COMPUTER-GUIDED APPLICATIONS

for Dental Implants, Bone Grafting, and Reconstructive Surgery

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To my wife Cristina, my son, Francesco,
and to my daughter, Chiara.
Marco Rinaldi

To my son, Giovanni.
Angelo Mottola

For their endless support and understanding
To my wife Sabrina, daughters Michelle, Samantha, Jacquelyn, and granddaughter, Jayden.
To my parents, Joseph and May.
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PREFACE

When patients present for treatment of missing teeth, often clinicians are under the illusion that dental implants are always the best treatment option regardless of the amount of existing bone.

Imagine if your dental practice was set in the world of Lilliput and you had to treat oversized patients like Mr. Gulliver. You would immediately realize that it would be impossible to place implants because of the substantial anatomical obstacles.

The foundation and philosophy of this textbook is to provide clinicians with sound strategies and protocols for the diagnosis, assessment, and successful treatment of patients who present with minimal and major anatomical obstacles. Clinical cases have been documented with sequential images and video footage to illustrate important concepts and the rationale for the prescribed treatment. It is not the purpose of this book to underscore the merits of dental implants as a treatment modality, nor to mandate particular types, diameter, length, or number of implants required to complete each case, because this will ultimately be the decision of the clinician. However, we have made every effort to explain the rationale and decision choices for the treatment rendered based on one underlying question that faces the clinician every day, "Is there enough bone?"

Today, unlike in the past, the supply of dental implants varies greatly from very short to very long, very narrow to very wide diameters, and with many different physical characteristics that separate the myriad of manufacturers' product lines. Therefore the estimation of the bone quantity necessary to insert an implant has been long conditioned by the industry in that the volumes considered to be minimal or maximal were those able to accommodate the implants that were produced. Nevertheless, even for the narrowest diameter implants, there are cases in which the bone volume is insufficient. Therefore there are potential implant receptor sites that do not offer sufficient bone volume to place an implant and represent an obstacle to treatment. This scenario describes very common anatomical realities that can best be visualized using three-dimensional imaging modalities represented by computed tomography (CT) and the lower radiation dose cone beam CT (CBCT) devices.

Although the dental implant literature describes classifications of bone in a general sense, there often is no direct path from the diagnosis to the therapeutic choices to offer our patients. When faced with the anatomical obstacle of insufficient bone, which would preclude the placement of dental implants, what treatment options remain for the patient? The purpose of this textbook will be to describe in detail two possible solutions to the problem: (1) "remove" the obstacle or (2) "avoid" the obstacle.

When there is insufficient bone volume, removing the obstacle requires rehabilitation of the receptor site by rebuilding the lost bone. Various types of bone grafting modalities have been shown to be the most predictable reconstructive approach, offering the highest guarantee of success. Minor defects often can be satisfactorily treated with particulate bone grafts and guided bone regeneration before or simultaneous with implant placement. However, major volumetric defects present a challenge because of the availability of intraoral donor sites capable of providing the sufficient amount of bone required to rehabilitate the site(s). Therefore in many cases, it may be necessary to use extraoral donor sites that require general anesthesia, increase trauma and patient morbidity, and increase treatment duration and the costs of the procedures. In addition, we must consider the risks and benefits of the suggested reconstructive therapy based on the age and general health of our patients.

Avoiding an anatomical obstacle can provide additional treatment alternatives that are less invasive and traumatic. The dental implant literature has reported the successful use of endosseous implants that are placed off-angle or placed in particular locations to avoid vital anatomical structures such as the maxillary sinuses or the mental foramina. These solutions include the pterygomaxillary implants performed by Jean F. Tulasne (1992), the use of zygomatic fixtures designed by Brånemark and as suggested by Paul Tessier (1989), the remote anchorage reported by Parel (2001), and the use of tilted implants reported by Krekmanov (2000), Aparicio (2001), and Malo (2003). In clinical practice, we often encounter patients who, for various reasons, had to give up complex bone reconstructions, so the use of angled implants seemed to provide less traumatic, less expensive, and faster solutions. However, placing tilted implants is anything but easy, especially when precision is required near vital anatomical structures.

It is difficult to plan an angled implant using standard diagnostic techniques. Orthopantomography offers only an overview but does not allow precise measurements because of inherent distortion. CT and CBCT dental scans reveal the third dimension through volumetric reconstructions, combined with the cross-sectional slices or vertical cuts, in a true, undistorted 1:1 ratio for accurate measurements. We can superimpose an implant template on these images only if it is vertical with respect to the occlusal plane (parallel to the section). An angled implant involves more than one cross-section, and therefore it is difficult to fully appreciate the path of the proposed implant without advanced interactive software applications. During the surgical procedure, using a full-thickness flap and direct vision still does not provide adequate assessment of deep structures. Therefore, in our experience with a "freehand" approach of placing these implants, we determined that it was at best an "approximate surgery" and thus considered undesirable for the precision that we required.

We therefore sought a solution using the diagnostic capabilities offered through CT and CBCT combined with advanced interactive treatment planning software

applications that would allow precise simulated placement of the implants. Today, it is possible to perform virtual surgery on the computer and then transfer this plan to clinical reality through the fabrication of stereolithographic resin models and a series of surgical guides, produced by specialized manufacturers. Computer-guided surgery can provide accurate and predictable solutions to our many cases through advanced diagnostic software and planning tools and incorporation of physical templates, specialized drills, and associated surgical instrumentation. Although most applications of this technology have been limited to implant placement, it was our desire to use these advanced tools for improved control of our bone grafting procedures.

The new digital workflow was incorporated into the variety of bone-grafting reconstructions through the use of stereolithographic models and surgical guides. We developed protocols for assessment of receptor and donor graft sites, including sinus augmentation procedures and the use of surgical guides to assist in the process, increasing accuracy and reducing patient morbidity.

Presently, all surgical procedures are planned on the resin biological model of the maxilla or mandible, fabricated from the CT scan data, before touching the scalpel to the patient. We cannot imagine performing surgery without these technologically advanced aids.

We strongly believe that computer-aided surgery is highly beneficial for cases in which we need to avoid anatomical obstacles and for cases in which we want to reconstruct deficient bone anatomy. It is also our opinion that computer-guided surgery, among the topics related to implant surgery, is the one most oriented to the future of our profession through these innovative applications of rapid prototyping techniques. These technologies are already in use in neurosurgery, used for cranioplasties, and in orthopedics for the fabrication of three-dimensional prototypes of missing bone structures. The potential application to reconstructive dental implantology through three-dimensional stereolithography and three-dimensional printing to produce replicas of the jaws will greatly improve diagnostic and therapeutic procedures.

Perhaps one aspect of computer-guided surgical procedures is use of the diagnostic information to inform our patients of their treatment alternatives and as a communication tool for all members of the implant team. Often, following a single diagnosis, different treatment plans may be proposed to a patient that may be difficult to comprehend. Bone grafting is advised only to create a foundation for later or simultaneous implant placement and prosthetic reconstruction. The three-dimensional images shown on the computer screen allow a clear depiction of the patient's individual anatomy and the recommended treatment in a simulated visual environment that is easier for the patient to understand. Additionally, it is therefore possible to help plan both the surgical intervention and the prosthetic outcome, providing for true "restoratively driven" implant reconstruction. The educated patient can then have an indisputably central role in the choice of the treatment. Therefore the three-dimensional views and the simulations with computer-generated images have an important communicative and medical-legal function, allowing for a positive doctor–patient relationship.

The first part of the book provides the basic rationale and principles of surgical techniques that are depicted in the second part, entirely devoted to clinical cases. In cooperation with the colleagues of the Anatomical School of the University of Bologna, we described the main anatomical obstacles to implant placement. Using dry skulls and cadavers, we performed and illustrated the most common surgical mistakes that can cause complications or serious injury to the patient. We think current techniques allow for the successful rehabilitation of the posterior maxilla, and we offer new concepts to enhance the surgical approach for sinus augmentation procedures considered obstacles for implant placement. Therefore we have included a chapter dedicated to the maxillary sinus, written by two otolaryngologists, who reviewed the pathophysiology of this region that can affect clinical treatment alternatives.

The evaluation of general health and the anesthetic management of patients are detailed in a chapter written by two anesthetists. The patient's state of health and the choice of anesthesia can strongly influence the clinical intervention (invasive or noninvasive surgery) and recommended therapeutic possibilities. The clinical cases presented in the book illustrate how to overcome the anatomical obstacles using a variety of different techniques, including minimally invasive flapless surgery, graftless surgery, use of tilted implants to avoid vital anatomical structures, and bone graft surgery with small and large grafts. Basic outpatient cases are documented, as well as more complex cases that necessitated general anesthesia and hospitalization. For each clinical case, we provided the preexisting medical condition and intraoral presentation, preoperative diagnostic considerations, surgical procedures with the most relevant technical steps, postoperative considerations, and photographs. In addition, designated clinical cases have been documented in entirety on video and can be found on the book's website at **www.rinaldidentalimplants.com.**

We hope that you will find the information provided within the various chapters to be thought provoking, and useful to your everyday practice. We wish you good reading and an enhanced vision for your future cases.

Remember, as Dr. Ganz states: "*There is a danger when we are bound by two-dimensional concepts when clearly we live in a three-dimensional world.*"

Marco Rinaldi
Scott D. Ganz
Angelo Mottola

CHAPTER 1

Anatomical Obstacles to the Insertion of Implants

Giovanni Mazzotti† and Alessandra Ruggeri

PLASTICITY OF BONE

Successful dental implantology implies specific knowledge of the maxillomandibular complex, combined with essential surgical and restorative skills. The diagnostic phase first requires appreciation of the patient's unique vital anatomical structures, which include blood vessels, nerves, and facial and muscle planes. Second, each potential implant receptor site must be evaluated based on the existing structure of the cortical and cancellous bone. The ability to assess individual bony anatomy has increased exponentially with the advent of three-dimensional imaging modalities, computed tomography (CT), cone beam CT (CBCT), the increase in power of today's personal desktop and laptop computers, and sophisticated interactive treatment planning software.

These software applications allow the clinician to perform in-depth diagnostic analysis and evaluation of highly accurate three-dimensional images processed in all planes of space quickly and cost effectively. However, to fully appreciate the diagnostic findings it is important to understand the nature of bone.

Bone is one of the most plastic tissues in human body. Its shape and structure can change in relation to numerous parameters such as load, age, physical activity, hormonal metabolism, diet, and environmental factors. As early as the second half of the seventeenth century, Galileo Galilei described the correlation between body weight and characteristics of bone size or how mechanical load affects bone biology. These observations were developed over the years by various authors who sought to further correlate changes in shape or structure with specific determinants. Clinical and experimental evidence has shown that pressure is a critical factor affecting the compactness of bone tissue. From a mechanical perspective, muscle contraction is the main determinant for the pressure stimulus, even in bones subjected to loading. In the upright position, for example, mechanical load of body weight on the hip joint is increased by muscle contraction of a factor up to six times higher in more intensive efforts. The opposite was observed in space flights, in which, in total absence of gravity, even after a few days, a significant decrease occurs in bone tissue, of both bone matrix and mineral component. This decrease was more prominent in bones of the lower limbs and the trunk. These conditions are only partially reversible after return to Earth if the period spent in the absence of gravity is greater than 3 months.

The mechanism of action that allows bone remodeling in relation to mechanical load and the work of the muscular component is not yet fully understood. Currently, the most accredited hypothesis refers to the ability of bone tissue, and particularly of the organic matrix, to generate electrical signals under load. In a bone subjected to mechanical loading, the part under the compressive effect becomes negatively charged and bone deposition occurs, whereas the part subjected to tensile stress becomes positively charged and bone resorption is observed.Experimental models also support this hypothesis, showing that, under the application of an electric current, bone deposition is observed at the cathode and resorption at the anode. These processes interact with the constant dynamic of bone tissue remodelling, in which the destruction and reconstruction of osteons occurs systematically and continuously at all stages of life.

On the other hand, it is not possible to predetermine the density of bone in different areas without instrumental analysis. Bone density, in fact, can vary not only for metabolic or dietary factors, as previously mentioned, but also for the occlusal load and the tone of the masticatory muscles, occlusion, and posture. In dental implantology these concepts can be applied to the biology of the bone–implant interface and to its response to masticatory loads. For any designated implant receptor site an accurate evaluation of bone tissue must be performed. Many classifications of bone density have been described since the dawn of modern implantology, such as that by Linkow (1970), who defined three bone structures based on the shape of the trabecular pattern and the size of the bone lacunae. The classification by Lekholm, Zarb, and Albrektsson (1985) distinguished among four bone types based on the proportion of cortical and cancellous components. The Misch-Judy classification also distinguished four classes (D1-D4) of bone density (and a fifth class, relating to immature bone).

Refinement of these four classifications in four points also has been proposed as follows:

1. Solely or mainly compact bone
2. Thick layer of compact bone surrounding a central region, with structural trabecular mesh very tight
3. Thin layer of compact bone surrounding the middle, with trabeculae still very dense
4. Thin cortical layer of compact bone enclosing a central portion with sparse trabeculae and large mesh (de Oliveira 2008)

†Deceased.

With the advent of CT imaging, technology helped define bone density based on relative values of the grayscale values within each CT scan. The units of measurement that determine bone density using medical grade CT has been termed Hounsfield units. Therefore an additional parameter of bone classification has been described in the literature (Norton, 2001).

DISTRIBUTION OF MASTICATORY LOADS IN THE SKULL

Forces of mastication are distributed within the skull along specific directions. The mandible is a separate and movable bone that transmits load to the maxilla, which is a fixed part of the skull.

Observed from the front, the maxilla has two processes: one medial to the frontal process and one lateral to the zygomatic process. The zygomatic bone is small in size, but structurally it is extremely robust because of its characteristic function and consists entirely of compact bone. From a functional point of view, it is a real keystone for the distribution of loads. It connects the maxillary bones superiorly with the frontal bone, medially with the sphenoid greater wing, and posteriorly with the zygomatic process of the temporal bone.

Forces are distributed along specific planes (Fig. 1.1)—a frontal plane through which the forces, on each side, medially through the frontal process of maxilla and laterally through the zygomatic process with the zygomatic bone and frontal process, close together around the orbital arch (see Fig. 1.1a). The orbital contour is composed of the supraorbital margin of the frontal bone, the infraorbital edge of the maxilla, medially the maxillary frontal process, and laterally the zygomatic bone. Indeed, the whole anterior orbital circumference is the first area of force distribution.

The zygomatic bone meets the zygomatic process of the temporal bone posteriorly, forming the zygomatic arch. Two distinct roots can be identified in the zygomatic process of temporal bone: a transverse root represented by the articular tubercle, which is part of the temporomandibular joint, and a longitudinal one posteriorly.The longitudinal root first goes posteriorly to the squame surface, slightly prominent like a delicate bas-relief. Once reaching the anterior surface of the mastoid process, the relief appearance continues with the inferior temporal line of the parietal bone.

Temporal lines give insertion to most of the temporal muscle; in particular, the inferior line provides insertion to the posterosuperior muscle bundles, and the upper provides insertion to the temporal fascia. Anteriorly, the temporal lines of the parietal bone converge toward the temporal line, the sturdy vertical pillar that separates the anterior surface of the frontal bone from its lateral aspect, where it takes part in forming the temporal fossa.

On the lateral surface of the skull is an elliptical region that, starting from the zygomatic bone, continues with the zygomatic process and extends to the squama of the temporal bone. This, in turn, is connected with the temporal lines of the parietal bone, which converge on the orbital process of frontal bone. The latter, articulating with the upper corner

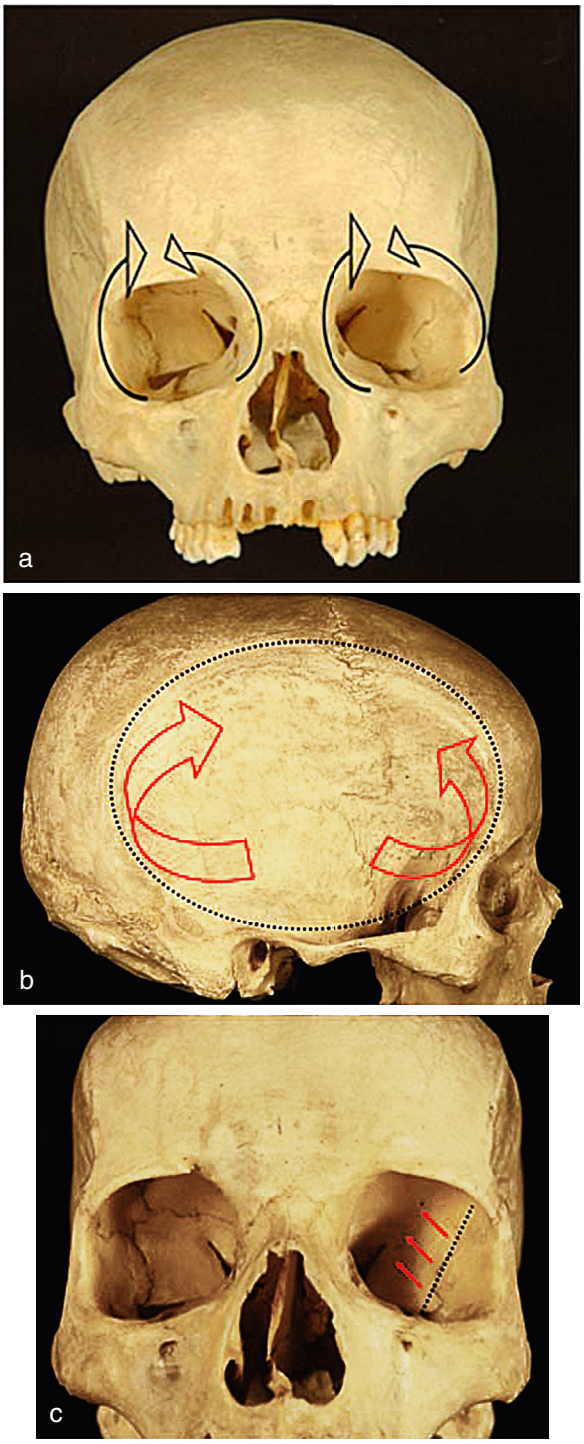

Figure 1.1 Distribution of masticatory loads in the skull. (a) Skull in the frontal plane. The lines of force, through the maxillary frontal process and zygomatic bone, end, as indicated by the *arrows*, on the anterior margin of the orbital cavity. (b) Skull, lateral aspect. Laterally, the lines of force form an ellipse; starting from the zygomatic bone they go upward and posteriorly to the zygomatic arch, ending on the temporal lines of the parietal bone, thus delimiting the insertion area of the temporal muscle *(dotted line)*. (c) Skull in the frontal plane. Posteromedially, on the lateral wall of the orbital cavity, the zygomatic bone articulates with the anterior margin of the great wing of the sphenoid, transmitting the lines of force, as indicated by the *arrows*, to the skull base.

of the zygomatic bone in the frontozygomatic suture, constitutes the temporal line.

The lines of force transmitted posteriorly from the zygomatic bone converge on this elliptical surface (see Fig. 1.1b). The upper portion of the temporal muscle extends on the whole surface, inserting onto the temporal surface of the zygomatic and frontal bones, the esocranic surface of the great wing of the sphenoid, facing the temporal fossa, the parietal bone, and the squama of temporal bone. The temporal muscle, inserted with its tendon onto the coronoid process of mandible, shows how the entire skull—neurocranium and splanchnocranium—is involved in the distribution of masticatory loads. The distribution of lines of force on the lateral aspect of the neurocranium reinforces this region in terms of bone compactness, and it is on this surface that the most powerful of masticatory muscles inserts.

In many animals, especially carnivores, the temporal muscle covers the entire lateral surface of the skull, inserting into a median bone crest, which characterizes the sagittal suture. This is one of the evidences supporting the thesis that the skull is an endoskeleton and not an exoskeleton.

The third trajectory of lines of force distribution across the zygomatic bone passes through the orbital process, which delimits anteriorly the lower and the lateral wall of the orbit (see Fig. 1.1c). The vertical portion of the orbital process articulates with the anterior margin of the great wing of the sphenoid bone and marks the anterior limit of the inferior orbital fissure. Through the great wing, the lines of force head to the body of the sphenoid bone and converge with those contralateral. The zygomatic bone is therefore the main structure responsible for the distribution of the masticatory loading.

The resulting compact structure lends itself very well to supporting the placement of dental implants. The only structure that could be damaged is the zygomatic nerve. Once the nerve enters the thickness of the bone, it divides into two nerves, the facial zygomatic and temporal zygomatic, for the innervation of the skin of the zygomatic region.

The zygomatic nerve also carries excitatory secretory fibers for the lacrimal gland, derived from the sphenopalatine ganglion. These fibers, however, anastomosing with the lacrimal nerve, come off in the posterior part of the orbital cavity before the orbital surface of the zygomatic bone.

The pterygoid process of the sphenoid bone consists of two laminae whose anterior margins join together defining posteriorly a V-shaped cavity—the pterygoid fossa, which gives insertion to the medial pterygoid muscle. The lateral pterygoid muscle, instead, originates from the external face of the lateral process and the infratemporal surface of the sphenoid great wing.

The base of the pterygoid process comes off from the sphenoid body with two roots: a smaller medial one and a more robust lateral one, which is attached to the point where the great wing continues with the body. Above, between the two roots and under the sphenoid body, the pterygoid canal (also called the vidian canal) runs sagittally. The anterior edges of two blades, fused together, delimit posteriorly the pterygopalatine fossa. Inferiorly, this anterior edge converges and joins the maxillary tuberosity. Finally, lower, the two laminae split and the pyramidal process of palatine bone inserts between them. The region of the convergence of the maxillary tuberosity, the pterygoid process, and the pyramidal process of the palatine bone is mainly composed of compact bone and can support dental implants. However, it must be noted that just medial to this site, in the palate, are located the posterior palatine foramen and the greater palatine canal (or pterygopalatine canal), containing the anterior palatine nerves and the descending palatine artery, which after leaving the palatine canal becomes the greater palatine artery. The size of the pterygoid process is extremely variable in thickness, height, and depth. Its development and the final conformation appear to be directly related to the size of the medial pterygoid muscle.

This is a further demonstration of the relationship between muscle activity and bone development.

ANATOMICAL PROBLEMS AND CONSEQUENCES OF EDENTULISM

Infratemporal Fossa

The infratemporal fossa, also known as infratemporal or zygomatic region, is a space normally not explorable because it is medial to the mandibular branch. The infratemporal fossa communicates frontally with the tuberosity of the maxillary bone, superiorly with the temporal region, posteriorly with the parotid lodge, medially with the pterygopalatine fossa, and inferiorly with the pharynx (Fig. 1.2). Communication with these regions is important for the spread of inflammatory processes and effusions or tumors that may expand into the infratemporal fossa from the orbit or nasal cavities. Its shape is somewhat irregular but could be compared to an inverted square-based pyramid.

The sides of this pyramid are then referred to as anterior, posterior, lateral, and medial walls. The front wall is constituted by the larger and most lateral side of the maxillary tuberosity.

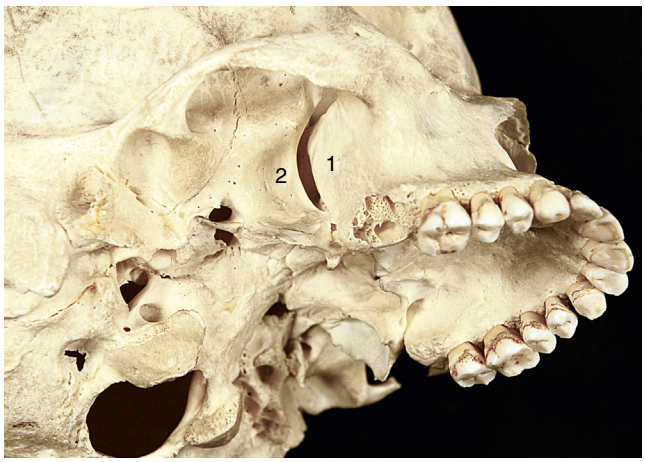

Figure 1.2 Skull, lateral aspect, detail of pterygopalatine fossa. *Point 1* indicates the anterior wall, corresponding to the tuberosity of the maxillary bone. *Point 2* marks the posterior wall, corresponding to the front surface of the pterygoid process of the sphenoid.

The back wall is represented by the anterior aspect of the parotid region. The lateral wall is largely defined by the zygomatic arch and the mandibular branch, which indeed represents the bone barrier for access to the fossa. The medial wall continues in depth with the pterygopalatine fossa. The boundary between the two regions is just conventional and can be identified as a paramedian sagittal plane that extends from the outer surface of the lateral lamina of the pterygoid process to the tuberosity of the maxillary bone.

The portion of the maxillary tuberosity located laterally to this plane belongs to the infratemporal fossa; the one located medially belongs to the pterygopalatine fossa. The medial side of the upper wall, or base, is constituted by the infratemporal surface of the great wing of the sphenoid. This horizontal surface, with mediolateral course, is separated from the infratemporal crest by the lateral aspect of the great wing, which has a vertical course and contributes to delimit medially the temporal fossa. More laterally, the upper wall extends along a plane running from the infratemporal crest to the zygomatic arch. The vertex of the infratemporal fossa reaches the insertion of the medial pterygoid muscle to the mandibular angle. It contains the following:

- Two pterygoid muscles, medial and lateral
- Internal maxillary artery
- Mandibular nerve

The internal maxillary artery and superficial temporal artery are the terminal branches of the external carotid artery. The division into the two branches occurs in the parotid lodge, right in the thick of the parotid gland. The internal maxillary artery is 4 to 5 cm long, and travels forward, upward, and medially with a very tortuous course. Its origin is located approximately 2 cm from the base of the skull, and its first part surrounds the medial aspect of the neck of the mandibular condyle. This proximity represents the most relevant risk when performing the resection of the mandibular condyle. In its brief course, the internal maxillary artery gives origin to approximately 14 branches, and the terminal branch is represented by the sphenopalatine artery.

Among the collateral branches, in addition to the muscular and meningeal ones, it is important to recognize the following:

- Inferior alveolar artery, first descending branch, enters the mandibular canal.
- Superior posterior alveolar artery branches off anteriorly and, through the maxillary tuberosity, reaches the maxillary sinus and the upper molars.
- Descending palatine artery, which enters the pterygopalatine canal; veins of the infratemporal fossa form two widely anastomosed plexuses.
- A more anterior alveolar plexus, originating from venules that cross the tuberosity of the maxilla. This extensively anastomosed plexus continues anteriorly with the posterosuperior alveolar vein, which merges into the facial vein, and posteriorly with the internal maxillary vein.
- A pterygoid plexus, more posterior, which is bordered medially by the base of the pterygoid process and laterally by the pterygoid muscles. This plexus continues with the internal maxillary vein, which joins the superficial temporal vein, continuing with the external jugular vein.

Venous plexuses of the infratemporal fossa also contract anastomoses with the intracranial venous sinuses through the meningeal veins and venous plexuses, which accompany the maxillary and mandibular nerves on exiting the skull. The mandibular nerve is the only mixed nerve of the three branches of the trigeminal nerve. It is joined by the motor root that originated from the neurons of the masticatory nucleus. The nerve has an intracranial portion and an extracranial portion. The intracranial segment is very short, approximately 1 cm, and goes from the Gasser ganglion to the oval foramen. The extracranial segment exits the skull through the oval foramen and, from the inferior surface of the sphenoid great wing, descends directly into the infratemporal fossa, medially to the lateral pterygoid muscle and laterally to the auditory tube.

Immediately after coming out of the foramen, the mandibular nerve gives origin to various branches, particularly muscle nerves, then inferiorly, after a course of 4 cm, it divides into two large terminal branches: the lingual nerve and the inferior alveolar nerve. Initially, the two nerves course close to each other, first between the two pterygoid muscles and then between the medial pterygoid nerve and ramus of the mandible. Finally, the lingual nerve runs under the mouth floor mucosa, reaching the apex of the tongue, and the inferior alveolar nerve enters the mandibular alveolar canal.

The mandibular nerve, the internal maxillary artery, and their branches course through the infratemporal fossa surrounded by loose connective that allows movement if they come in contact with space-occupying bodies or masses.

The Pterygopalatine Fossa

The pterygopalatine fossa belongs to the deep region of the face. It is a region normally explorable only after removal or demolition of many anatomical structures. In fact, it is located medially, and then more deeply than the infratemporal or zygomatic region, so that it is regarded by many authors as the most medial and deep portion of the infratemporal fossa. Because of the importance of the anatomical structures that pass through it and for a better definition of its limits, it is more useful to consider it as a region in itself. The pterygopalatine fossa can be assimilated to an inverted square-based pyramid. Its size varies depending on the development of the maxillary and sphenoid sinuses and is approximately 2 cm in height and 1 cm at the base. Its borders are then defined by a base, a vertex, and four walls: anterior, posterior, lateral, and medial (see Fig. 1.2). The base is bounded by the underside of the body of the sphenoid bone at the level of the sphenoid sinus, which, in fact, constitutes the vault of the region. More laterally and anteriorly, the base of the pterygopalatine fossa continues with the lower orbital fissure, anteriorly delimited by the posterior edge of the orbital floor, belonging to the maxillary bone, and posteriorly by the inferior edge of the sphenoid greater wing. The anterior wall corresponds to

the tuberosity of the maxillary bone. In particular, the most medial part of the tuberosity belongs to the pterygopalatine fossa and the lateral part is located in the infratemporal fossa. The portion belonging to the pterygopalatine fossa has two or three posterior holes for the passage of posterior alveolar nerves and arteries. The posterior wall is constituted by the anterior surface of the pterygoid process.

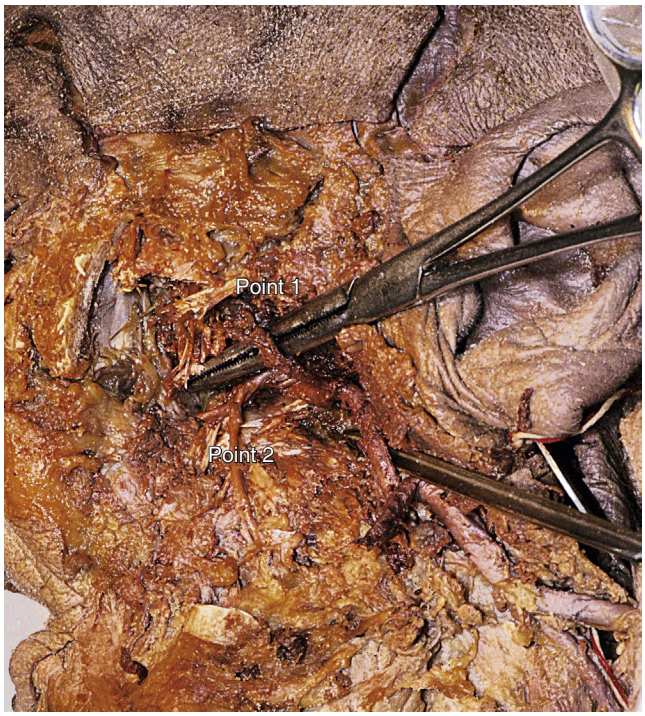

Figure 1.3 Cadaver dissection, detail of the pterygopalatine fossa region and the first portion of the internal maxillary artery with its bifurcation. *Point 1* indicates the course of the internal maxillary artery, which deepens in the medial portion of the pterygopalatine fossa after bifurcation. *Point 2* indicates the collateral branch that turns down, corresponding to the mandibular artery.

The round foramen, crossed by the maxillary nerve, is located where the pterygoid process continues with the vault, and immediately below it is located the pterygoid canal, or Vidian nerve, for the transit of the homonymous nerve and artery. The medial wall is formed by the vertical plate of the palatine bone. Superiorly, the plate is divided into two processes bordering the sphenopalatine incisures. The anterior process is called orbital, because it contributes to define the orbital cavity posteriorly, while the posterior is the sphenoidal process, which articulates with the sphenoid bone.

The sphenopalatine incisure, meeting the body of the sphenoid bone, becomes the sphenopalatine foramen, which connects the pterygopalatine fossa with the corresponding nasal cavity, allowing the passage of sphenopalatine vessels and nerves. The lateral wall faces directly into the infratemporal fossa, and the boundary between the two regions is the imaginary plane already described for the medial wall of the infratemporal fossa. The apex of the pterygopalatine fossa is sited inferiorly and is formed by the meeting of the tuberosity of the maxilla with the pterygoid process and the lower portion of the vertical plate of the palatine bone. At this site, in adults, the three bones weld together forming an extremely robust bone buttress.

The pterygopalatine canal and the accessory palatine canals open medially to this region. The pterygopalate fossa, despite its small size, contains important vascular and nervous structures. The maxillary artery enters the pterygopalatine fossa and runs in close contact with the tuberosity of the maxilla, sometimes leaving a groove-shaped impression (Fig. 1.3). In the infratemporal fossa it gives origin to the descending palatine artery, which descends through the palatine canal, and continues with its terminal branch, which through the foramen reaches the oral cavity as the greater palatine artery. The location of these vital structures is important because they can be accidentally punctured during surgical procedures of bone harvesting or the insertion of implants in the region of the maxillary tuberosity (pterygomaxillary implants), resulting in potential complications (Fig. 1.4). The maxillary

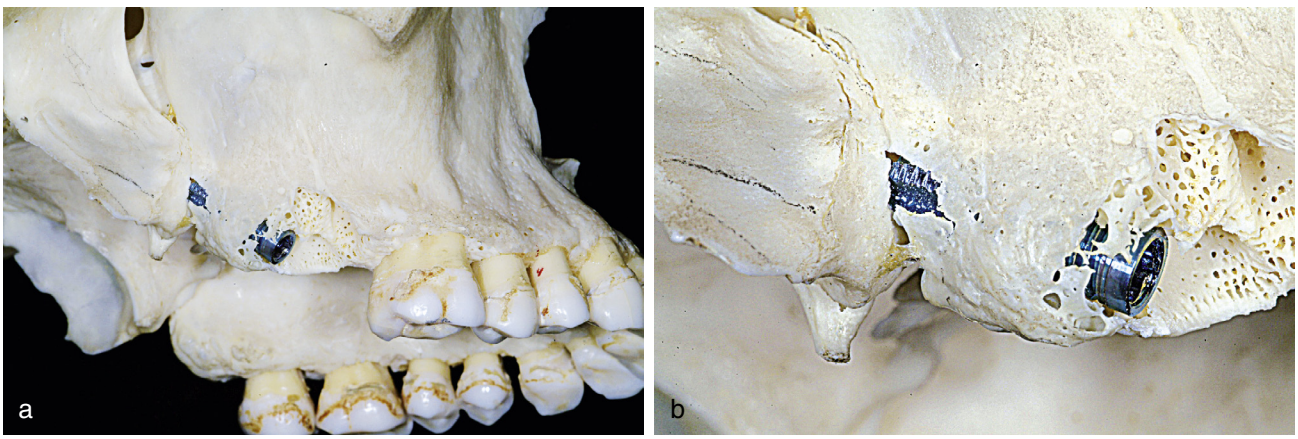

Figure 1.4 (a) Skull, lateral aspect. Detail of the pterygopalatine fossa. A dental pterygoid implant was inserted at the point of convergence of the maxillary tuberosity, pterygoid process, and pyramidal process of palatine bone. (b) Enlarged image. The welding of the three bones gives place to a robust buttress that ensures optimal implant stability.

nerve, after passing through the round foramen of the sphenoid bone, enters directly into the pterygopalatine fossa. It traverses anterolaterally and enters the inferior orbital fissure to reach the orbital floor, where at first it approximates the orbital groove and into the orbital canal to finally emerge with its terminal branch from the infraorbital foramen. In the pterygopalatine fossa, it gives origin to several branches: the middle meningeal nerve and the zygomatic nerve, which contains both sensory fibers to the skin of the zygomatic region, postganglionic parasympathetic fibers to the lacrimal gland, and three or four thin sphenopalatine nerves that connect it to the homonymous ganglion. It also gives origin to the posterior alveolar nerves, which through the maxillary tuberosity reach the upper molars, and the anterior alveolar nerve, which heads to the upper canines and incisors. Finally, the pterygopalatine fossa contains the pterygopalatine ganglion or sphenopalatine Meckel ganglion. This is an encephalic parasympathetic ganglion, approximately the size of a lentil, sited under the maxillary nerve and lateral to the sphenopalatine foramen.

The ganglion receives fibers from the vidian nerve, which contains sympathetic fibers, sensory and motor fibers to the elevator muscle of the soft palate and the muscle of uvula, and parasympathetic fibers from the facial nerve. All of these fibers only pass through it, unlike the parasympathetic ones, which terminate in the ganglion neurons. Various nerves emerge from the pterygopalatine ganglion, including the nasal posterosuperior and palatine nerves (Figs. 1.5 and 1.6).

Maxillary Sinus

The maxillary bone, the same as the other main bones of the face, is a pneumatic bone, containing within it the maxillary sinus, the largest of the cavities connected to the nasal cavities. The location, size, and topography of the maxillary sinus is the most common anatomical obstacle to the insertion of dental implants in the posterior maxillary regions. The natural postextraction atrophy process limits the availability of subsinusal alveolar bone both in vertical height and horizontal width. As a result of these limitations, many surgical techniques have been proposed to overcome this anatomical obstacle because it is often desired to replace the missing dentition in this region. Some methods aim to transform part of the empty sinus cavities with bone grafts into the sufficient new volume of bone required for the placement of implants (sinus augmentation). Other methods attempt to avoid involvement of the sinus cavities altogether, using implants placed in a tilted fashion anterior or posteriorly to the sinus (tilting implant) (Figs. 1.7 through 1.9).

The maxillary sinuses ostia are in communication with their corresponding nasal fossae through the hiatus that opens in the middle meatus (see Fig. 1.9). The maxillary sinuses, just approximately shaped at birth, acquire the final shape only after the growth of permanent teeth.

The cavity of the maxillary sinus, however, expands through the individual's entire life, because of processes of bone resorption, such as osteoporosis, and reduction of masticatory forces. The variability of the maxillary sinus is such that it cannot be ascribed a defined model, but must be assessed for each subject; the normal average volume is approximately 11 to 12 cm^3. Maxillary sinuses can have a volume as great as 25 to 30 cm^3 and tend to extend into the thickness of the surrounding bone, particularly, through the frontal process up to the medial margin of the orbit in the zygomatic and palatine bone. Even though very rare, very small maxillary sinuses are seen, with internal volumes of 2 to 3 cm^3. In this case, the bone walls are very thick and the teeth roots are quite far from the sinus cavity. Some sinuses contain internal septa or bone plates—generally incomplete—that delimit smaller cavities that may become points of collection for effusions. The presence of bony septa must be absolutely identified when a sinus augmentation procedure is planned. The presence of a bony septum can be an obstacle to the surgical procedures, but occasionally it can also be used favorably during sinus augmentation procedures (see Chapter 2). The specific and individual topography of the maxillary sinus cannot be adequately appreciated without the use of three-dimensional imaging modalities such as CT or CBCT. Therefore it is strongly recommended that for any procedure involving this region, three-dimensional imaging be used preoperatively to assess the involved sinus.

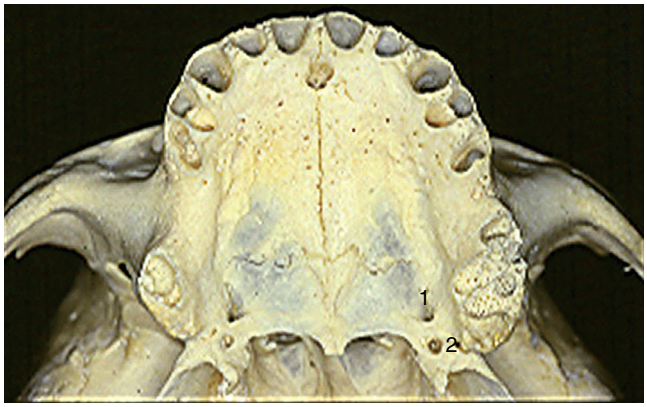

Figure 1.5 Skull showing the hard palate. *Point 1* indicates the greater palatine foramen. *Point 2* indicates the lesser palatine foramen.

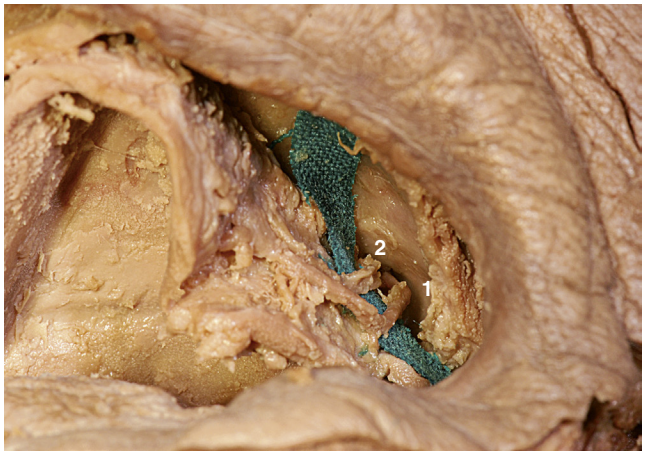

Figure 1.6 Cadaver dissection after elevation of the hard palate masticatory mucosa at the level of the greater palatine foramen. *Point 1* corresponds to the greater palatine artery, before its bifurcation. *Point 2* represents the greater palatine nerve.

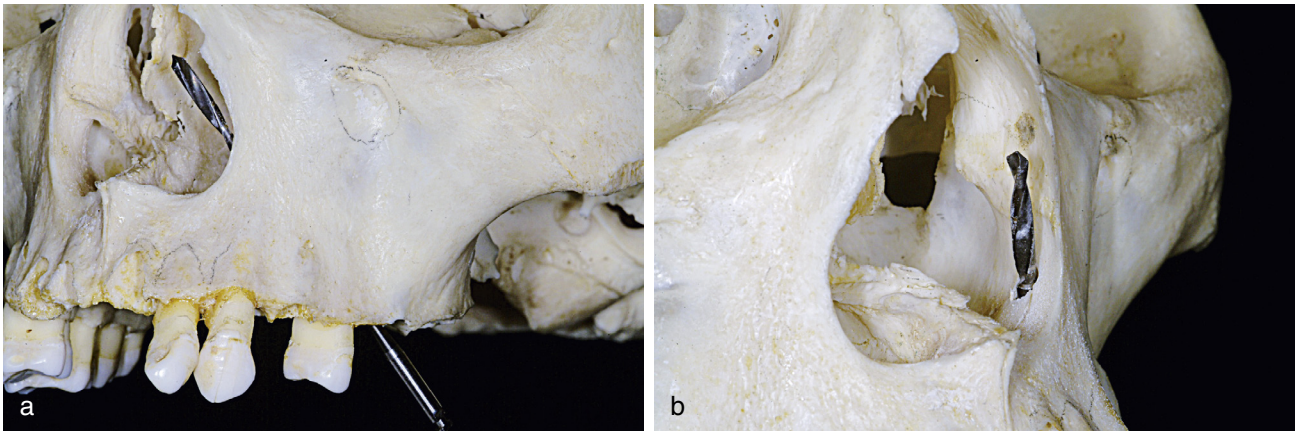

Figure 1.7 Skull in the frontal plane. (a) Detail of the superior alveolar process. (b) Bone was perforated in the premolar site to simulate the insertion of a tilted dental implant. The resulting risk is therefore the penetration of the drill in the nasal cavity.

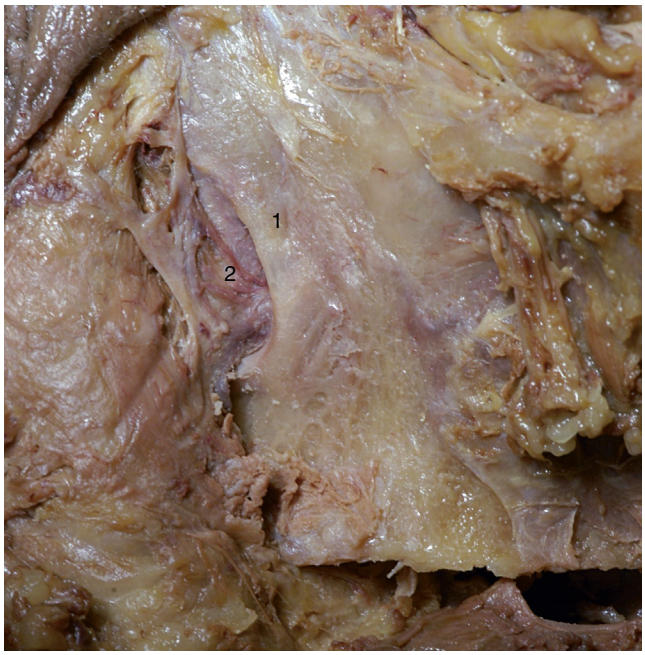

Figure 1.8 Cadaver dissection, detail of the frontal facial region. Enlargement of the anterior orifice of the nasal cavity, the pyriform cavity. *Point 1* indicates the bony margin of the pyriform aperture. *Point 2* shows the lining mucosa of the nasal cavity.

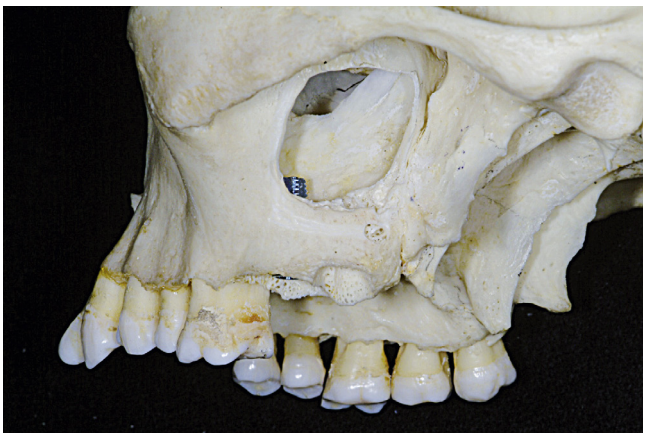

Figure 1.9 Skull, lateral aspect. Detail of the superior alveolar process and access to the maxillary sinus by the tuber maxillae. Implant insertion in the molar site can result in perforation of the sinus floor.

The maxillary sinus is covered by the nasal cavities mucosa, which continues through the maxillary hiatus; following inflammatory processes, the mucosa swells easily, increasing up to several millimeters in thickness and thereby occluding the maxillary hiatus. The cavity of the maxillary sinus also may be described as a square pyramid, lying horizontally, with medial base and lateral vertex; walls are distinguished as anterior, posterior, superior, and inferior. The base of the pyramid corresponds to the medial wall of the nasal cavity, in which, at the level of the middle meatus, opens the maxillary sinus ostium (see Fig. 1.9). The opening of the sinus in the isolated maxillary bone is very large. In the skull it is closed posteriorly by the vertical plate of the palatine bone and the insertion of the inferior nasal concha, which articulates with the anterior and posterior conchal crests, respectively, on the maxillary frontal process and on the vertical plate of palatine bone. The orifice portion that remains below the inferior concha is normally obliterated by a mucous membrane. Sometimes, however, in this region, the mucosa can be perforated by one or more accessory sinus orifices (in ~20% of individuals).

Indeed, the maxillary sinus orifice is a canal 7 to 8 mm long and approximately 4 mm wide. Its direction is anteroposterior, lateromedial, and from the bottom upward; it opens in the middle concha behind the uncinate process of the ethmoid bone and under the ethmoidal bulla. This direction makes the catheterization of the canal extremely difficult; furthermore, just above its opening are located the anterior ethmoid cells and the opening of the frontonasal canal, which drains the frontal sinuses. Therefore, in the case of sinusitis of these sinuses, the purulent exudate (pus) produced can flow into in the maxillary sinus; if left untreated, sinusitis of frontal sinuses can result in maxillary sinusitis. The base of the maxillary sinus is divided by the inferior nasal concha in an upper and

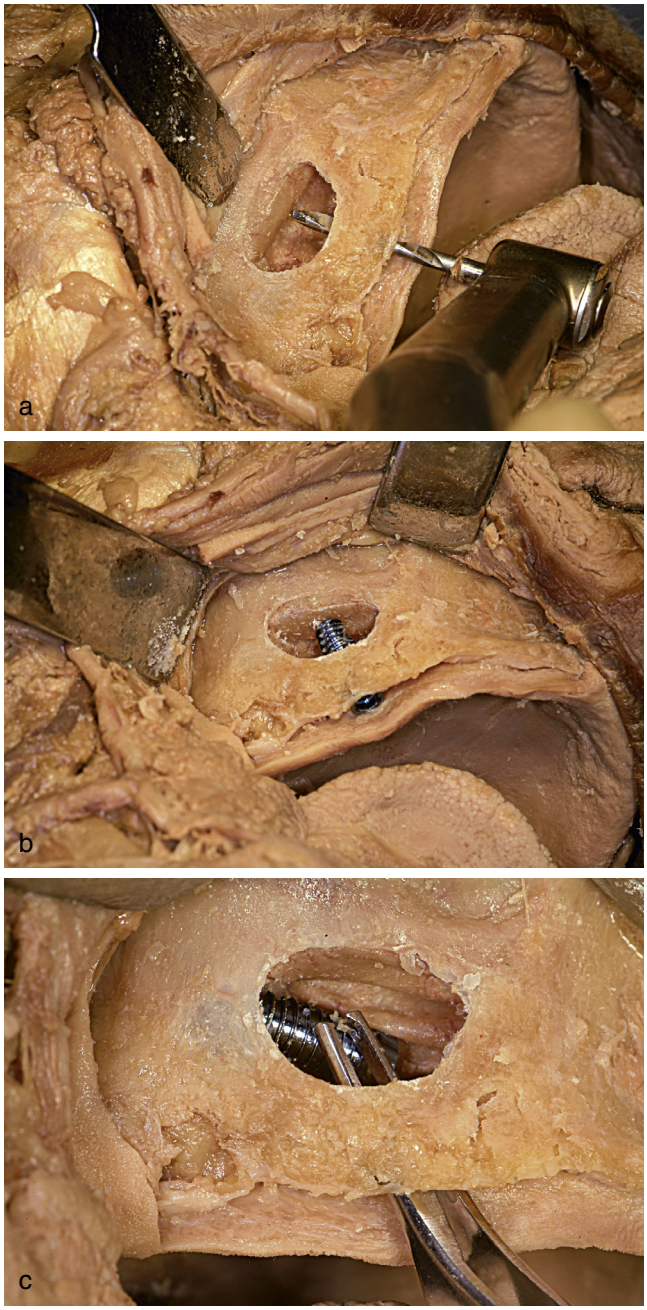

Figure 1.10 Cadaver dissection on the frontal plane. (a) Detail on the superior alveolar process and simulation of a dental implant insertion in the molar site. The reduced thickness of the bone crest and the reduced verticality of the alveolar process may determine the perforation of the sinus floor resulting in the penetration (b) and potentially the implant dislocation in the sinus cavity (c).

a lower portion. In the lower portion, anteriorly, the opening of the nasolacrimal canal is located, which continually drains lacrimal fluid. The opening of the inferior concha for surgical drainage of the maxillary sinus must always be performed approximately 2 cm posteriorly to the orifice.

Apex of the Maxillary Sinus

The apex of the maxillary sinus is located laterally and corresponds to the medial surface of the zygomatic bone. Depending on the degree of maxillary sinus pneumatization, the zygomatic bone can be completely invaded by the sinus, which expands throughout the whole thickness of the bone.

Walls of the Maxillary Sinus

The anterior wall, which corresponds to the cheek, is also known as buccal. Superiorly, it reaches the orbit lower margin, while the lower border, extremely variable, remains above the roots of the canine or first premolar. The wall is extremely thin, with a thickness of approximately 1 mm (Fig. 1.10). Anteriorly, it presents a depression termed the canine fossa, and 4 to 5 mm below the margin of the orbit the infraorbital foramen is crossed by the homonymous nerve, the terminal branch of maxillary nerve. The posterior and lower walls are represented by the maxillary tuberosity. One wall continues the other following the tuber curvature, and thus it is difficult to establish a clear boundary between the two. Below, on the border between the posterior and the lower wall, the maxillary tuberosity is juxtaposed to the sphenoid pterygoid process. The upper wall, or orbital bone, forms the floor of the orbit. It is extremely thin and on the orbital side, posteriorly, by the lower orbital fissure, presents a groove—the infraorbital groove (or sulcus). Proceeding anteriorly, the groove becomes deeper, forming a canal—the infraorbital canal—which opens anteriorly with the homonymous foramen. Because of the thinness of the wall, the infraorbital canal protrudes inferiorly in the maxillary sinus. In its course the infraorbital nerve gives origin to the superior alveolar branches that run in the thickness of the sinus anterior wall. Considering the wall thinness (1 mm) and the proximity of the bone canaliculi to the mucosa, it is understandable how inflammation of the maxillary sinus is liable to evoke dental neuralgia, which is usually transient when properly treated.

The Mandible: Mylohyoid Line

The inner surface of the mandibular body is seen in the medial region, starting from the third molar, as a rather rough bony ridge, heading obliquely, down and forward, and is named the mylohyoid line (Fig. 1.11a, b). The identification of the morphology of this anatomical structure is very important for implant planning in the mandibular bone. If unrecognized through two-dimensional diagnostic images such as those provided by conventional radiology (e.g., the panoramic radiograph) (Fig. 1.11c), serious bleeding complications can occur. During the preparation of implant sites the surgical drills will come into contact with the lingual cortical bone. The operator may find a strong resistance to the thickness and shape of this cortical bone, which could lead to increased pressure on the drill to complete the osteotomy. If the drill perforates the mylohyoid line cortex, it can penetrate into the very vascularized sublingual region causing a potential and dangerous hemorrhagic episode (Figs. 1.12 through 1.16). Therefore copious bleeding can occur that may result in elevation of the mouth floor, airway obstruction, and mediastinal tamponade, serious complications that have been reported in the literature.

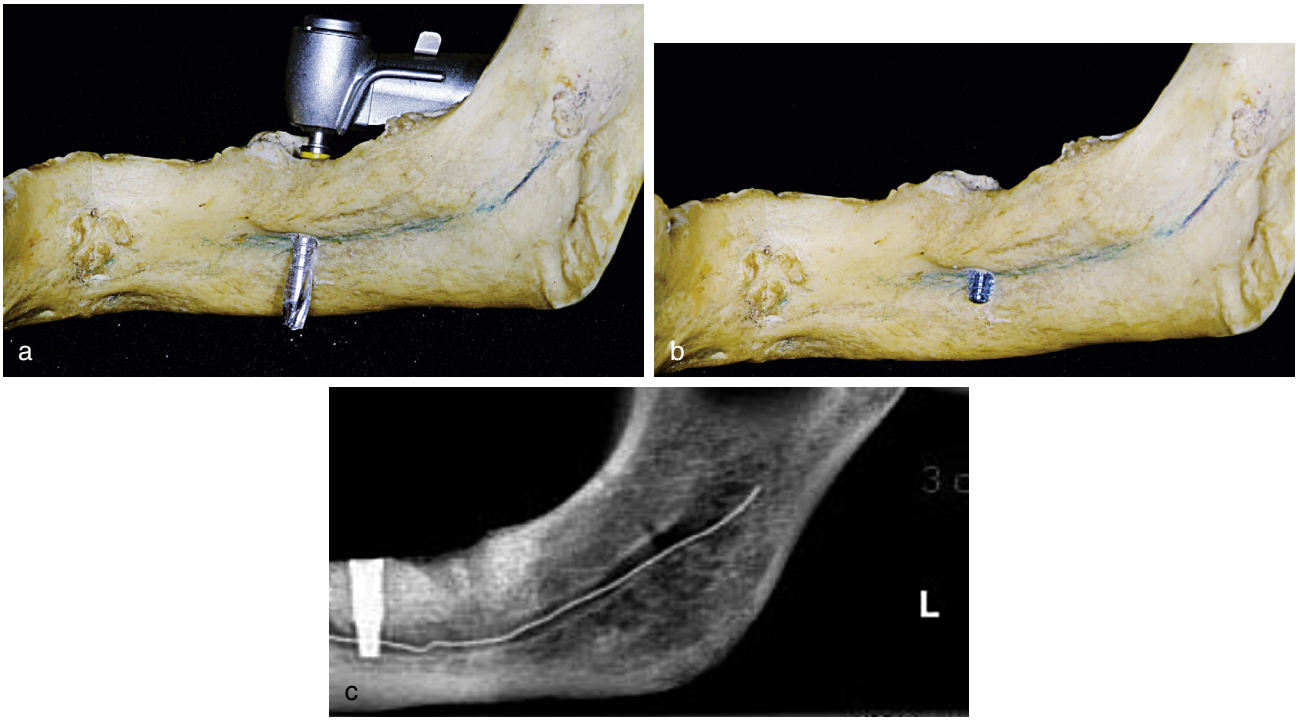

Figure 1.11 (a) Medial surface of the mandible showing operator's error when the drill is accidentally excessively inclined lingually. (b) This involves first a perforation of the sublingual lodge with the consequent damage of structures contained in it. If the drill goes beyond the mylohyoid muscle, inserted onto the mylohyoid line, marked in *blue*, it will get to the suprahyoid region and the submandibular lodge. (c) The two-dimensional view of the orthopantomogram does not allow appreciation of the serious mistake committed during the surgery. In the first and second molar sites the lingual cortical bone perforation can injure the mylohyoid artery, running in the homonymous groove.

Figure 1.12 Insertion of five implants in a dry mandible. In the vision from above, similar to the operator's perspective during implant surgery, the implants appear correctly positioned.

The mylohyoid line gives insertion to a large and powerful muscle, a depressor of the mandible termed the mylohyoid muscle, which also constitutes and defines the floor of the oral cavity. The mylohyoid muscle separates two distinct upper and lower regions. The upper portion, clothed by the oral lining mucosa and delimiting the oral cavity walls on which the tongue rests directly, is named the sublingual region (see Fig. 1.16). The lower portion delimits the submandibular space, which is accessible through the neck, is covered by skin, and constitutes the suprahyoid region (Fig. 1.17). The sublingual region is the anterior portion of the oral cavity floor. It has a triangular shape whose apex, located anteriorly, corresponds to the retroincisal region. The base, posterior and curvilinear, corresponds to the deep part of the tongue; the sides of the region, left and right and also curved, are delineated by the lower dentogingival arches. This area is susceptible to bleeding complications because of the proximity with the sublingual artery.

As mentioned earlier, the whole sublingual area is covered by the oral mucosa, smooth, pink, and rather transparent, which thickens by the midline and becomes a proper mucosal fold. It reaches the lower surface of the tongue, up to its apex, connecting it to the floor of the oral cavity in correspondence to the dentogingival arch, and is referred to as the lingual frenulum. On each side of the frenulum posteriorly, a small tubercle or papilla is seen, the sublingual caruncle, which, opened at its apex, enables the exit of the contents of the submandibular duct (Wharton duct), the excretory duct of the homonymous gland, directly in the oral cavity. Exploring the oral cavity floor after the elevation of the oral mucosa, a cavity termed the sublingual lodge is found and is bounded anterolaterally by the inner surface of the mandibular body (above the mylohyoid line, where it can be observed as a small depression, the sublingual fossa, which accommodates the homonymous gland), posteromedially by the hyoglossus muscle, superiorly by the oral lining mucosa, and inferiorly by the mylohyoid muscle.

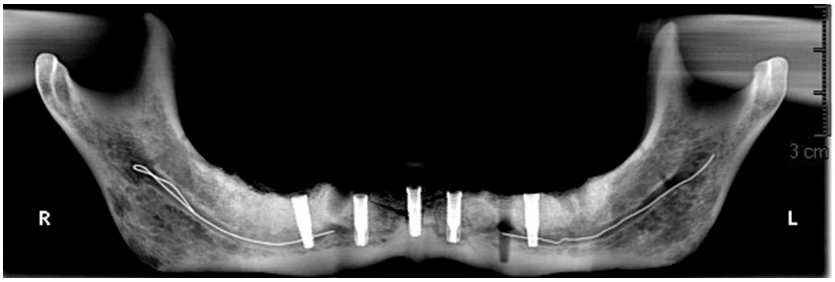

Figure 1.13 The mandible undergoes x-ray (orthopantomogram). Implant length appears correct (it seems there has been an alveolar nerve involvement).

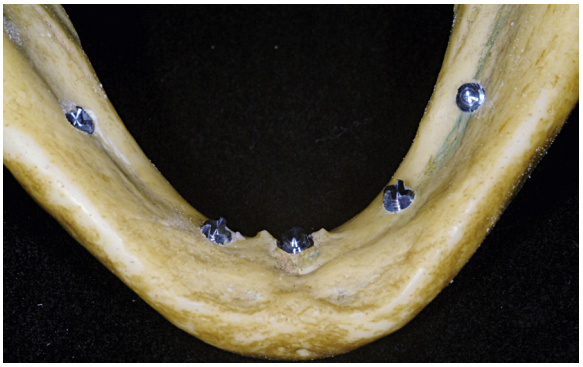

Figure 1.14 The view from the bottom shows the serious errors committed in insertion of the implants. Alveolar nerves have not been perforated by the implant insertion, but the anatomical structures on the oral floor have been damaged. All implants, in fact, have perforated the lingual cortical bone.

Figure 1.16 Oral cavity dissection in a cadaver. After the elevation of the oral mucosa, the mylohyoid line and its insertion into the mylohyoid muscle were exposed. In the case of mandibular atrophy, the alveolar process reduction causes "surfacing" of the oral cavity floor and consequently of the mylohyoid line.

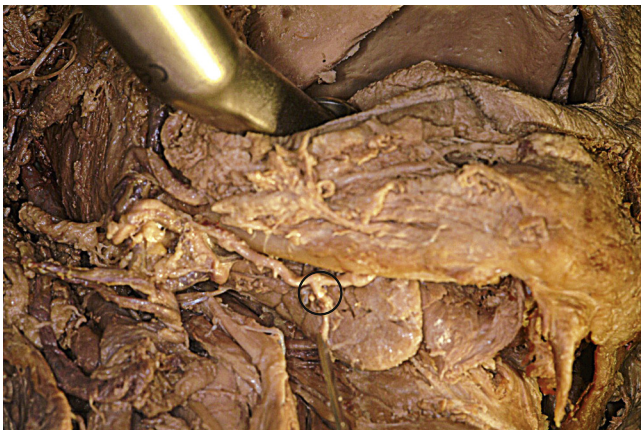

Figure 1.15 The same error described in Fig. 1.13 was achieved on a cadaver. The drill *(circle)* perforating the lingual cortical bone can damage vascular and nerve structures of great importance, such as the sublingual artery.

Figure 1.17 Suprahyoid region dissection in a cadaver. It shows the mylohyoid muscle perforation resulting from the penetration of the drill, indicated by the *arrow,* in the submandibular lodge.

Several structures are contained within the sublingual lodge: the sublingual gland, the anterior extension of the submandibular gland, the submandibular duct (Wharton duct), the sublingual artery, and a branch of the lingual artery of approximately 2 mm. Furthermore, the sublingual vein and the lingual nerve, a branch of the trigeminal mandibular nerve that runs very shallow by the third molar, then deepens and loops around the submandibular duct, reaching the sublingual gland and the apex of the tongue ventral surface. The suprahyoid region corresponds to the anterior and superior part of the neck and is bounded laterally by the anterior margins of sternocleidomastoid muscles, inferiorly by a horizontal line at the level of hyoid bone, and superiorly by the lower margin of the jaw, up to the mandibular angle. From the outer surface, it is covered by the skin, the subcutaneous tissue, blood vessels, and small surface nerves and the suprahyoid fascia and subfascial layers. The suprahyoid fascia derives from the cervical aponeurosis, whose external surface corresponds to the platysma muscle, with vessels and nerves, while the deep surface doubles to form the sheaths of the underlying muscles that constitute the subfascial layers. These are the digastric, stylohyoideus, mylohyoideus, and hyoglossus muscles. The whole mylohyoideus muscle belongs to the suprahyoid region and constitutes its largest portion, delimiting it from the upper sublingual region. The anterior bundles insert on the mylohyoid line, converging centrally on a median raphe of connective tissue, and the posterior bundles extend downward onto the hyoid bone.

In addition to the muscles, subfascial layers are also represented by the voluminous submandibular gland (Fig. 1.18), lymph nodes, deep vessels, and nerves. The submandibular gland is contained within the submandibular lodge, placed inferiorly and anteriorly to the mylohyoid muscle. The lodge is delimited laterally by the mandible inner surface (in correspondence to a depression termed the submandibular fossa, placed inferiorly and posteriorly to the mylohyoid line), medially and superiorly by the mylohyoideus and hyoglossus muscles, and inferiorly and laterally by the cervical aponeurosis. The gland consists of a voluminous body and a smaller anterior extension. The body lies within the submandibular fossa and is in contact inferiorly and medially with the mylohyoid muscle and posteriorly with the digastric and stylohyoid muscles; the submental veins and arteries, deriving from the facial artery, run on its lateral face (see Fig. 1.18). The extension heads anteriorly, above the mylohyoid line and muscle, resting on it and coming in contact medially with the hyoglossus muscle.

The submandibular gland salivary secretion reaches the oral cavity through the long and thick submandibular duct (Wharton duct). It originates from the medial aspect of the gland, and then runs on the mylohyoid muscle, reaching the sublingual lodge, ending in the sublingual caruncle at the level of the frenulum. The lingual artery, a branch of the external carotid artery, courses behind the posterior margin of the hyoglossus muscle, runs forward through the mandibular lodge, leaves it to penetrate the muscle itself, and reaches the genioglossus and the longitudinal muscle

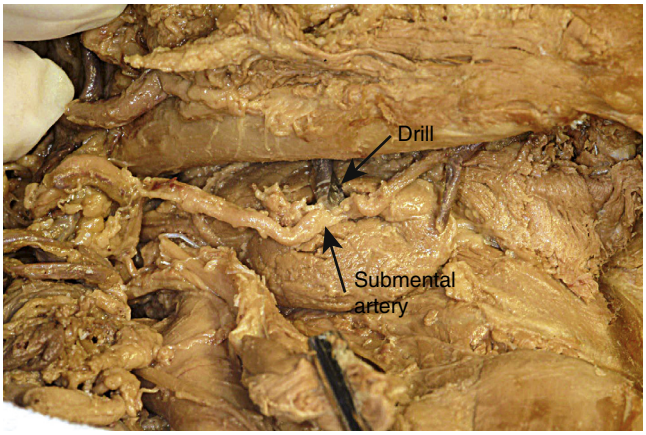

Figure 1.18 Suprahyoid region dissection in a cadaver. Penetrating the submandibular lodge, the drill can damage the submental artery.

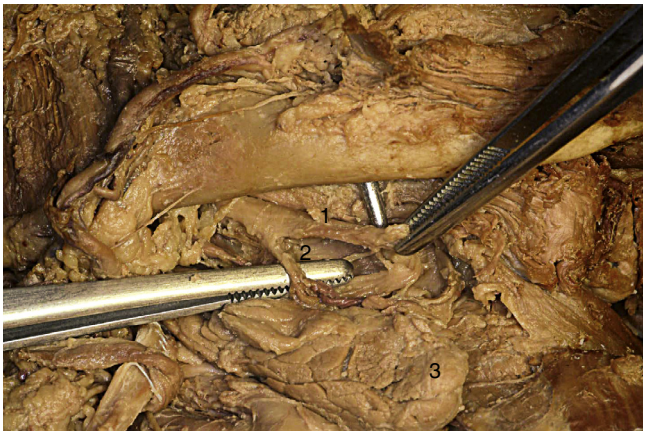

Figure 1.19 Suprahyoid region dissection in a cadaver. The drill, penetrating the submandibular lodge can injure the lingual nerve *(1)* and its anastomosis *(2)* that goes to submandibular gland *(3)*.

of the tongue body, ending at the tongue apex. Along its course before reaching the tongue, the lingual artery gives origin to the sublingual artery, which, running on the oral cavity floor and medially to sublingual gland, provides blood supply to both the mucosa and the gland. The sublingual artery anastomoses with branches of the submental artery that originated from the facial artery. The facial artery, also a branch of the external carotid artery, reaches the suprahyoid region, running from the bottom upward and from the back to the front on the lateral aspect of mylohyoid muscle, limited posteriorly by the digastric and stylohyoid muscles, reaching the submandibular gland, and then surrounds the mandible lower margin, thereby arriving in the facial region. Along this course it originates the submental branches that run anteriorly (see Fig. 1.18). The vital vessels and nerves described here can be accidentally involved during implant site or donor bone harvesting surgical procedures from the symphysis and mandibular ramus, which can cause dangerous bleeding of the mouth floor that is often difficult to control (diathermocoagulation, ligation), resulting in elevation of the floor of the mouth and life-threatening airway obstruction (Fig. 1.19). Therefore subperiosteal flap elevation

and adequate protection of tissues during the action of rotary instruments is always recommended. In addition, implant sites should always be carefully planned preoperatively with three-dimensional imaging modalities to appreciate the local anatomy and avoid the perforation of the lingual cortical bone.

Mandibular Canal and Mental Foramen

The mandible, or lower jaw, is a median bone of the skull situated at the lower and frontal portion of the face. It is constituted by a main part, the body, from which arise two ascending portions, the rami. The body, shaped like a horseshoe with its concave side facing posteriorly, has two faces, one anterolateral and one posteromedial, a lower margin, the bone base, and an upper margin, represented by the alveolar process. The alveolar process is composed of two parallel bone plates, external and internal, connected by small bony plates, the interdental septa, which define the alveolar cavities accommodating the teeth. The mandibular rami rise from the posterior side of the body, forming an obtuse mandibular angle. Rectangular in shape, the rami have two faces, one lateral and one medial, in continuation with the body corresponding faces. The lateral side, which is flat, presents in correspondence with the angular rough surface, the masseter tuberosity, which gives insertion to the masseter muscle. In the center of the medial surface, which is more flattened, the mandibular canal opens and runs inside the mandibular bone, below the mylohyoid line. It is bordered by a large orifice, the mandibular foramen, facing posteriorly and medially and delimited by a small bony plate that is variously developed and extends upward, named the mandibular lingula or Spix spine (Fig. 1.20).

At its origin, the mandibular canal size is approximately 4 mm, then it decreases progressively to 2 mm. Along its course it describes a curve, concave anteriorly and superiorly, and moves laterally toward the buccal cortical bone or plate, always remaining below the dental alveolar cavities, with which it communicates through small orifices at the apex of each alveolus. The canal course is divided into three segments: posterior, middle, and anterior. The posterior segment, at its entrance, has an oblique course downward and forward and is located in the region of the mandibular ramus. The middle segment, approximately horizontal, is located by the molar region, very close to the lingual cortical plate of the mandibular body. This segment is approximately 6 mm from the apex of the third molar, 7 mm from the second molar, up to a distance of approximately 9 mm from the second premolar. Along its course the middle segment of the mandibular canal runs linguobuccally toward the lateral face of the body and reaches its deepest point, which is approximately 10 mm.

The third segment, the anterior segment, begins at the level of the apex of the second premolar, with an anterosuperior and laterobuccal direction. This third segment gives origin to a short branch of the mental canal after approximately 1 cm, which runs in a lateral direction in the frontal region of the mandible, to end at the mental foramen, located just

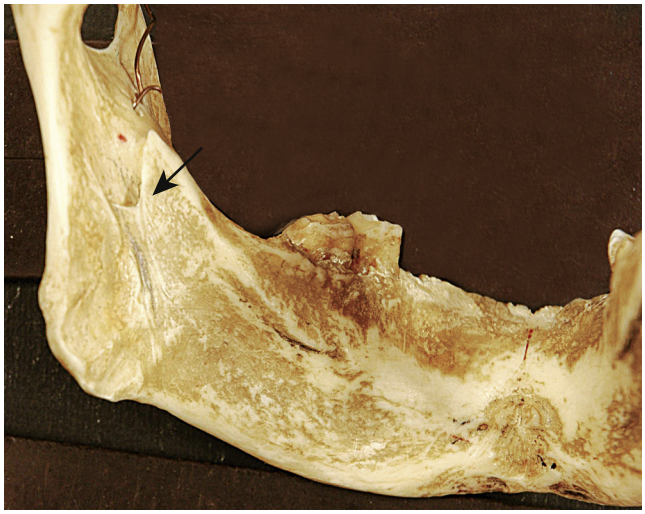

Figure 1.20 Medial surface of the mandible. The *arrow* indicates the entrance of the mandibular canal, represented by the mandibular lingula (Spix spine).

by the second premolar. The mandibular canal then shrinks and continues heading forward, remaining below the dental apexes, in the incisive region, thereby becoming a thin and long channel, the incisive canal.

Small ascending canals, originating from the upper wall of the mandibular canal, reach the apexes of the dental alveoli and teeth roots, crossed by thin vascular and nervous branches.

After the loss of the teeth and directly a result of the loss of the direct load transmitted by the tooth roots to the bone, the mandibular jawbone can undergo atrophy of the inferior alveolar process. On the contrary, the bone of the lower cortex and the symphysis region remains intact as it gives insertion to muscles bundles, maintaining its trophism and robustness.

As a further consequence after the mandibular atrophy, the alveolar canal undergoes changes in position. As a result of bone resorption at the level of the superior margin, the canal gradually centralizes, thereby modifying its original topography as described by Cawood and Howell in their classification of edentulous jaws (Cawood JI, Howell HA. A classification of the edentulous jaws. Int J Oral Maxillofac Surg 1988;17:232–236). The inferior alveolar canal contains the inferior alveolar artery, one of the medial collateral branches of the internal maxillary artery. Running along the canal, the inferior alveolar artery gives origin to small branches that penetrate through the root apical foramina of the lower teeth and traverse through the root canals to ensure the dental pulp blood supply. In addition, the alveolar artery gives origin to the mental artery, which exits the homonymous foramen and travels forward to vascularize the soft tissues of the mental region.

The inferior alveolar canal also contains the inferior alveolar nerve, collateral to the posteromedial branch of the trigeminal mandibular nerve (the fifth pair of cranial nerves) (Fig. 1.21). The inferior alveolar nerve, as does the

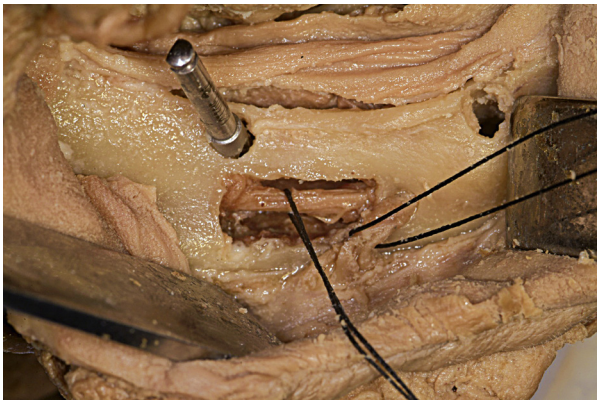

Figure 1.21 Oral cavity dissection at the level of the lower dental arch in a cadaver. After elevation of the mucosa, the bone was denuded; a small window was opened on the lateral aspect of the mandibular body to show the presence of the canal which runs the inferior alveolar nerve, held by a suture.

Figure 1.22 Lateral aspect of the mandible in the premolar region. The drill is shown at an incorrect angle, too vestibular, which leads to perforation of the mental canal and foramen.

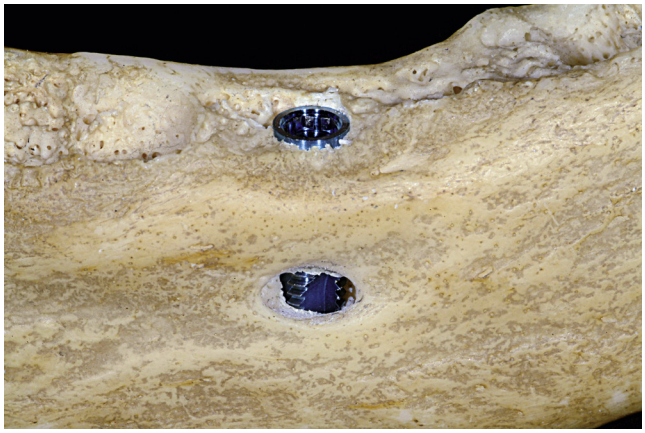

Figure 1.23 Lateral aspect of the mandible in the premolar region. The picture shows the incorrect insertion of a dental implant in the premolar site determining its emergence at the mental foramen.

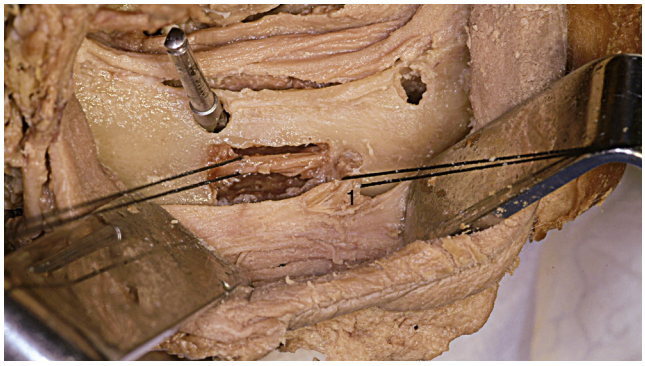

Figure 1.24 Oral cavity dissection in the lower dental arch in a cadaver. The course of the mandibular canal and the alveolar nerve is shown. *Point 1* indicates the mental nerve exiting the mandibular canal across the mental foramen to innervate the soft tissues in the mental region.

alveolar artery, enters the canal through the mandibular foramen and runs through the canal itself, from the top to the bottom, from the back to the front, and from lingual to buccal. It also gives small collateral branches that penetrate into the tooth root apices at the level of each alveolus, thereby providing innervation to each tooth and the correspondent periodontal and gingival tissues. In proximity of premolars, along its course, the inferior alveolar nerve gives a branch that enters the mental canal (Figs. 1.22 through 1.24) and exits the homonymous foramen, as the mental nerve, for the sensory innervation of the chin soft tissues. Finally, the terminal portion of the inferior alveolar nerve runs through the incisive canal as the inferior incisive nerve.

POSTEXTRACTION ATROPHY OF THE MAXILLA AND MANDIBLE

With the loss of teeth, masticatory function decreases and the alveolar bone resorption process begins. A different pattern of resorption occurs depending on whether it affects the upper or lower jaw. In the upper jaw, resorption is mainly horizontal, affecting bone thickness and involving mostly the vestibular component. The direction of resorption is centripetal. In the mandible, resorption depends on the sector considered; anteriorly, horizontal resorption is more pronounced, whereas posteriorly the vertical component is more relevant. These resorption patterns produce alterations in the intermaxillary relationship, leading to a progressive prognathism. This terminal bone atrophy determines a proper skeletal class III malocclusion with a massive increase in the distance between the two arches, producing an aged appearance. The bone density also decreases considerably in both arches, because in the absence of function the bone quality is always lower. Thus the degree of atrophy and bone density can vary quite substantially—even in the same individual—depending on the considered bone segment. However, as always happens in biology, several factors can accelerate these processes. In fact, a diet poor in calcium and vitamin D, especially in postmenopausal women, or consumption of large amounts

of caffeine contribute to cause bone resorption. Also, local factors, such as severe periodontal disease, incongruous prosthesis, and tobacco abuse can cause such problems. Anatomically, a significant change in the soft tissues can be observed. In fact, the attached gingiva tends to decrease and the insertion of the muscles of the mouth floor becomes increasingly shallow.

In the lower jaw the inferior alveolar nerve becomes increasingly more superficial. In the upper arch the palate assumes a characteristic flat shape, vestibules become progressively more shallow, and the maxillary sinus increases greatly in size. These changes determine a decrease in the tone of the lip muscles, resulting in a lowering and retreat of the labial commissure, giving a "sad" aspect to persons affected by bone atrophy.

Several authors have proposed diverse classifications of bone resorption, often differing only in small details. The Cawood and Howell Classification (1988), to which almost all scientific papers refer, is surely the best known.

RESIDUAL (AMOUNT OF BONE) BONE QUANTITY

Cawood and Howell Classification

The Cawood and Howell classification, even acknowledging that each individual can have quite peculiar resorption characteristics, focuses on two main aspects The first is that the basal bone does not change significantly after the loss of the teeth, and the second is that the resorption takes place after a defined pattern, similar in all the individuals. In the mandible, anteriorly, the bone resorption is predominantly vestibular (horizontal and centripetal); posteriorly, it is mainly vertical. In the maxilla, resorption is primarily horizontal and centripetal (prevalently vestibular).The authors divided the clinical pictures in six classes (Table 1.1).

Classification of Lekholm, Zarb, and Albrektsson

The classification of Lekholm, Zarb, and Albrektsson (1985) is as important as that of Cawood and Howell; in fact, the bone quality affects both the bone–implant interface and the stabilization of the implant (Table 1.2). It takes into account, analyzing them, both types of bone present in the jaw—cortical bone and trabecular bone.

Classification of Misch

Misch's classification (1990) is very similar to that of Lekholm and Zarb, which distinguishes four types of bone density (DI to DIV). Misch divided the density pattern into four classes (Table 1.3).

The D-I type of bone density is found exclusively in the anterior mandible, type D-II is in both the posterior mandible and anterior maxillary bone (rarely in the anterior mandible), type D-III in the anterior maxilla (rarely in the posterior maxillary in the posterior mandible), and type D-IV is typical of the posterior maxilla.

TABLE 1.1 Cawood and Howell Classification (1988)

Classification	Description
CLASS I	Dentate alveolar ridge
CLASS II	Immediate postextraction alveolar ridge
CLASS III	Well-rounded ridge form, adequate in height and width
CLASS IV	Knife-edge ridge form, adequate in height, but inadequate in width
CLASS V	Flat ridge form, inadequate in height and width
CLASS VI	Depressed ridge form, with some basal bone loss evident (without predictability of how it may evolve)

TABLE 1.2 Classification of Lekholm, Zarb, and Albrektsson (1985)

Type	Description
TYPE I	Compact cortical bone
TYPE II	Compact cortical bone and dense trabecular bone thick
TYPE III	Thin cortical bone and abundance of dense trabecular bone
TYPE IV	Very thin cortical bone and low density trabecular bone

TABLE 1.3 Classification of Misch (1990)

Classification	Description
Density D-I	Compact cortical bone
Density D-II	Porous cortical bone, dense trabecular bone
Density D-III	Porous cortical bone, loose trabecular bone
Density D-IV	Loose trabecular bone

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CHAPTER 2

Bone Grafts

Marco Rinaldi, Scott D. Ganz, Angelo Mottola, Stefano Pagnutti, Alessandro Gasbarrini, and Luca Boriani

INTRODUCTION

Marco Rinaldi, Angelo Mottola

Because of the pathologic causes and other events that lead to tooth loss, the bone volume available for implant placement is often insufficient. In the clinical case presentations in which bone volume has been compromised, the main task becomes the reconstruction of the lost bone to allow for proper implantology. It has been stated that, "bone reconstruction is the challenge for every oral and maxillofacial surgeon" (Federico Hernandez Alfaro). To accomplish the task, biologic material is required. Even the smallest amount of bone that accumulates on the surgical bone drill and is then used to fill a small defect, or a massive block of bone used for a serious defect, can be regarded as bone harvests and grafts, although the clinical and operational situations are very different. The grafting of biomaterials used abundantly in dentistry requires treatment under various clinical presentations. These materials, often used with satisfaction and success, have indications and limits. They can be used to spare the patient trauma resulting from sampling and harvesting procedures and sometimes for the operator to avoid technical difficulties of harvesting a sufficient quantity of bone for reconstruction.

All persons professionally interested in the subject constantly seek out better and more reliable materials. This is true even if the surgical specialist has been taught, sometimes in contrast with some scientific works, to believe in the reliability of autologous bone, which continues to be considered the gold standard among the graft materials. This belief is clearly demonstrated in the section of clinical cases in which autologous bone has been widely and successfully demonstrated. Currently, several treatment options are available for grafting reconstruction, and patients can be treated with various methods. As an example, with a fully edentulous presentation it is possible to perform reconstructive surgery with bone grafts, followed by the placement of numerous implants to support a very sophisticated prosthetic rehabilitation. It is also possible to use fewer implants, placing them with a distal tilt to use the available bone for a Toronto bridge or even to place just two implants for a simple overdenture reconstruction (Fig. 2.1). These treatment options often decrease according to the patient's state of health or the financial limitations of the patient. Therefore the clinical indications of available techniques and the patient's personal choices must be taken into account. It is obvious that it is not possible to provide every patient with a bone reconstruction to replace lost bone volume to support dental implants, but it is equally obvious that with sophisticated diagnostic and surgical modalities, we may treat many more patients than ever anticipated. When evaluating each patient presentation, it is necessary to consider the time required for healing and bone regeneration. Ideally, when tooth extractions are planned, if the situation is favorable and speed is not a factor, it may be possible to avoid bone grafting altogether by performing extractions conservatively, possibly adding a biomaterial such as l-PRF (an autologous blood product) or just protecting the naturally occurring blood clot by accurately suturing the gingival flaps (Figs. 2.2 and 2.3).

INDICATIONS FOR BONE GRAFTING

Marco Rinaldi, Angelo Mottola

Indications for bone grafting can be absolute or relative. Absolute indications correspond to those situations in which, because of a defect in or height or width, it would be impossible to place any implant. Relative indications are those situations in which bone reconstruction may allow the insertion of an adequate number of implants. As already stated, the clinician is always free to choose whether bone reconstruction is necessary, based on his or her knowledge and opinions. Therefore it is anticipated that short and thin implants will not be considered for treatment for the examples shown in this textbook; however, each clinician will decide which clinical presentations will allow for less than standard implants, or when to perform a bone reconstruction to gain adequate width and height (Fig. 2.4). It is advisable to be flexible and assess the patient comprehensively, including the patient's expectations and general state of health, rather than trying to define the operating limits by just measuring millimeters in width and height. Other patient-related considerations include the crown-to-root ratio, interarch distance, antagonist/opposing teeth, masticatory forces, the presence of parafunctions or malocclusion, aesthetic expectations, gingival biotype, smile line, and the desired type of prosthetic rehabilitation. Bone defects in height or width that make it impossible for the placement of implants represent absolute indications for bone grafting (Fig. 2.5).

Bone defects in height or width for which bone grafting may allow standard implant size (diameter and length) and optimal implant placement represent relative indications for bone grafts (Figs. 2.6 and 2.7). An adequate bone volume, in fact, enables prosthetically driven implant placement to optimize the morphologically appropriate shapes, the prosthetic emergence profiles, and the quality of the final restoration (Fig. 2.8). For the assessment of bone receptor sites, it is necessary to use modern radiographic techniques, such as computed tomography (CT), because the clinical examination

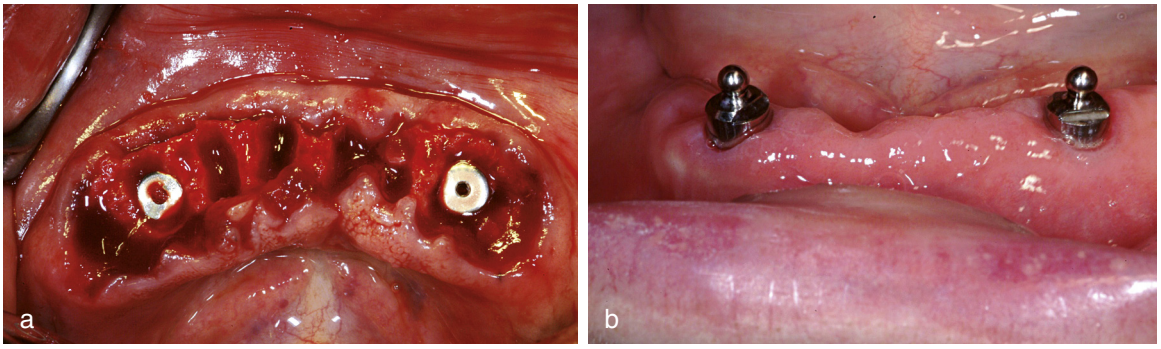

Figure 2.1 If allowed by the treatment plan, bone defects may not be treated and implants are placed where possible (a) to provide an overdenture (b). This cannot be done if the treatment plan is more ambitious.

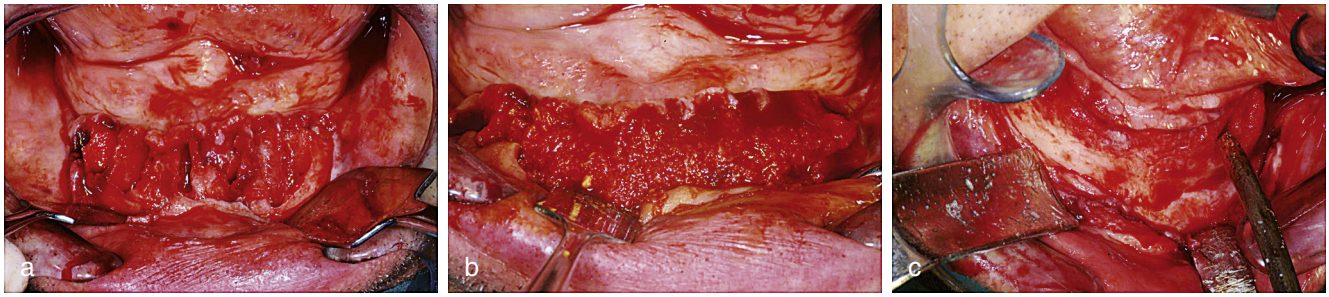

Figure 2.2 (a) Immediate postextraction situation. (b) Freeze-dried human bone graft (BTM, Banca del tessuto muscolo scheletrico, Istituti Ortopedici Rizzoli, Bologna, Italy). (c) Situation after 4 months.

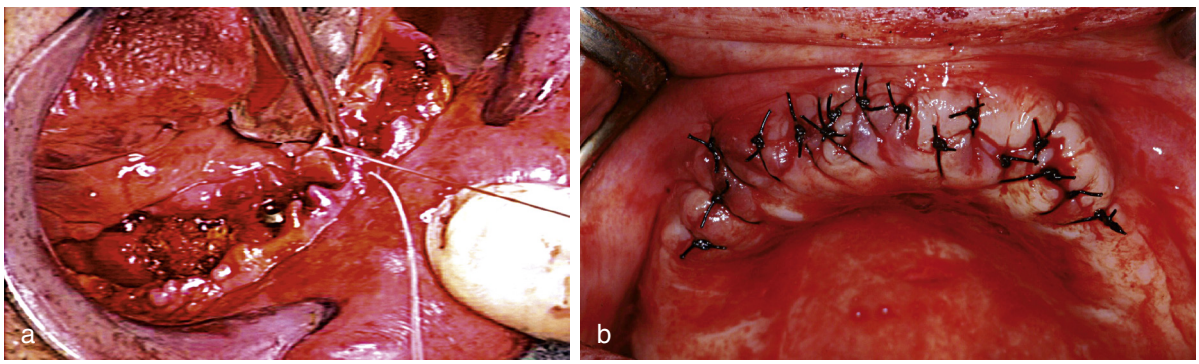

Figure 2.3 After the extractions, to protect the blood clot and the grafted biomaterial, the Schuchardt's gear suture is used, thus joining each papilla with the gingival parable of the other gingival flap (a, b).

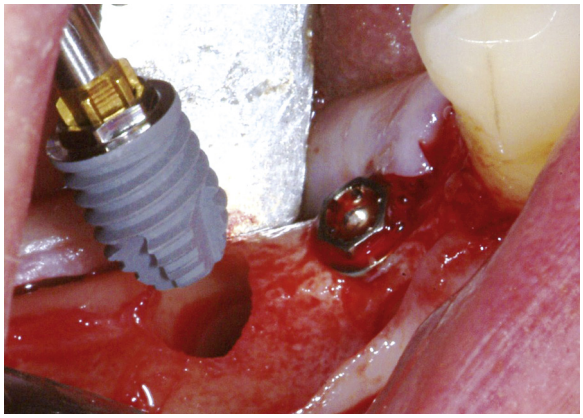

Figure 2.4 Seven-millimeter short implants. In some situations they may represent an alternative to grafting. (NOBELSPEEDY, Shorty, NobelBiocare AB, Goteborg, Sweden.)

alone and two-dimensional radiography are not sufficient. Also, the choice of bone harvesting donor sites requires a three-dimensional assessment of the available bone to identify the most suitable sites.

ELEMENTS OF BIOLOGY OF BONE REGENERATION

Stefano Pagnutti

Introduction

Bone grafting, either autologous or performed with biomaterials, and guided bone regeneration techniques with tentlike membranes, are all based on the ability to activate tissue regeneration processes at the site of the intervention, enabling the regeneration of a part of the lost tissue

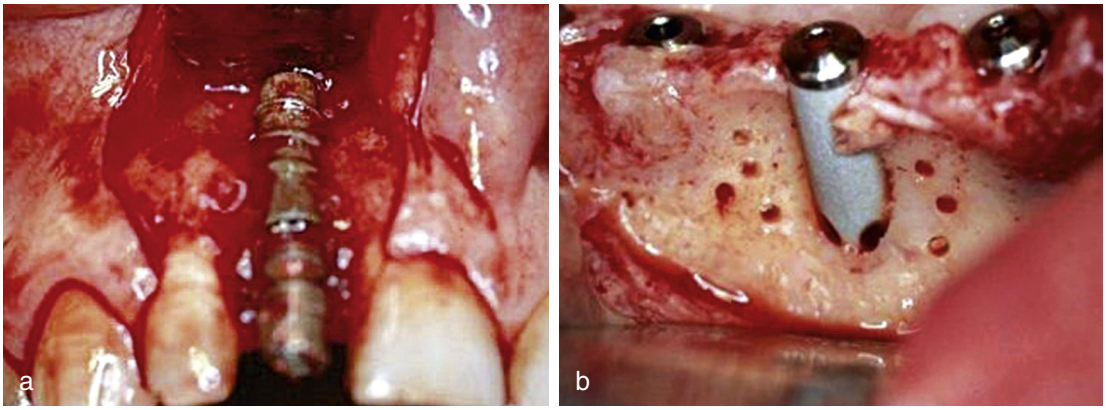

Figure 2.5 (a, b) Bone defects that make implant insertion impossible (absolute indications for bone grafting).

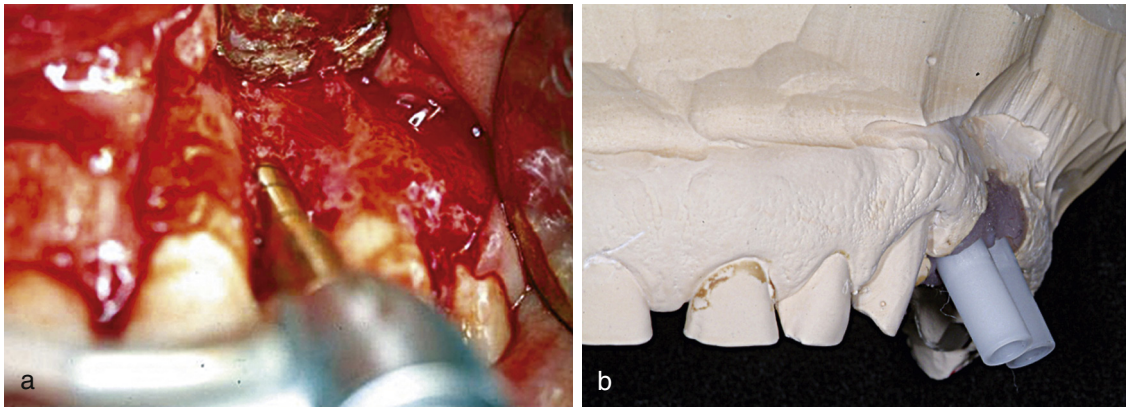

Figure 2.6 (a, b) Bone thickness defects lead to the insertion of buccally tilted implants.

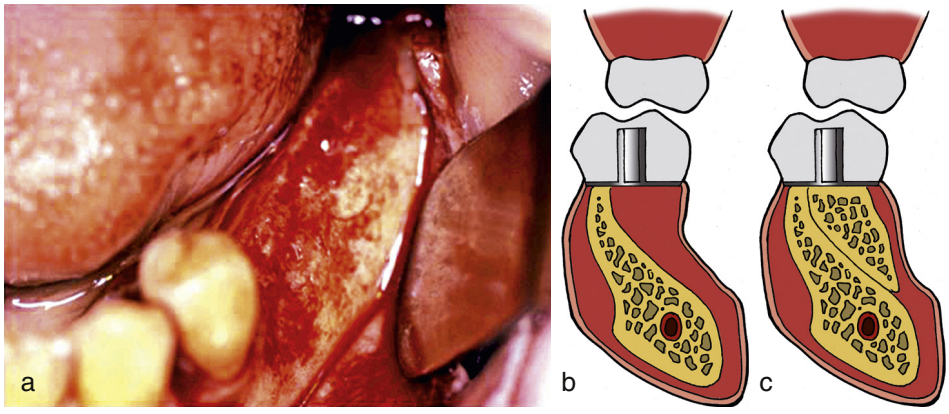

Figure 2.7 (a) Bone resorption has affected mainly the buccal aspect. (b) Even if it was possible to insert implants, they would be too lingual and there might be problems with the occlusal relations with the antagonists. (c) A graft would improve the prosthetic rehabilitation (relative indication for grafting).

and thereby restoring both the anatomy and function of the bone site. Once activated, the regeneration process takes place through a succession of biochemical, cellular, and tissue factor events defined a priori with respect to the surgical intervention by the biologic characteristics of the bone. The surgery therefore cannot alter the sequence of these events nor affect the speed with which they occur. It may, however, and unfortunately, create unfavorable conditions for bone regeneration that could result in intervention failure. It is therefore necessary to understand the fundamental events of bone regeneration and the precautions necessary during surgery to enhance the normal course.

Tissue Triad

From a (strictly) biologic point of view, to allow for tissue regeneration, the so-called tissue triad must be present; it

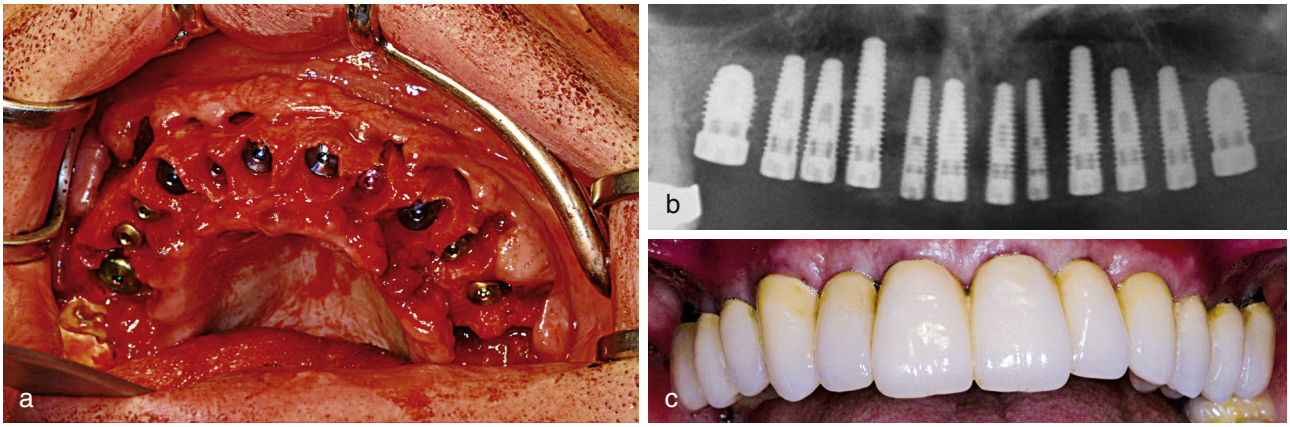

Figure 2.8 When allowed by the bone volume (a) implant diameters and lengths can be optimized (b) in relation to the teeth to be replaced (c).

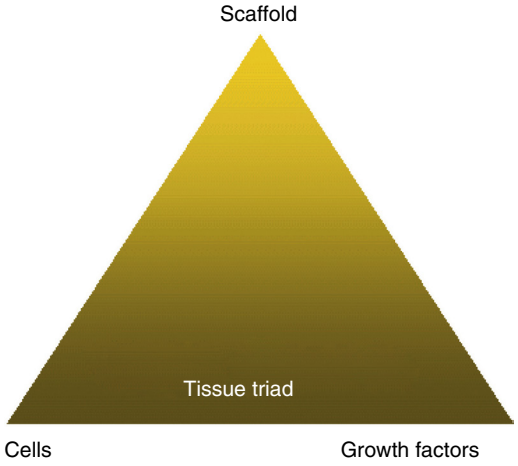

Figure 2.9 The tissue triad shows the three necessary elements for the tissue regeneration to take place: scaffold, cells, and growth factors.

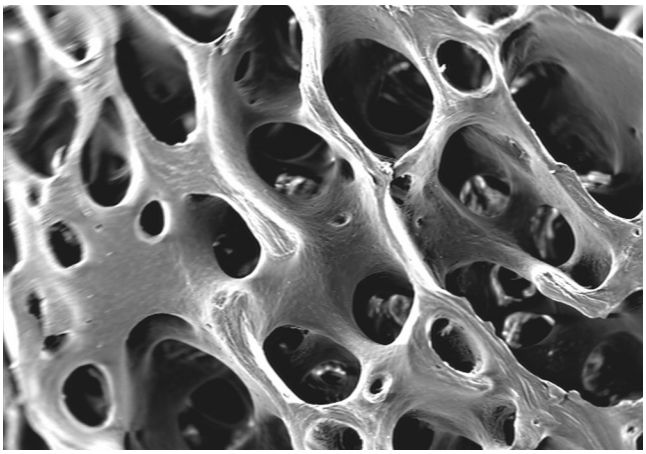

Figure 2.10 Trabeculation of cancellous bone: the three-dimensional structure of the bone provides mechanical support to vessels and cells (osteoconduction).

includes three elements: a scaffold, cells, and growth factors (Fig. 2.9). The scaffold is represented by the material (autologous or not) that is grafted to repair the bone defect. Its function is to create a spatial structure capable of accommodating and supporting the cells and the tissue elements (e.g., blood vessels) that will colonize the grafted volume for regeneration to occur. This feature is crucial because the cellular and vessel diffusion is impossible in an empty space. The graft thus contributes to the important first osteoconductive effect, acting as a physical space that can be colonized by cells and blood vessels, to which it gives mechanical support (Fig. 2.10). The osteoconductive effect does not require any interaction of biochemical type between the graft and the recipient tissue, but depends only on the biomaterial characteristic physical parameters—in particular, its morphologic and surface features (such as the pore size, surface roughness, and others). In the case of autologous bone grafts being of the same tissue subject to the regeneration, these parameters are clearly already optimal. Cellular elements are directly responsible for regenerative events; more precisely, in the bone tissue the osteoblasts produce the new matrix, part of which is subsequently mineralized.

In the case of autologous bone grafts, part of the osteoblasts, consistent with the degree of necrosis resulting from the duration of ischemia caused by the sampling, will also be transferred to the recipient site within the autologous tissue. In this case, the grafted material in addition to the previously mentioned osteoconductive effect, exerts, at least partially, an osteogenic effect—that is, a direct bone tissue generation, thanks to the viability of cellular elements contained within it.

The third element necessary for bone regeneration is growth factors, which are a very large number of chemical signals, mainly peptides and proteins, that trigger and modulate the various processes involved in the bone regeneration. Their presence is necessary because regeneration as a whole is a special event, limited in time and space, that does not occur under physiologic conditions. In other words, it is a sequence of events to be triggered, modulated during its progress, and finished, once the regeneration has taken place. Typically, the action of growth factors is exercised through significant changes of their local concentration, not only in relation to their absence or presence. In addition, at any given time, the final observed effect is often determined

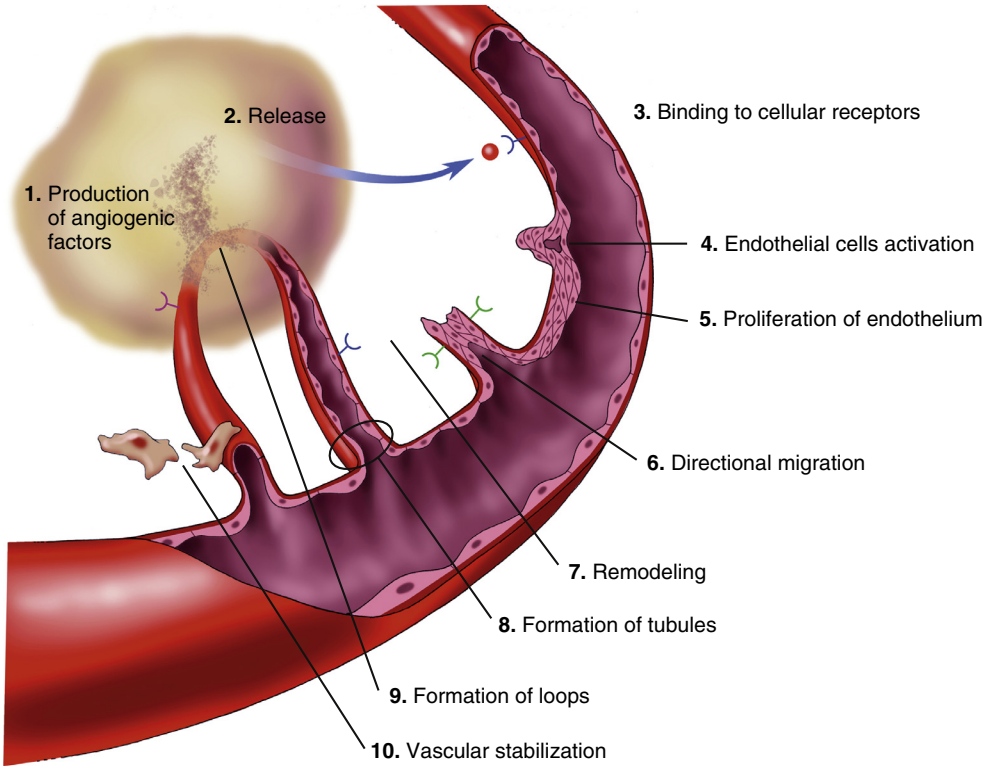

Figure 2.11 Sprouting angiogenesis: vascular endothelium proliferates, generating loops that will increase within the grafted site.

by the ratio between the concentrations of the various factors involved.

Also, growth factors, such as cellular elements, reach the grafted site from the patient's living tissues by being carried by the bloodstream or synthesized and secreted by cellular elements (also transported by the blood or present at the level of the recipient bone).

Growth factors, and in general signaling molecules whose concentration varies during the regenerative process, are responsible for the osteoinductive effect—that is, the biochemical activation of tissue and cellular events that lead to the bone tissue regeneration and then to the filling of the defect. In the case of autologous bone grafts, a small proportion of these factors is already present in the graft itself, although the concentration of these factors may change, which can trigger the regenerative events, mainly as a result of local (blood) supply of the recipient tissue. The action of growth factors on target cells is expressed not only by activating, after binding to specific receptors, specific intracellular events (genes switch on or off, up-regulation or down-regulation of specific biochemical pathways, etc.) but also attracting by chemotaxis the same cellular elements to the site to be regenerated.

Events of Bone Regeneration

Angiogenesis

Angiogenesis is the first event to be observed in the bone regeneration process (Fig. 2.11). It consists of the permeation of the grafted site by a thick capillary network. Formation of this network will allow the site to be colonized by cellular elements, which, in fact, are brought to site by the bloodstream. Formation of new blood vessels occurs by sprouting (budding) of already existing vessels. Under the action of growth factors, endothelial cells are stimulated to divide and arrange loops, which grow, especially in length, and invade the grafted site.

Growth factors involved in this process are many. Among the best known—because of the studies on tumoral angiogenesis—is VEGF (vascular endothelial growth factor), known in at least in six different isoforms. Equally important is a series of other factors, including PDGF (platelet-derived growth factor), resulting from platelet degranulation, a key event in blood clot formation, and others such as different forms of FGF (fibroblast growth factor) and members of the TGF-β (transforming growth factor beta) family. It is interesting to note that angiogenesis is in fact triggered by a cascade of inflammatory signals (Fig. 2.12). In the evolutionary sense, the adaptive significance of this phenomenon is that events of regenerative and reparative type are induced when the body suffers a traumatic insult. In this sense, the preparation of the graft recipient bed and the partial decortication, performed with a scraper, a small round bur, or other tool, not only promotes the blood supply (and especially capillary network formation) but also creates an inflammatory event—localized—capable of triggering the increase of angiogenic factor concentration. Angiogenic events occur in a rather small amount of time (it is assumed within 96 hours from

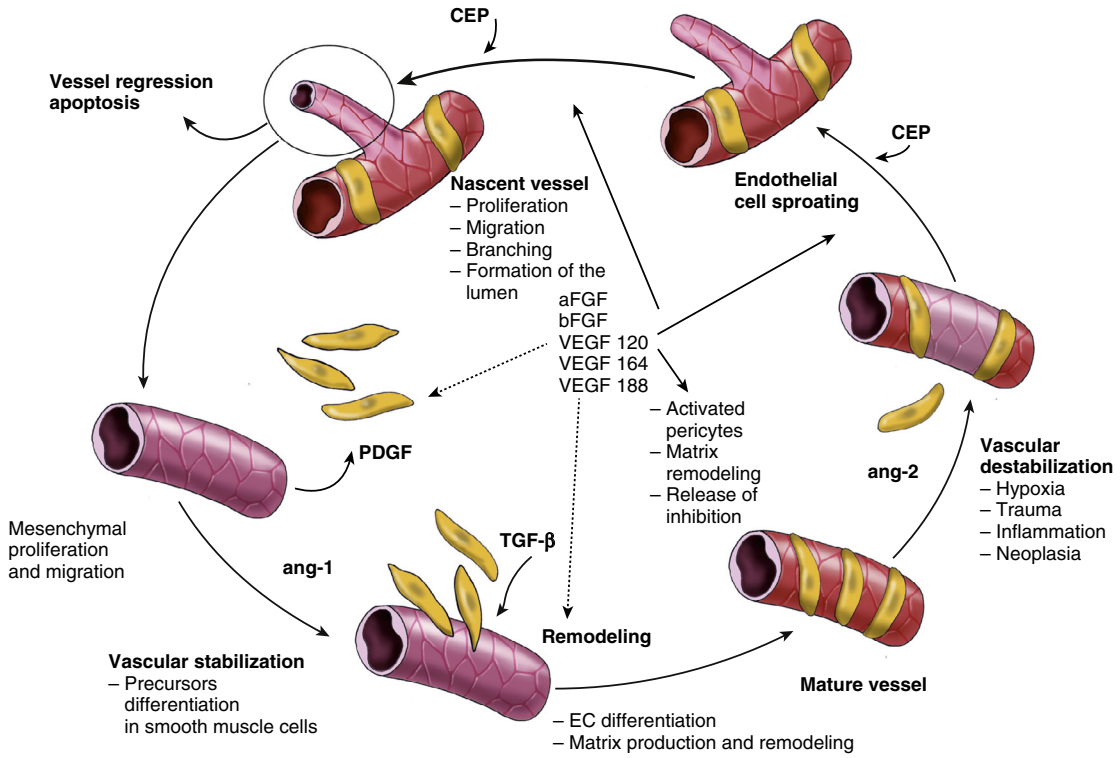

Figure 2.12 The main molecular signals involved in angiogenesis include VEGF, IGF, TGF-β, PDGF. CEP, Endothelial cells. ang-1/2, Angiopoietins. PDGF, Platelet-derived growth factor. VEGF, Vascular endothelial growth factor. FGF, Fibroblast growth factor. TGF-β, transforming growth factor beta.

implantation) and play a crucial role in the success of the whole regenerative process. Partial angiogenesis leads to a volumetrically defective regeneration. Grafted material not colonized by the vascular network will undergo resorption (if absorbable, as in the case of autologous bone), or, if non-absorbable, osseointegration (at best hypotheses), or will be encapsulated by fibrous tissue.

Morphogenesis

Once the grafted site is colonized by blood vessels, changes in permeability of vascular endothelium cell junctions, induced by specific growth factors, allow quiescent mesenchymal cells that are always present in the bloodstream to leave the vessels. These cells are not yet fully differentiated elements that retain the capability to differentiate into different cell types, such as fibroblasts or osteoblasts (multipotency). In the context of bone regeneration, specific molecular signals (in part shared with the proangiogenic signals), among which the BMP (bone morphogenetic proteins) have particular importance, induce their differentiation into osteoblasts, that is active cells. This differentiation process is known as morphogenesis. From a molecular point of view, it is interesting to note that the action of these growth factors requires the presence of specific extracellular matrix molecules. In the case of bone tissue, the presence of the bone collagen type I (present only in this tissue), which acts as a specific coactivator of pro-osteogenic signals, is necessary. It works as a sort of "confirmation signal" of the morphogenetic event, ensuring that the differentiation of mesenchymal cells into osteoblasts takes place only where they will effectively carry out their functions.

Osteogenesis

Mesenchymal cells differentiating into active osteoblasts undergo major ultrastructural modifications, clearly visible by transmission electron microscopy. The most evident is the occupation of a significant portion of cytoplasmic volume by the rough endoplasmic reticulum, the site of synthesis of the proteins to be excreted. The active osteoblast (Fig. 2.13), in fact, synthesizes and secretes the bone extracellular matrix. It is a mixture of proteins and proteoglycans; the most abundant secretion, however, consists of tropocollagen molecules, which, outside the cell, will organize into microfibrils, fibrils, and bone collagen fibers. The active osteoblast is also characterized by the expression and activity of alkaline phosphatase, a tetrameric surface glycoprotein. This protein is present in different isoforms that also could reflect different stages of maturation of the cell. Although it is believed to play a key role in the process of bone mineralization, its biologic function is still not exactly understood. From a histologic point of view, osteoblasts are arranged in single-cell filaments surrounding the portion of bone trabecula in the process of growth (Fig. 2.14). Cells are interconnected by gap junctions that connect the cytoplasm and enable the coordination of the metabolic activity of the entire group of cells.

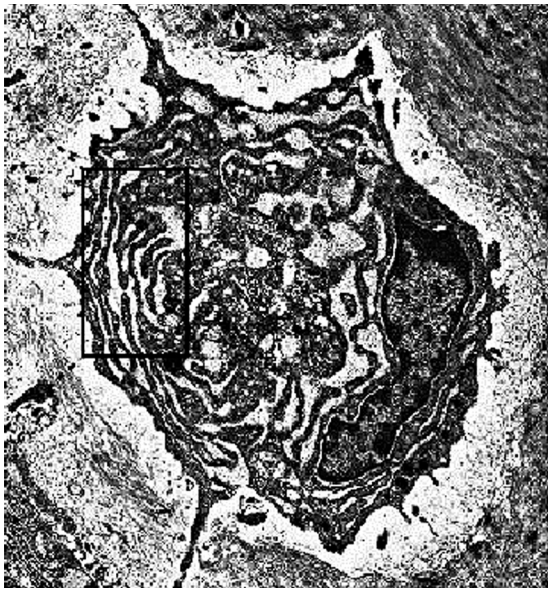

Figure 2.13 (Transmission) electron microscopy: osteoblast. Cellular cytoplasm of an active osteoblast, rich with mitochondria and, above all, rough endoplasmic reticulum, the site of synthesis of the proteins to be excreted. In the box a portion of rough endoplasmic reticulum is highlighted.

Collagen fibers produced by osteoblasts, recognizable by their typical transverse striations, and spaced approximately 70 nm because of the regular arrangement of tropocollagen molecules within them, are subsequently mineralized by placing on them a calcium and phosphorus complex salt (bone apatite) (Fig. 2.15) The mechanism of collagen fiber mineralization is still under study, but it is supposed to occur based on the fact that the regular structure of collagen could present nucleation centers for the formation of mineral crystals, facilitating their deposition (this physical process is called epitaxy). Structural regularity of collagen fibers is also responsible for their birefringence, a property used in optical microscopy for analysis of histologic sections, because when illuminated with polarized light, they refract and become very bright, allowing the identification of newly formed tissue areas (Fig. 2.16). In addition to the proregenerative action, because of its peculiar regular structure, bone collagen is also able to promote specific cellular events. For brevity, a review of cellular adhesion is presented. Both osteoblasts and osteoclasts are capable of joining bone collagen as a result of recognition by cell surface proteins, such as integrins, and

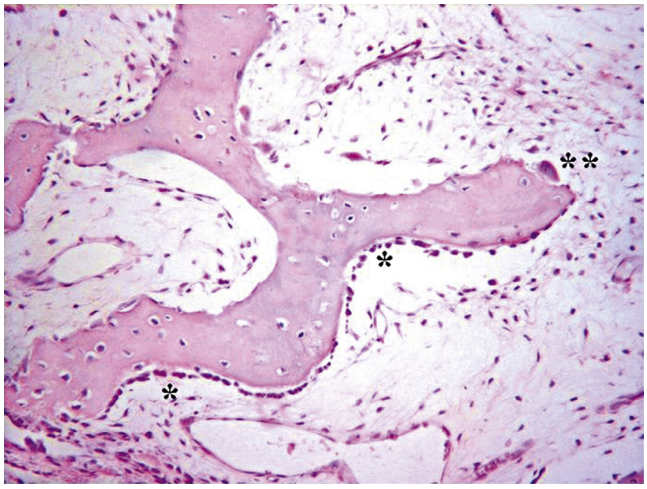

Figure 2.14 Osteoblasts lined up along a bone trabecula: osteoblasts (asterisk) are arranged in single-cell filaments close to the trabecular bone. In this picture an osteoclast (double asterisk) is also recognizable. Within the trabecula, osteocytes are visible in bone gaps.

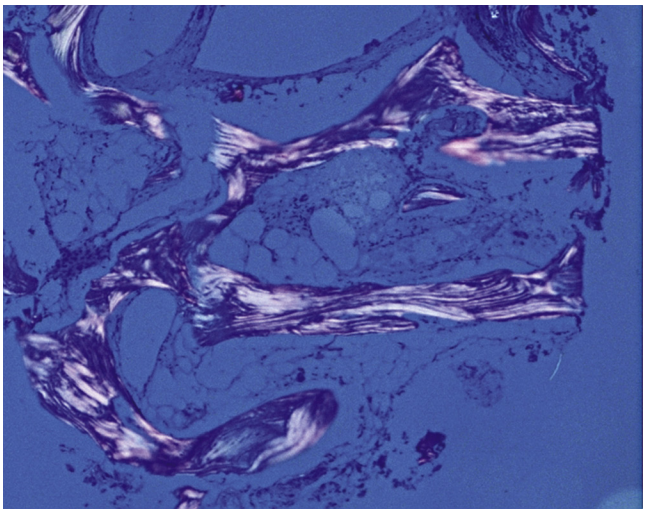

Figure 2.16 In polarized light, bone histologic sections show birefringence of collagen fibers within them. (Courtesy of Dr. Danilo Alessio Di Stefano.)

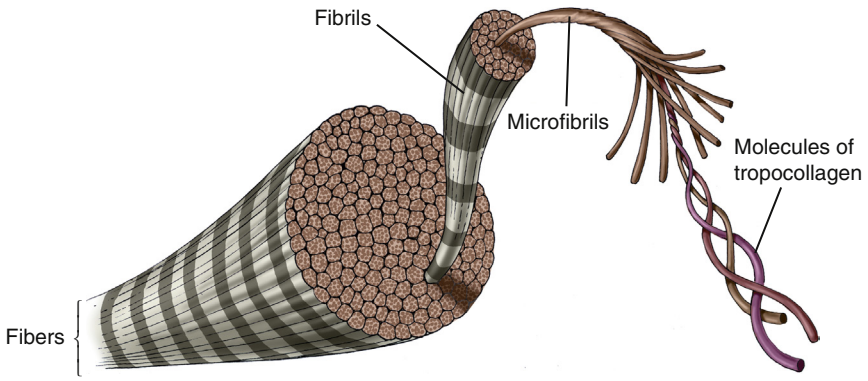

Figure 2.15 Collagen structure: molecules of tropocollagen secreted by osteoblasts are organized in microfibrils, fibrils, and fibers.

tropocollagen-specific amino acid sequences, such as the RGD sequence, consisting of the amino acids arginine, glycine, and aspartate. During the process of bone formation some osteoblasts get incorporated into the bone trabecula, becoming osteocytes (see Fig. 2.14). Osteocytes are interconnected through a network of cytoplasmic extensions passing through thin canals. The function of osteocytes is probably to secrete specific protein signals. There also could be other functions that may be further defined through continued extensive studies.

Osteoclastic Resorption

Subsequently, another line cell line will appear in the graft site, the osteoclasts, which will differentiate from precursor cells coming from the bloodstream belonging to the monocyte-macrophage line. Osteoclasts are responsible for bone mineral matrix degradation. From a morphologic point of view the osteoclast is easily recognizable because it is a multinucleated cell, derived from the fusion of mononuclear elements. The first step of the matrix degradation activity is the cell adhesion to the mineral. Subsequently, it forms a tight seal with the mineral portion, isolating a surface portion under the cytoplasmic membrane and creating a closed volume. Within this volume, the cell secretes, through proton pumps and ion channels present on the cell membrane, hydrogen ions (H^+), which partially dissolve the bone apatite and expose the collagen fibers on which they were deposited. The creation of this seal provides the osteoclast, in its portion in contact with the mineral part, the typical "ruffled border" appearance (Fig. 2.17). From an ultrastructural point of view, the creation of the seal corresponds to specific cytoskeletal changes that allow membrane adhesion to the underlying mineral. These changes lead to ultrastructural formation of rings of actin filaments, clearly visible in immunofluorescence microscopy and characteristic of this cell type. From a biochemical point of view, the osteoclast is distinguished by the expression and activity of several markers, including the lysosomal enzyme tartrate-resistant acid phosphatase (TRAP), which could act as a regulator of other proteins of the extracellular matrix involved in bone metabolism, such as bone sialoproteins and osteopontin, modulating the degree of dephosphorylation. These proteins, together with collagen, are some of the major substrates of the osteoclast adhesion, and their phosphorylation/dephosphorylation may be linked to the osteoclast movement. Osteoclasts, in fact, migrate by amoeboid movement on the mineral surface, leaving resorption traces or trails, observable by scanning electron microscopy (Figs. 2.18 and 2.19). The process of detachment, migration, and adhesion could be modulated by the phosphorylation/dephosphorylation cycle of extracellular matrix proteins mentioned earlier.

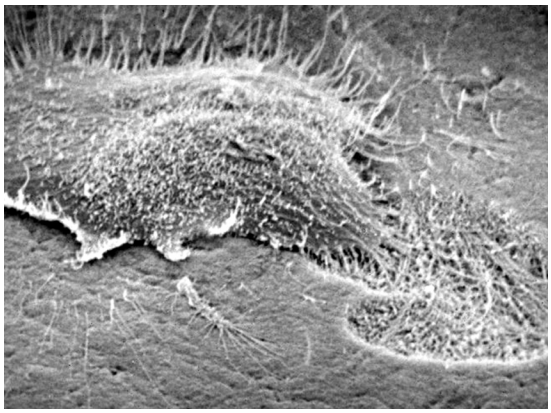

Figure 2.18 Osteoclast migration on the bone surface.

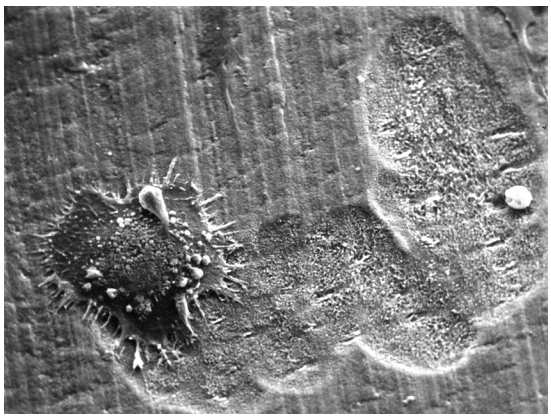

Figure 2.19 The osteoclast is able to move on the bone surface with amoeboid movement, sequentially digesting its portions.

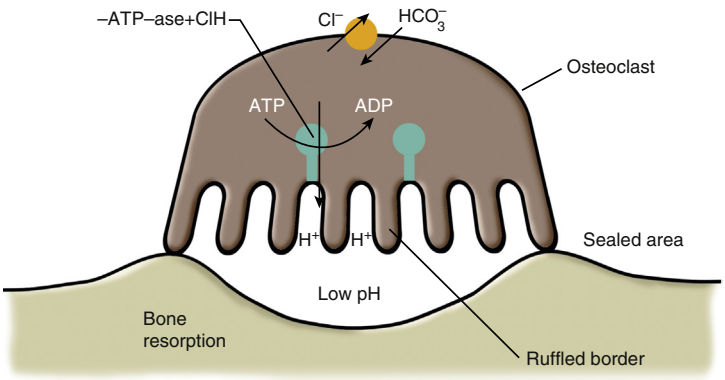

Figure 2.17 The osteoclast adhesion to bone surface produces a closed volume, within which are secreted H^+ ions that degrade the bone mineral component.

Bone Remodeling

The presence of osteoclasts, together with the action of osteoblasts, makes possible bone remodeling, the mechanism by which the mineral part of bone tissue is continuously reshaped by resorption and redeposition. This continuous turnover addresses two physiologic needs: first, it allows the bone trabecula to arrange spatially and structurally to respond in the best way to the forces of static and dynamic load that they have to bear; second, the continuous deposition/resorption process of the mineral component enables fine control of calcium blood levels, which should be maintained within fairly narrow ranges. For these reasons, osteoclast activity is regulated by various hormones such as parathyroid hormone, calcitonin, and others. Endocrine imbalances can therefore conduct pathologic alterations of bone metabolism (e.g., osteoporosis). The joint activity of osteoclasts and osteoblasts achieves an important result: if the grafted material is recognized and degraded by osteoclasts (as in the case of autologous bone), it will be physiologically replaced by patient's living bone tissue. Alternatively, as in the case of other grafting materials, two different outcomes could occur.

In the first, the material will be degraded through various mechanisms (e.g., hydrolysis) whose kinetic energy is generally not aligned to regeneration and remodeling processes. In this case, typically, the material is degraded before being replaced, and the regeneration process leads to an avolumetrically defective result. In the second, the material is not destroyed through other mechanisms and is poorly or not degraded by osteoclastic activity. In this case, the grafted material lingers for a long time within the newly formed bone tissue, with no consequences if the intervention was performed just for aesthetic purposes, but with the possibility of a functional deficit (lower resistance to loading forces) if the site has been regenerated for the purpose of insertion of osseointegrated implants.

Creeping Substitution

In the case of cortical bone grafts of autologous or homologous origin, the mechanism leading to bone regeneration, rather than occurring by apposition (on them) of new bone tissue, develops from the beginning through a specific substitution remodeling process named "creeping substitution." Revascularization of the cortical tissue by vessels from the recipient bed and the periostium is particularly slow, because of the high density of the cortical component; the only points of entry for the new capillary network are the rare haversian canals. For this reason, the first forming bone observed after placement of such grafts is localized on the contact surface between the graft itself and the recipient bone bed. In this example, active osteoclasts from the recipient bed begin to demolish graft small portions, which will then be filled by the action of osteoblasts by a new mineral lamellar component. Over time, the whole graft will be remodeled and become part of the normal bone turnover.

Regenerative Potential of the Grafted Site

As mentioned previously, angiogenesis is the first event—and key event—for bone regeneration to occur. Formation of new blood vessels takes place only from the bone surfaces surrounding the defect. It follows that, all other conditions being equal (bone quality, general metabolic conditions), a theoretical criterion can be established to define the regenerative potential of bone defects: the regenerative potential of a defect site will be greater the larger the viable bone surface is that surrounds it (from which new blood vessels can burgeon) and the lower the volume of the defect. This criterion, although theoretical, is not quantitative and is based on the assumption of the homogeneity of all the other conditions. This does, however, represent a good index of the intrinsic difficulty of bone regeneration that is going to be performed. Therefore bony defects are classified on a scale ranging from a minimum to a maximum regenerative potential, in one-, two-, three-, or four-walled defects. In fact, volumes being equal, the extent of bone surface from which blood vessels can emerge is the first decisive factor for the success of regeneration.

Clinical and Applicative Considerations

Based on the previously described biochemical and biologic mechanisms by which bone regeneration takes place, it appears that angiogenesis is the most clinically manageable event. Procedures carried out in preparation of the recipient site and, later, in the positioning of the graft affect, significantly, the correct occurrence of the angiogenesis. From a surgical point of view, therefore, it is necessary to pay particular attention to the preparation of the recipient bone bed, to enable vessel growth through the graft, removing the fibrous tissue that could act as an impediment, and, above all, providing an early sign of proinflammatory response, allowing for the activation of the molecular mechanisms of proangiogenesis. It appears obvious from this discussion that any local application of anti inflammatory drugs would result in the failure of bone regeneration, by inhibition of the signals that should initiate the angiogenesis. In the case of particulate bone grafts, it is also advisable not to overpack the material, to allow for adequate space between adjacent chips so capillaries can enter the grafted site. Finally, the importance of proper stabilization of the graft is essential and a clear requirement because any micromotion with respect to the recipient bed would cause the destruction of the fragile capillary network, preventing colonization of the graft by the capillaries. Similarly, it is necessary to ensure maximum contact between bone bed recipient and graft. Any gap constitutes an impassable barrier for newly forming vessels, which cannot grow in a vacuum but require a physical support.

What is the Future for Bone Regeneration?

At present, good surgical practices/techniques are the only clinical procedures that somehow act directly on the biology of bone regeneration (graft site preparation, compaction of the bone chips, graft stabilization), all of them affecting, directly or indirectly, the angiogenesis process. Theoretically, however, it can be assumed that both angiogenesis and other phases of bone regeneration could be affected by different (other) modalities. An example of this is given by the incorporation of growth factors (mainly bone morphogenetic proteins) in the field of the bone regeneration. This approach appears promising, although at present the high cost involved to obtain recombinant proteins is still an obstacle for clinical application on a grand scale. In addition, this approach requires a single

growth factor to be used (because of the previously mentioned cost reasons), although it is apparent that the physiologic stimulation takes place through the interaction of many factors.

An alternative approach is to use demineralized bone matrix (of homologous or xenogenic origin) obtained from cortical bone by complete demineralization. The remaining bone collagen, of both human and animal origin, added to the grafted material, contains a cocktail of growth factors capable of exerting an osteoinductive effect. In this case, however, it cannot be defined as osteoinduction in the strict sense, but only as a facilitation of the regenerative event, as within the Demineralized bone matrix (DBM) the growth factors have a basal concentration (and can vary considerably among individuals). From a theoretical point of view, another very promising approach provides the addition of stem cells to synthetic or natural scaffolds, aimed at increasing the graft osteogenicity. However, this type of application (which in any case would be legally limited to the use of stem cells from the same patient) is still a long way from being used for large-scale clinical applications due to various problems inherent in both obtaining both the selection and multiplication of the cells themselves, in addition to their suitable handling (equal to those in which the drugs are prepared and distributed).

INTRAORAL BONE HARVEST

Marco Rinaldi, Angelo Mottola

Bone defects that can be treated under local anesthesia in a dental operatory, possibly with the aid of conscious sedation (see Chapter 5), are limited-extent defects. It is very useful to develop a three-dimensional view of defects to quantify precisely the volume of bone that must be grafted and therefore harvested from a donor site. The main donor sites in the oral cavity are the mental symphysis and the mandibular ramus.

Minor Harvests

In addition to the main sites, there are also minor sites such as the maxillary tuberosity, the zygomatic bone, inter-implant sites, and also the bone recovered from the preparation of implant sites. In some situations, these small samples (Figs. 2.20 to 2.26) can be used for the correction of small defects and to help fill in gaps around a larger bone block.

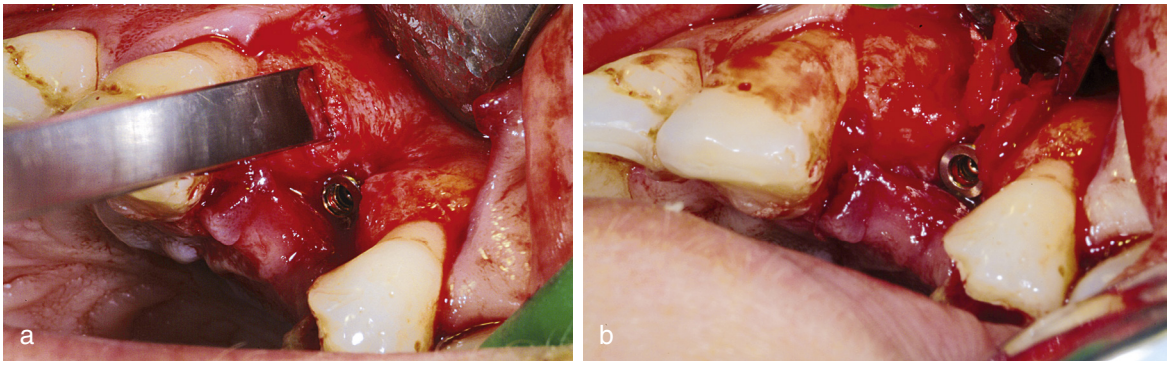

Figure 2.20 (a) The chisel removes bone from the buccal surface. (b) Harvested bone graft.

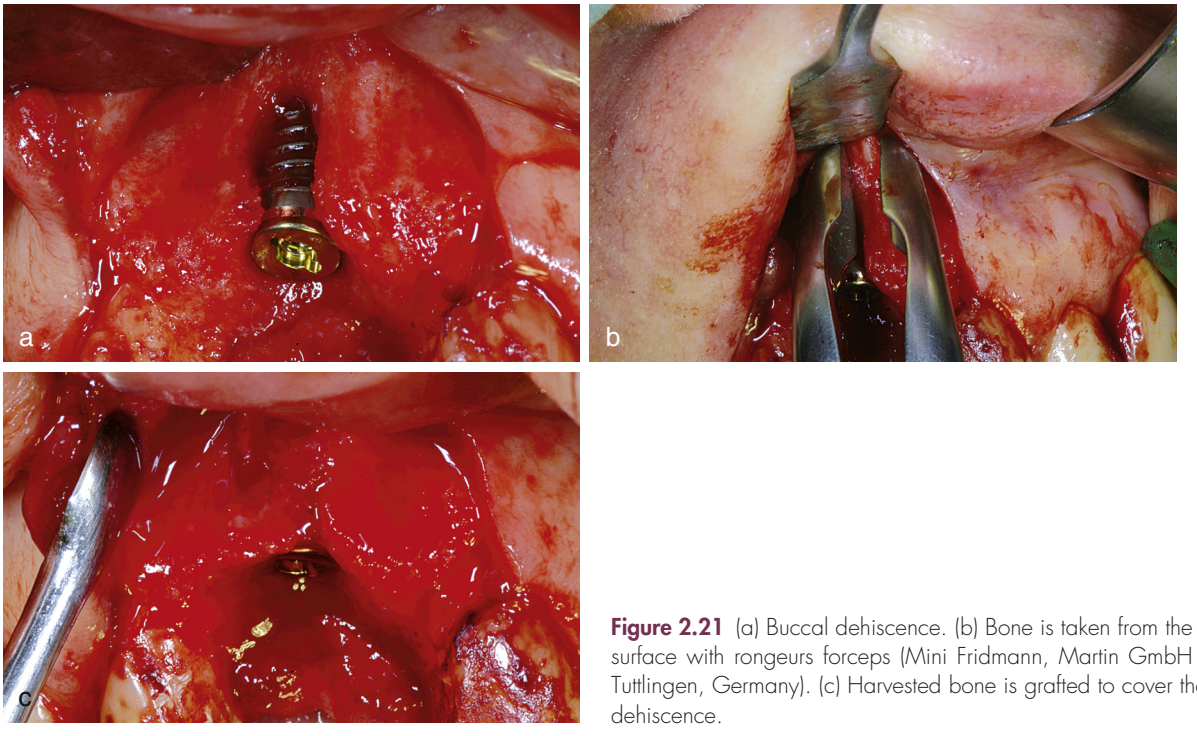

Figure 2.21 (a) Buccal dehiscence. (b) Bone is taken from the buccal surface with rongeurs forceps (Mini Fridmann, Martin GmbH & Co, Tuttlingen, Germany). (c) Harvested bone is grafted to cover the bone dehiscence.

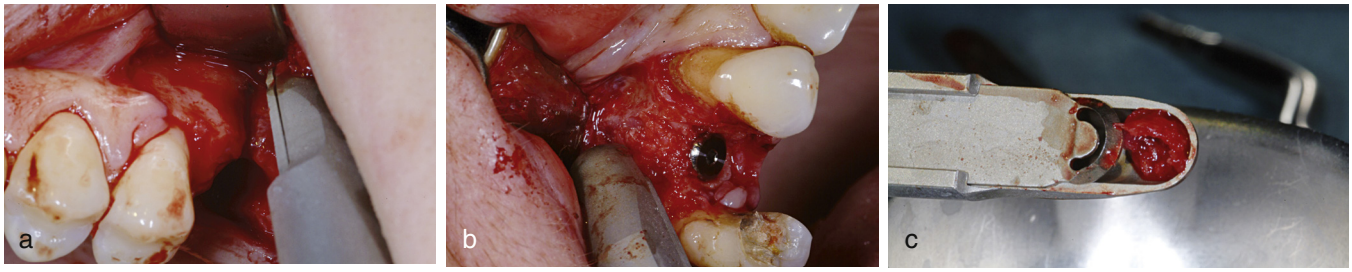

Figure 2.22 Apposite tools (a, b) enable surgeons to recover a certain amount of bone (c).

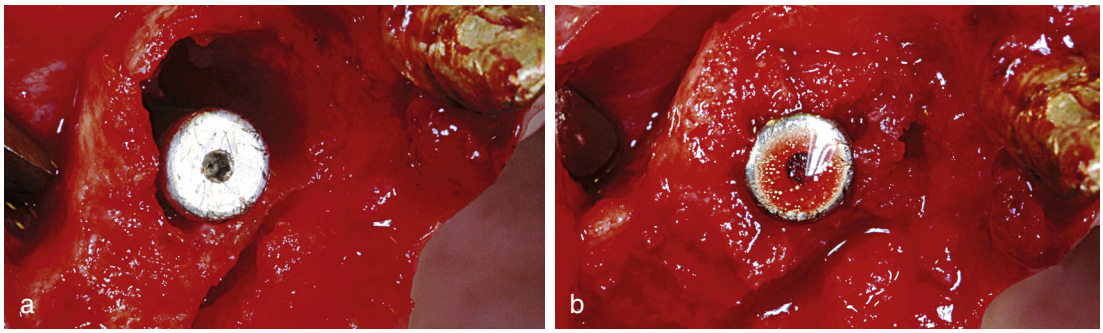

Figure 2.23 The recovered bone is used to fill the remaining space in a postextraction implant (a, before; b, after).

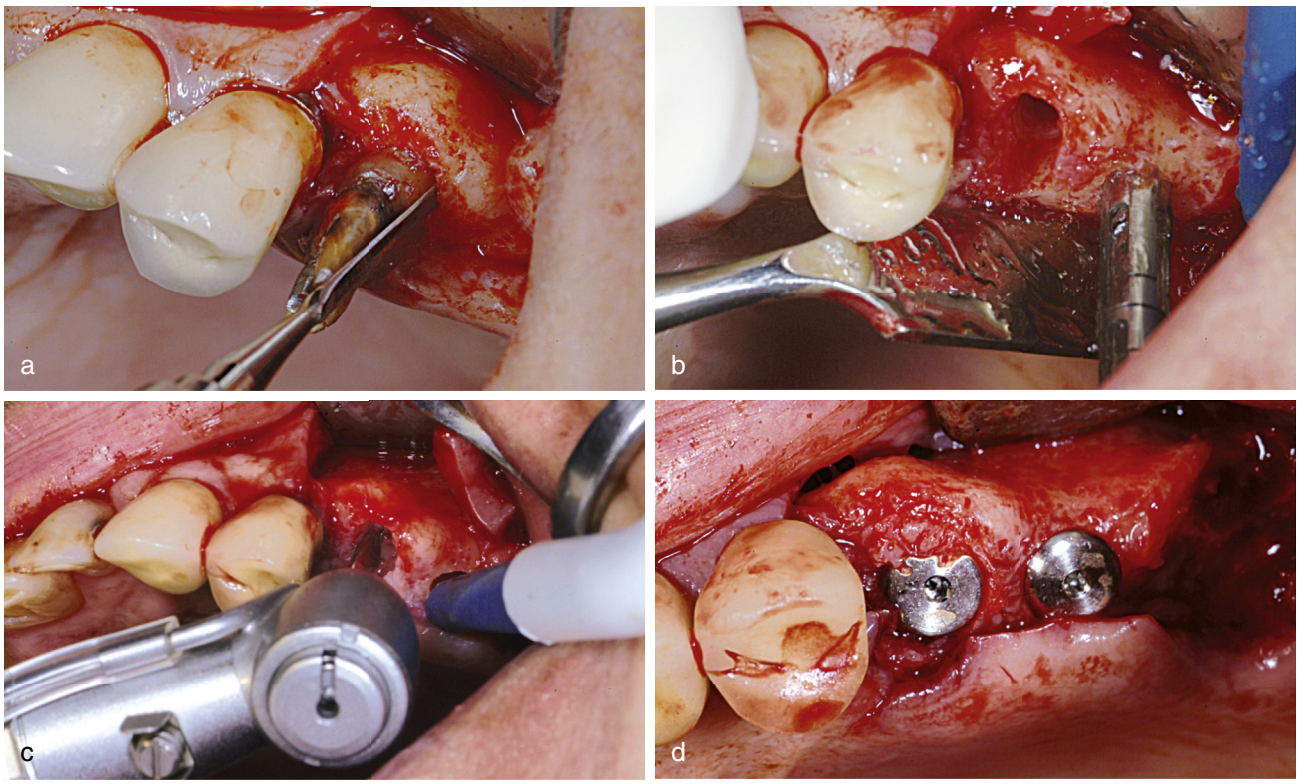

Figure 2.24 (a) Conservative root extraction with periotome (NobelBiocare AB, Goteborg, Sweden) of the root of 2.5. (b) Preparation and bone harvesting from the 2.6 site with a trephine bur. (c) Preparation of the postextraction implant site in the 2.5 site. (d) Inserted implants (NOBELSPEEDY, NobelBiocare AB, Goteborg, Sweden); bone harvested with the bur is used to fill the postextraction defect.

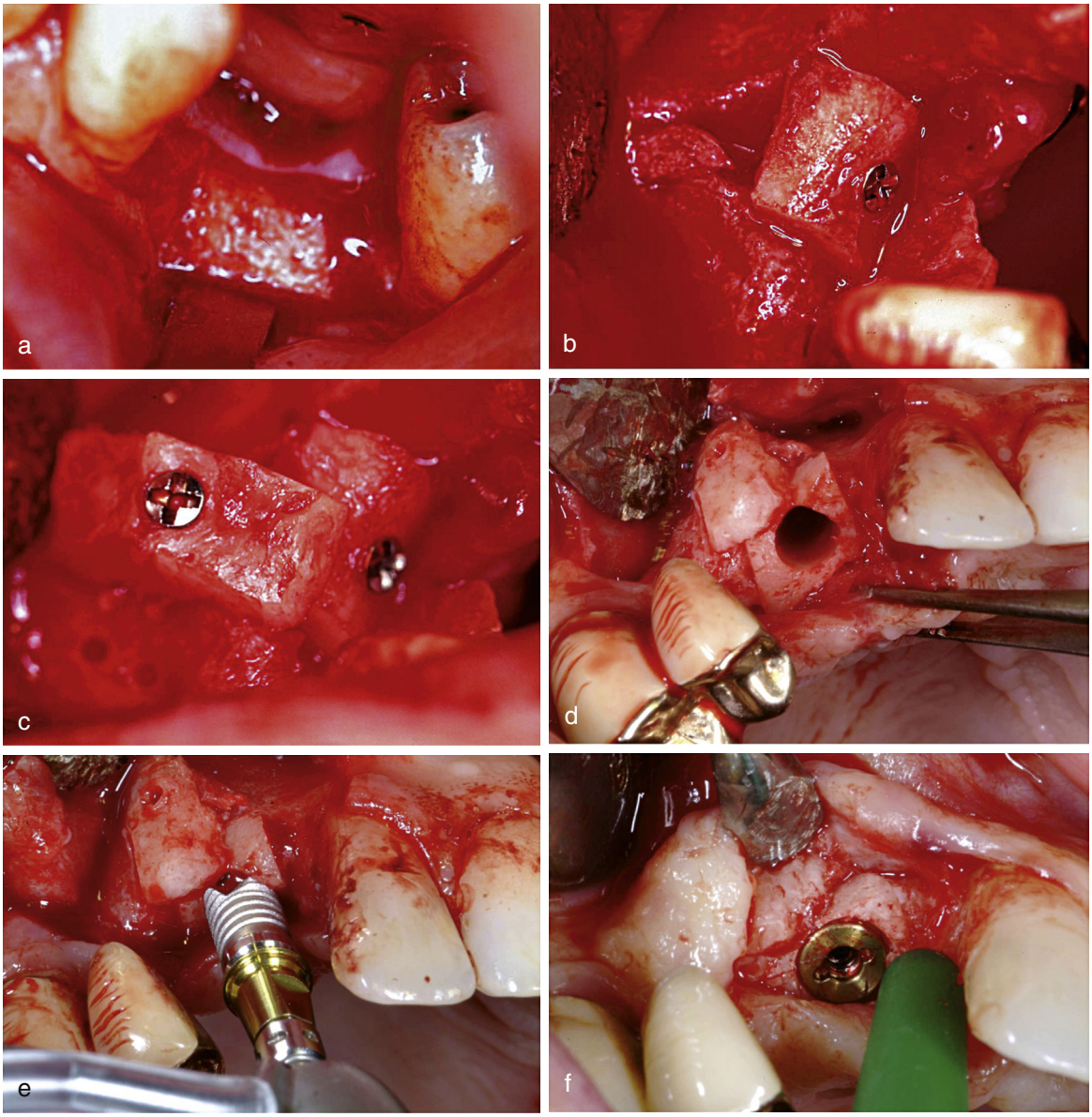

Figure 2.25 Bone sampling from edentulous alveolar bone crest, which, because of the proximity of the mental foramen, will be rehabilitated with a bridge, and not with an implant. It has been used as an onlay graft on which was placed a second graft, taken from the mental symphysis. (a) Bone sampling from the edentulous site. (b) Graft on the recipient site aimed to reconstruct the height of the defect; fixation was obtained with a vertical screw. (c) Second graft, fixed buccally and on the first graft. Fixation was obtained with a transverse screw. (d) Healing of the two grafts at 4 months. (e) Implant placement (XIVe Æ, Dentsply-Friadent, Mannheim, Germany). (f) Implant osseointegration in the grafted bone after 4 months.

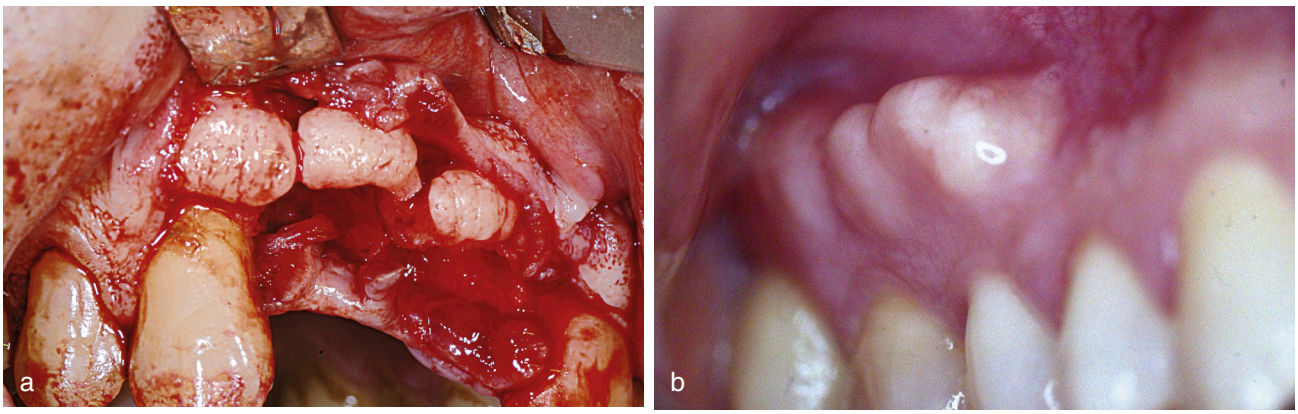

Figure 2.26 Exostoses (a, b), if present, can be used as a graft.

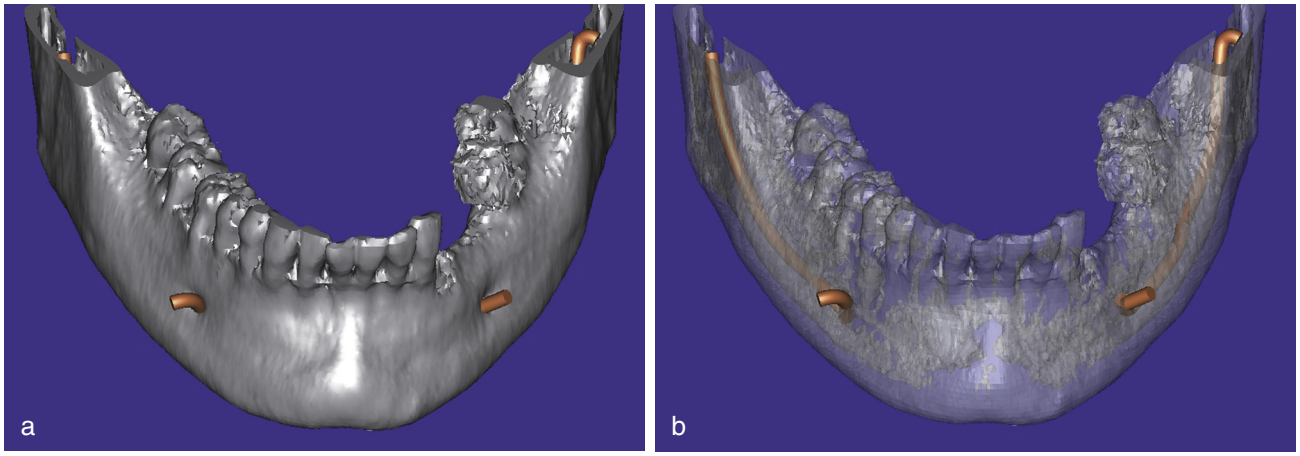

Figure 2.27 (a) Three-dimensional computed tomography (CT) view. (b) CT three-dimensional view: software for image processing (SimPlant Æ, Materialise NV, Leuven, Belgium) allows changing the transparency to visualize the deep anatomical structures. The course of the alveolar nerve is highlighted in red.

Harvests From Mental Symphysis

Donor Site. The site for harvesting bone from the mental symphysis is located between the two mental foramina, the mandibular base, and the apexes of the mandibular anterior teeth. It is essential that this prospective area should be studied with a CT/cone beam CT (CBCT) scan to evaluate the bone topography and the bone volume actually available (Figs. 2.27 to 2.31). The well-known "Rule of 5s" provides for a safe distance of 5 mm from the apices of the incisors (see Fig. 2.31), anterior to the mental foramina and above the mandibular inferior edge. This rule had some important guidelines in the past, when modern imaging techniques were not readily available in daily practice. Today, we prefer to design customized samples after studying the three-dimensional anatomy from CT/CBCT images. Using the computer software applications with undistorted views, it is possible to make the necessary measurements and also to fabricate three-dimensional stereolithographic STL resin models. Use of these technologies enable the simulation of the surgical intervention and represent a significant aid to the surgeon in the choice of the most suitable location for the bone sample to be harvested.

Anesthetic Technique. The use of mental nerve anesthesia is usually adequate with infiltrations of local anesthetic that contain a vasoconstrictor throughout the whole area to reduce the bleeding. Conscious sedation is often advisable for these procedures when applicable.

Access. To access to the symphysis there are two main incisions (Fig. 2.32): one sulcular and one buccal. The sulcus incision is preferred when the vestibule is shallow and there is considerable tension of mental muscles, whereas it is advisable to choose the buccal incision in the case of gingival inflammation and periodontal bone loss in anterior teeth and in the presence of prosthetic crowns. The sulcular incision is more conservative because it preserves more of the periosteal and muscular structures. Normally it is also necessary to perform releasing incisions at the distal ends of the first incision. In the case of small bone samples to be harvested, linear vertical incision can also be used and bone removed with a corer type of instrument or drill. In the case in which the recipient graft site is close to the donor site, it is convenient to design a flap that allows adequate exposure of the recipient bed. The incision should then continue toward

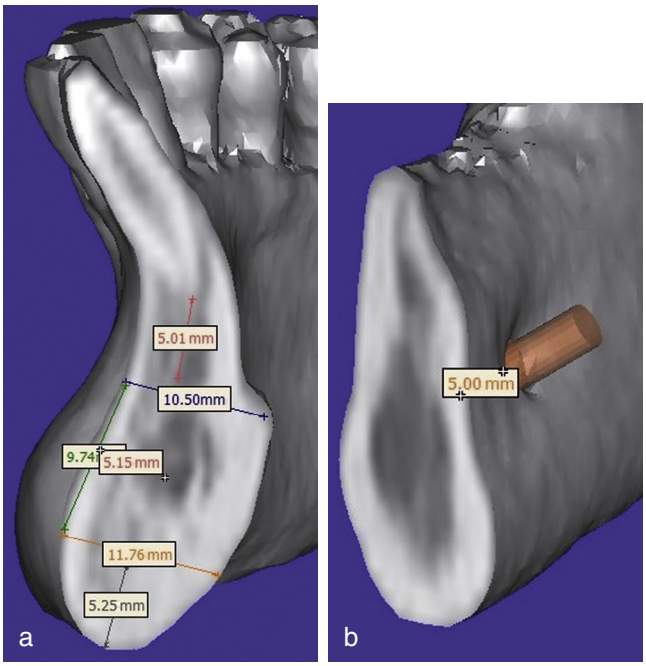

Figure 2.28 (a, b) Proceeding from a three-dimensional CT image, with implant planning software (SimPlant Æ, Materialise NV, Leuven, Belgium) it is possible to make sections (clipping) on oblique sagittal planes at any point in the image and perform any measurement. Here we see the Rule of 5s rule applied to the section. Measurements indicate 5-mm distance from the dental apexes, 5 mm from the mandibular edge, and in b, 5 mm from the mental foramen. Keeping this safe distance it is possible to harvest a block, approximately 1 cm high and 5 mm thick, without going too deep. The Rule of 5s is a general rule and has little value when the procedure can be performed directly and the presence of the anatomic obstacles can be evaluated.

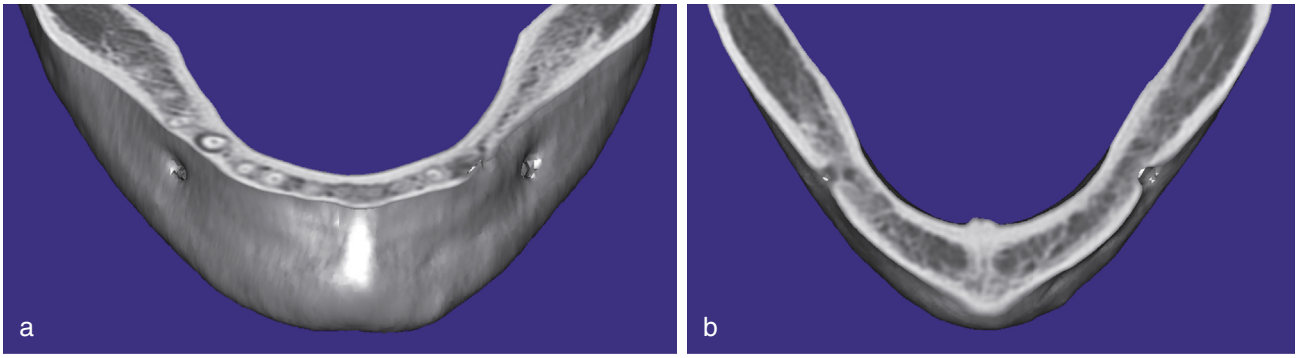

Figure 2.29 The software also can perform axial sections. (a) In this section, incisor apexes are still visible; a sample at this level could affect their vitality. Therefore it is necessary to lower the cutting height, as in b; the section passes through the mental foramina.

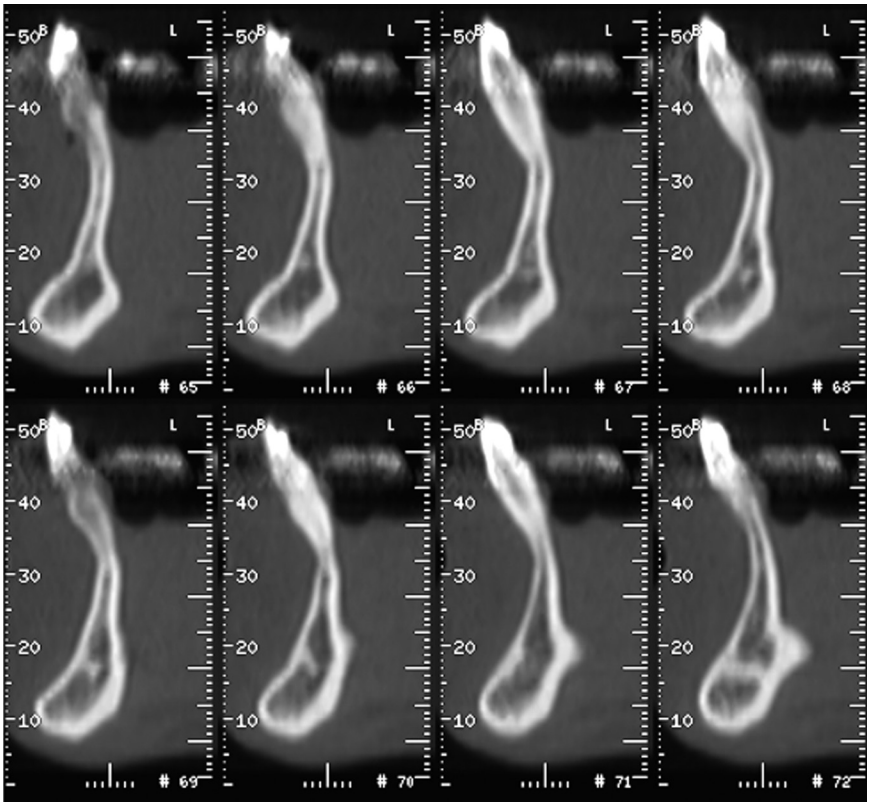

Figure 2.30 CT image reformatted in the sagittal oblique plane: the extreme thinness makes the symphysis mostly unsuitable for bone removal.

the receiving site, and the release incisions may not be necessary (Fig. 2.33).

Osteotomies and Bone Harvesting. Once the symphysis bone has been revealed through careful reflection of the mucogingival tissue, it is advisable to demarcate the harvest boundary by making small perimeter holes with the drill, a dermographic pen, or a harvest guide designed on a physical replica of the bone using a three-dimensional model (see section on STL models and surgical guides for harvests and grafts) (Fig. 2.34). Different tools can be used for the osteotomies, such as fissure-type burs mounted on straight or angled handpieces, sagittal or reciprocating saws, diamond discs, trephines, and piezoelectric instruments, depending on the operator's preference (Figs. 2.35 to 2.37). Reciprocating saws tend to stick and skip if the bone is very compact, whereas sagittal saws are more handy to use in the anterior area and in the mandibular ramus; both to make only linear cuts. Diamond discs perform straight cuts as well and require adequate safeguards to protect soft tissues. Cutting depth is defined by disc diameter. Fissure burs mounted on a straight handpiece are often used for their ease of handling because they ensure a greater possibility of properly defining the donor harvest site.

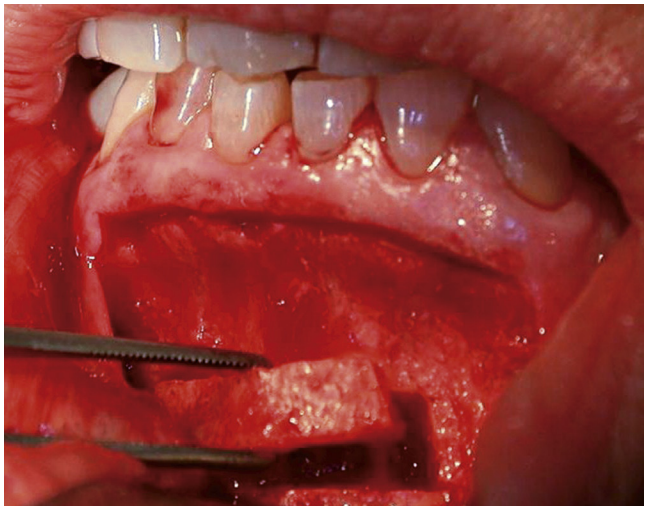

Figure 2.31 Sometimes, to avoid damage to incisor apices and impairment of vitality, the symphysis bone removal is low, near the base of the mandible.

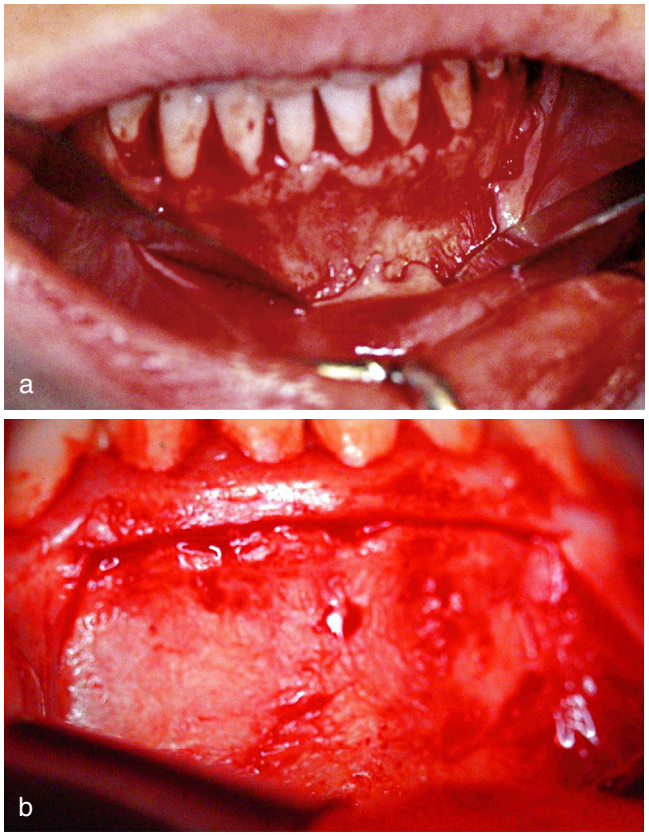

Figure 2.32 Access to the symphysis can be achieved (a) by sulcular incision or (b) by vestibular incision. (Courtesy of Edizioni Quintessenza, Milan, taken from Quintessence International 2001; 7/8 :233-240.)

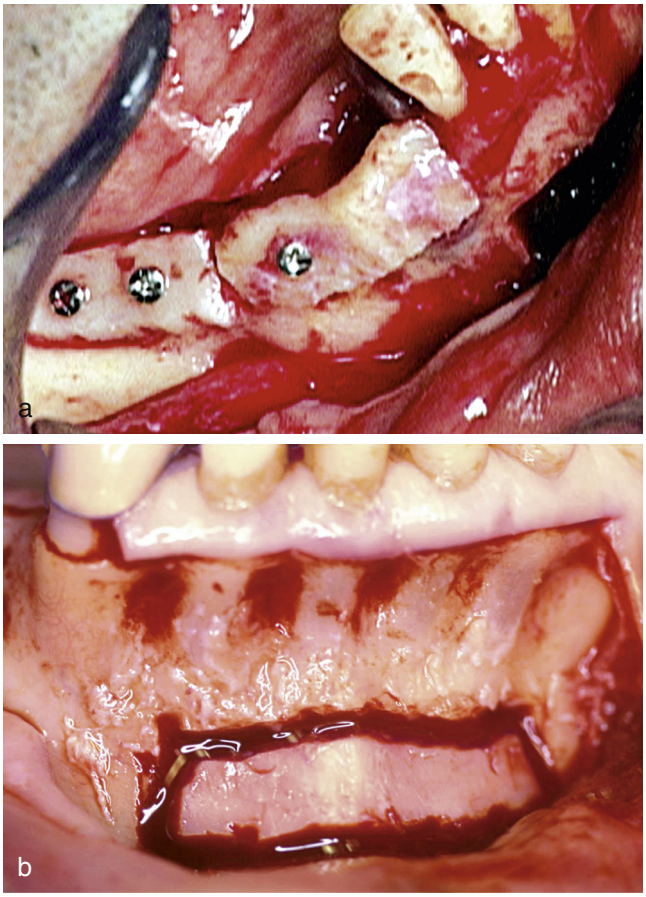

Figure 2.33 (a, b) When graft and donor sites are adjacent, it can be performed a single access flap.

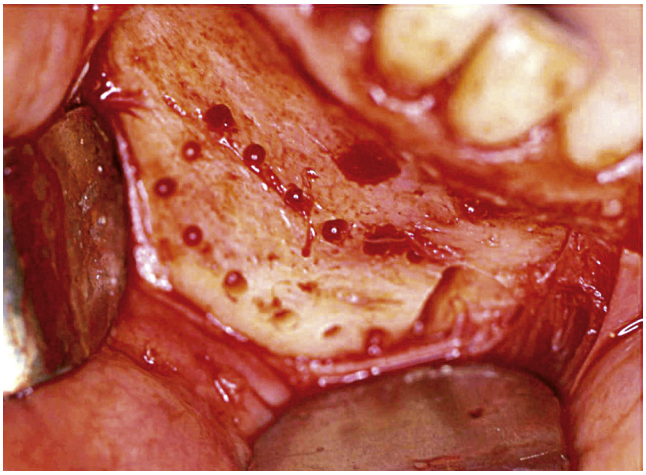

Figure 2.34 Perimeter holes border the area to be removed.

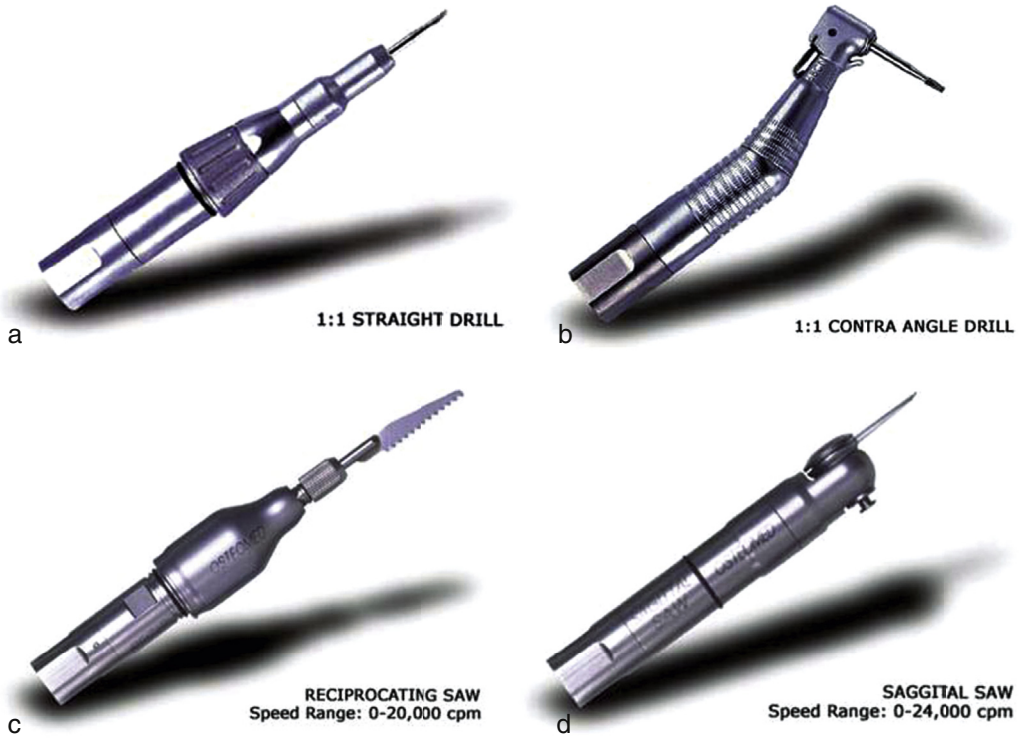

Figure 2.35 Tools for osteotomy (Osteomed LP, Addison, Tex, USA). (a) Straight handpiece with fissure bur. (b) Contra-angle handpiece with fissure bur. (c) Reciprocating saw. (d) Sagittal saw.

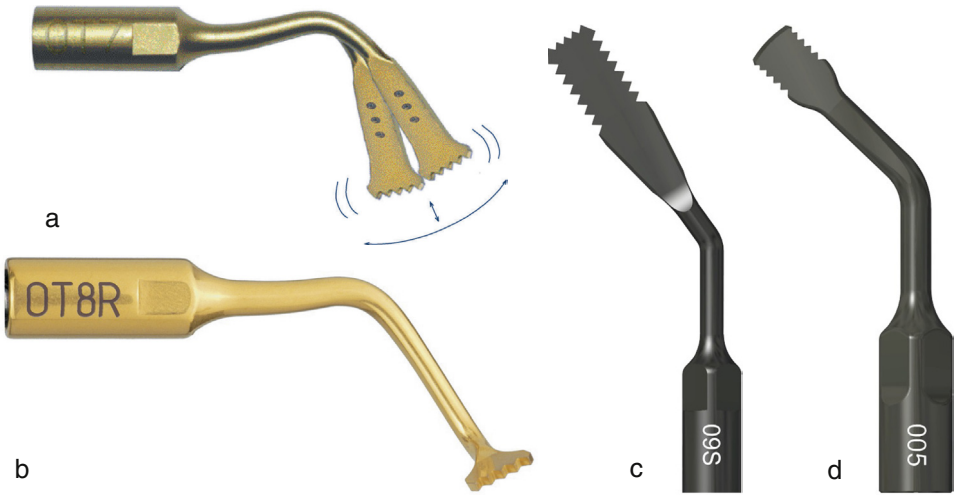

Figure 2.36 Inserts for piezoelectric surgery: OT 7 (a), OT8R (b), O9S (c) and 005 (d). (a and b, Piezosurgery Æ, Mectron, Genova, Italy, c and d, Surgysonic, Esacrom, Bologna, Italy.)

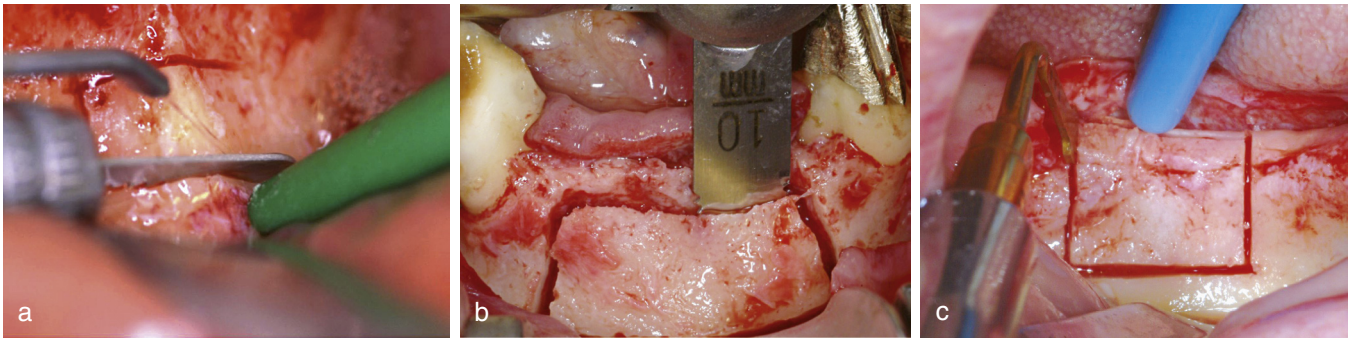

Figure 2.37 Reciprocating saws (a) tend to stick, whereas sagittal ones (b) are more comfortable in the anterior area (c). Osteotomy by piezoelectric instrument (OT 7).

When using harvest guides, fissure burs allow the operator to follow, as with a stencil, the contour of the guide and to create any shape (Fig. 2.38). Moreover, because the fissure bur's working length is known, it is possible to control the depth of the cuts. Regardless of the technique used, the osteotomies should never be too deep and should always be designed after careful review of a CT/CBCT scan to adequately assess the patient's anatomy. Once the extent of cuts has been determined the goal is to remove the donor bone block from the site. To remove the block, simply cut the cortical bone around the perimeter, paying close attention to the corners while visually ensuring the completeness of the cortical osteotomy. Generally, if osteotomies are well executed, the bone block is easily removed by chisels and gentle hammering (Figs. 2.39 and 2.40). The size and shape of the harvest are determined by the morphology of the recipient site.

Sometimes, certain anatomical features of the symphysis can be used advantageously for grafting. For example, depending on the anatomical reality, you can use the harvested bone from the symphysis to manage the desired donor shape through contouring or to create a wedge or an L-shaped graft (Figs. 2.41 to 2.44). The mental symphysis can be used as a source of bone even when particulate bone is needed; coring burs are used in these cases (Fig. 2.45).

Treatment of Donor Site and Suture. After bone harvesting, the topical use of an oxidized cellulose gauze is usually sufficient to control the bleeding; rarely, it is necessary to use the monopolar or bipolar coagulator. Filling the void left at the donor site with ancillary biomaterials and/or using membranes to promote bone regeneration is optional. The access wound is closed with a two-layer suture technique. The first layer is performed with an absorbable suture wire, which stabilizes the mental muscle to the periosteum; the second layer then closes the mucosal plane. The wire goes deep at the base of the flap, anchoring into muscle, and then returns higher to allow for fixation to the periosteum, or if for some reason this is difficult, the bone itself. The bone suture technique that we advocate is performed after drilling a couple of small holes in the thickness of cortical bone at the more cranial level of the osteotomy within, through which the wires pass (Rinaldi 2001). When tightening the knot, the adhesion of the mental muscles to the bone is immediately observable (Figs. 2.46 and 2.47). Compared to the periosteal suture, bone suture offers greater resistance, allowing support for the heaviest loads needed in this area. The chin wound is constantly stimulated by speaking and varied facial expressions and thus is rarely at rest. Using this technique may prevent the frequent complication of flap dehiscence. Some authors recommend a pressure bandage on the symphysis in the immediate postoperative period to control swelling (Figs. 2.48 to 2.50).

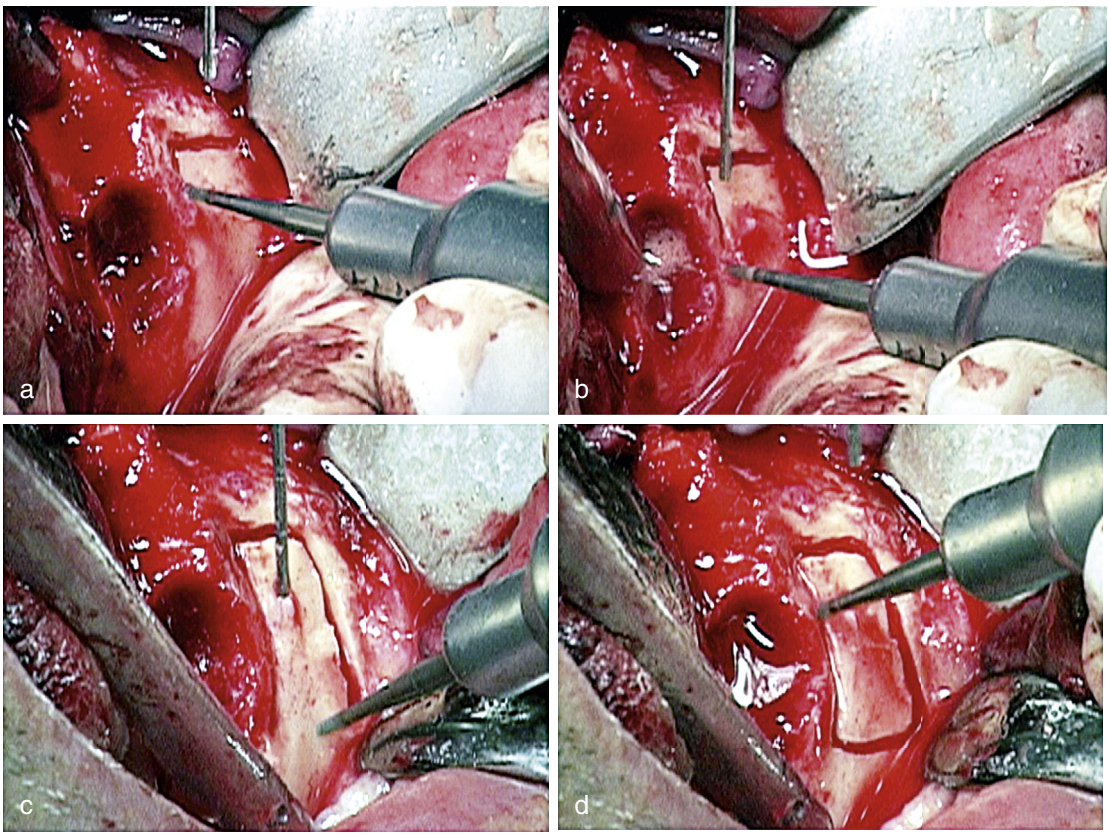

Figure 2.38 Paramedian bone harvesting from mental symphysis: (a-d) fissure bur cuts the cortical bone block to be harvested.

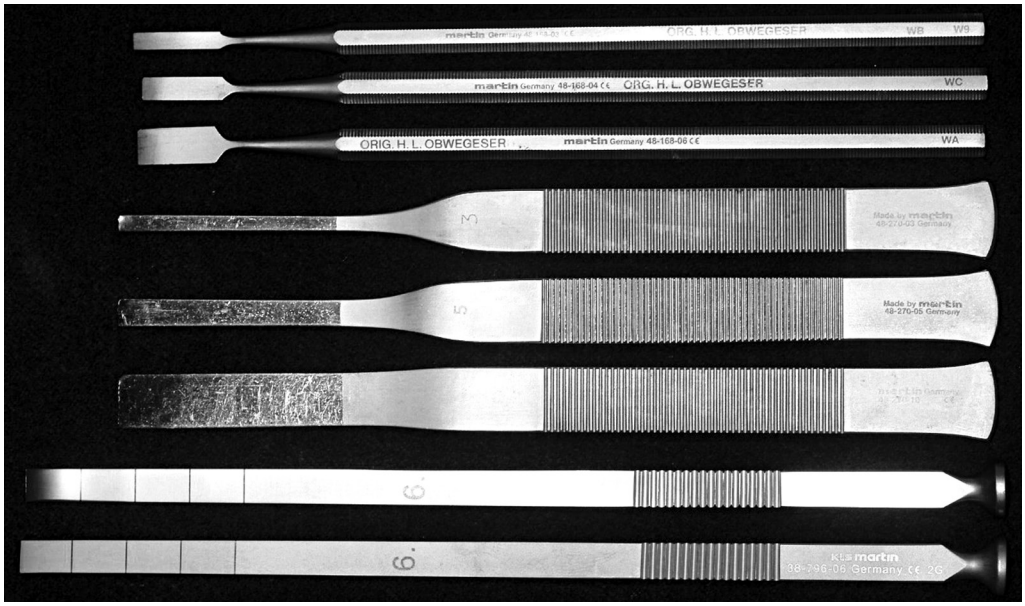

Figure 2.39 Chisels used for bone harvesting: from bottom to top Epker, Tessier, Obwegeser (Martin GmbH & Co, Tuttlingen, Germany).

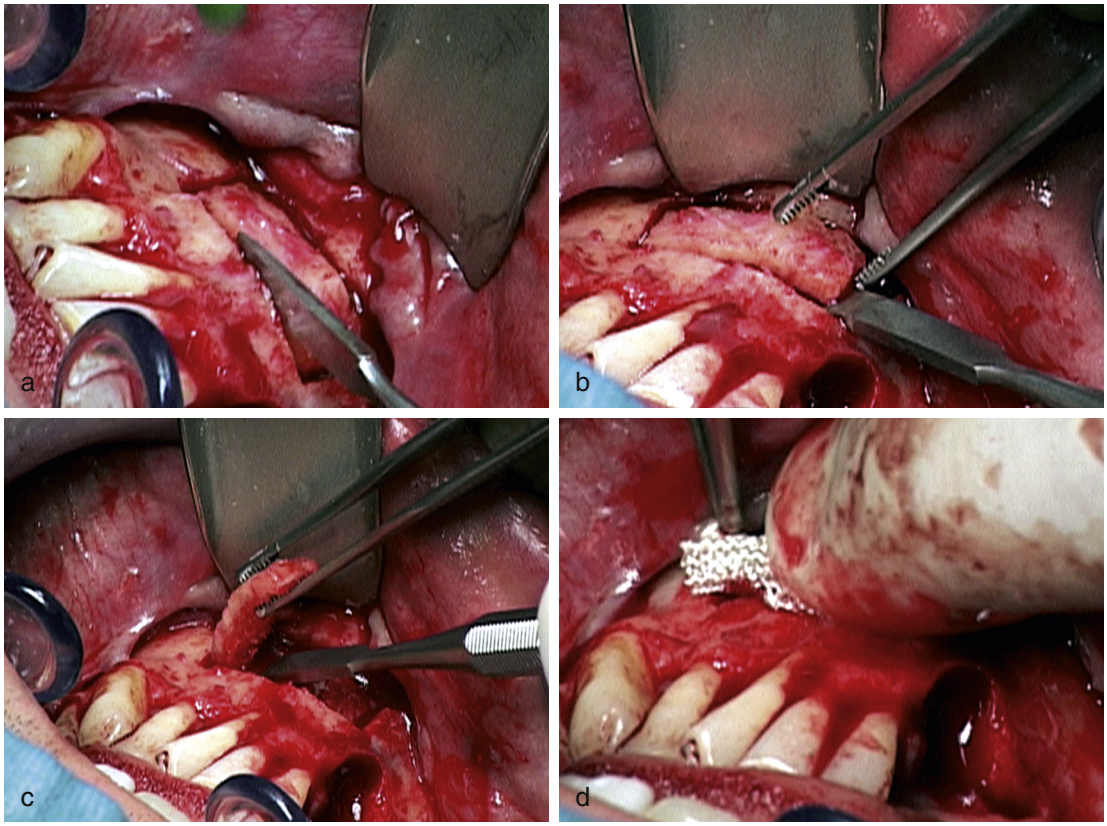

Figure 2.40 (a) Harvest borders are refined by a chisel. (b) The block begins to be removed as the chisel is introduced through the osteotomy. (c) Harvest removing. (d) Hemostasis by oxidized cellulose.