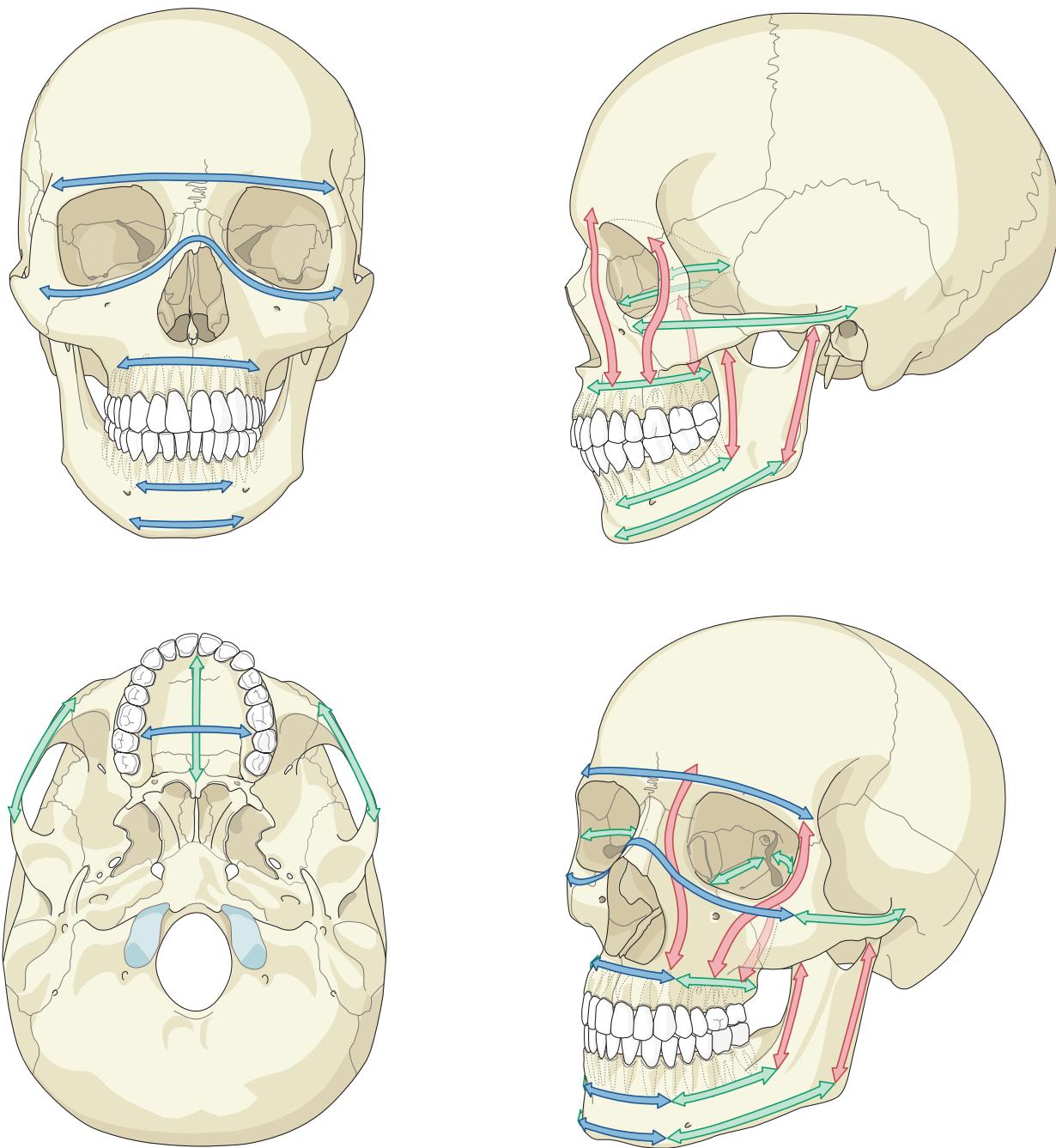


Fig 1.3.1-5 Transversal (blue), vertical (red), and sagittal (green) buttresses of the facial skeleton.

2 Mandible biomechanics in detail

- The mandible displays behavior consistent with a curved beam supported by a sling at each end (muscles).
- The load surface (superior surface) functions as the contact point with the midface (teeth, dentures).
- Load points vary in location from posterior to midline to posterior (contralateral) and, being consistent with natural physics, the locations of stress (tension and compression) vary depending on the load (bite) location.
- There is no muscle (dynamic) support at the midline during loading. Functional loads in this immediate region develop primarily compressive stresses at the upper margin and tensile stresses at the lower margin.
- The geometry of the mandible, being consistent with curved beams, develops the majority of stress at any load site at the superior and inferior margin of the structure. When structural bone is separated by injury (eg, fracture, osteotomy), devices used to restore geometry are most efficient in functional support when placed in areas of maximal tensile natural stress. Stresses are typically minimized at the mid-section of a curved suspended beam (neutral zone) depending on the load pattern. Increased stress develops in tension or compression zones.
- However, because the change between compression and tensile zones occurs rapidly during function, the placement of osteosynthesis material in the so-called neutral zone is an established technique, especially to treat fractures in the lateral body of the mandible, and is often very effective because the “neutral zone” is mislabelled and is not “neutral.”
- Devices used to repair a damaged mandible will have the most predictable long-term observable results if, following application, the original pre-injury stress distribution is re-established. Devices, regardless of size (strength, stability), that significantly alter the stress patterns may present with failure. Biology also requires that a fracture site has a “quiet” environment for cellular healing (lack of disruptive motion).
- Areas of the mandible (mid-body) that have experienced fracture and plate application for repair will experience alternating stresses depending on bite location. Loads posterior to the fracture site will result in compression at the superior margin at the fracture site and tension at the inferior margin. Loads anterior to the site will lead to the opposite stress patterns. Only as healing progresses can tensile stresses be conveyed at the fracture area. Compressive stress, however, can present by contact of the fracture segments.

3 Midface biomechanics in detail

Midface biomechanics are less understood due to significantly more complicated geometry and loading conditions. However, basic tenants of mechanics must apply.

- The midface occlusal surfaces experience load conditions of equal magnitude and opposite direction to those of the mandible.
- The areas of the structure which are the stiffest due to material properties and geometry have the lowest probability of deformation when loaded and experience the greatest forces during function. In the midface, medial and lateral vertical components of the maxilla and zygoma (medial and lateral buttresses by convention) support force flow preferentially through these structures during load application at the occlusal surface.
- Soft-tissue contraction of the masseter sling (muscle groups) develops equal forces at the origin and insertion with stresses distributed differentially due to significant differences in geometry of the midface and mandible.
- Soft-tissue attachments including fascia contribute to overall stability of components (ie, temporal fascia), and, when damaged during injury or repair, will alter stress distributions of local structures.

4 Repair of structures

- Systems that most accurately re-establish the uninjured state (including geometry and material properties) and result in the least damage to biological structures and mechanisms will be most predictable in observable outcomes.
- Damage to a system may occur with repair techniques least sensitive to the contributions of soft tissue (blood supply) for function and cellular healing.

When treating a fracture, it should be understood that bone and the material for osteosynthesis build a complex interacting system. The stability of an osteosynthesis is not only dependent on the size of a plate or screw but also on its placement, material properties, application technique, and the condition of the bone (size, density, cellular orientation). Under favorable conditions and with proper device application, the bone serves as a buttress and provides a path for functional forces to act on each side of the fracture, developing strain patterns while remaining stable enough for mastication without failure and uneventful healing. The weaker the bone is, the less it can add to the stability of an

osteosynthesis construct. In this case the material used for osteosynthesis must be stronger (in essence must remain stable under functional loading while serving as a pathway for forces to develop patterns of strain).

The most predictable approach in repairing any dynamic and complex system is to create a solution that mimics the natural functional state and minimizes additional damage to the system when engaging in repair (respect the soft tissue, delicately apply devices that are consistent with the material requirement of the natural structure, and return force distribution to normal, allowing for uneventful healing).

1.3.2 Fracture and blood supply

A fracture disrupts not only the mechanical but also the biological continuity of bone. The circulatory situation after a fracture influences to a large extent the subsequent healing process, whereby the level at which circulation is disturbed has a major impact on the outcome. If afferent vessels are injured outside the bone, or if the fracture includes larger vessels like a nutrient artery, then main bone areas are compromised. In all cases intracortical vessels like those in Haversian and Volkmann canals are interrupted along the fracture plane. The intracortical circulation is a low-pressure system. Following injury, clotting occurs inside the interrupted vessels, which stops the bleeding. Moreover the inhibition of efflux leads to congestion, followed by further clotting. This leaves the fragment ends without proper blood

supply. If a reconnection to circulation is not gained within a few hours, the occlusion of vessels becomes irreversible and the osteocytes in the compromised bone undergo necrosis.

A functioning circulation is a prerequisite for a successful healing process. While vascular recovery occurs relatively fast in soft tissues, the situation is more complex inside bone, especially compact bone, because space for new vessels has first to be opened. After 2–3 weeks a recanalization of existing but thrombosed vascular pathways starts (**Fig 1.3.2-1**). The areas of dead bone are removed by osteoclastic activity, starting from the perfused bone and gradually entering the necrotic area along the reopened vascular canals (**Fig 1.3.2-2**), removing dead bone. New vessels follow the osteoclasts;

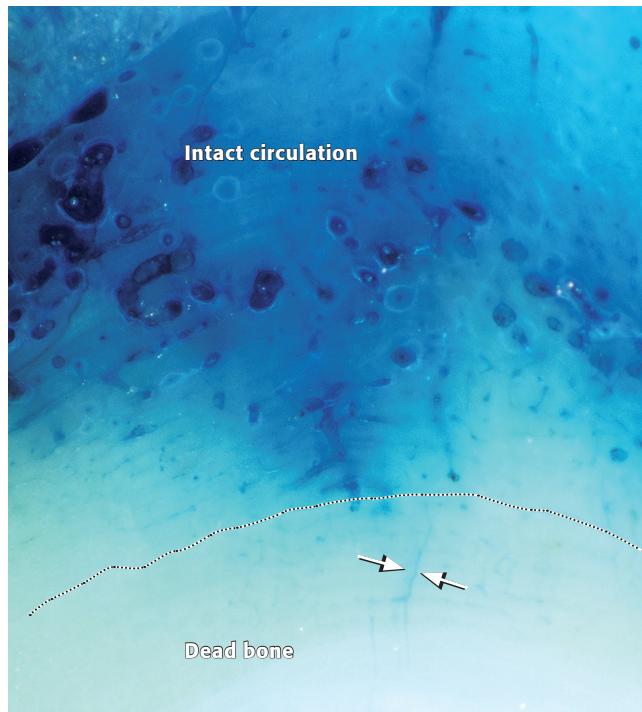


Fig 1.3.2-1 Disturbed perfusion of compact bone. The blue marker stains the region of intact circulation. At the border to the disturbed area (dotted line) the vessels regain access to circulation (arrows).

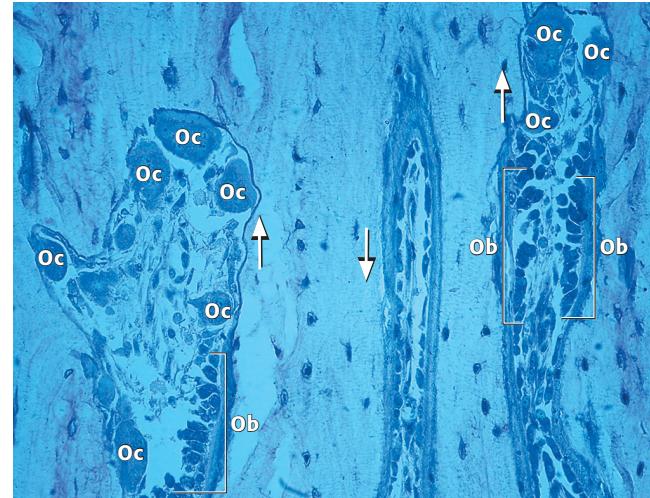


Fig 1.3.2-2 Intracortical remodeling in an area of disturbed perfusion. Osteoclasts (Oc) "drill" canals into the old bone, osteoblasts (Ob) fill these canals with new bone. Arrows indicate direction of osteon growth.