Atlas of Virtual Surgical Planning and 3D Printing for Cranio-Maxillo-Facial Surgery

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Editors

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Springer

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ISBN 978-3-031-94494-9 ISBN 978-3-031-94495-6 (eBook)
https://doi.org/10.1007/978-3-031-94495-6

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Preface

This Atlas represents the evolution of a scientific and systemic thought, rooted in a profound reflection on the need for a new "humanization" of medicine that strongly considers technological innovation and progress at the same time not forgetting the responsibility of clinicians' role. The advent of technology and the introduction of artificial intelligence opened new scenarios regarding the care of the patient. It becomes essential to be engaged in a deep consideration of the ethical value of technology that enhances the human dimension of health professionals. Concretely, this means applying all the opportunities offered by technological innovation, including artificial intelligence, to good clinical practices while respecting Ethics and Morality. For this reason, the paradigm shift must allow technology and the humanization of care to pass through an emotional, relational, and practical educational path to meet population health needs, which today must consequently include innovation and technology, defining what we in Udine have named Techno-Humanization.

Each topic of this book is the result of a human relationship among colleagues worldwide who share a common passion: medicine as a Science that renews and enriches, and the human being as a Priority. Together, we have collaborated by highlighting in each chapter the innovative work in the field, expressing the best doctor-patient relationship, extraordinarily supported by virtual reality, which in the last decade has become an essential tool for providing the best care to our patients in the head and neck district. All this is an expression of the rapid progress of Medicine and Surgery, which recognizes its foundations in education, research, innovation, and the conscious use of technologies, and must inevitably consider the Humanization of Care a founding principle.

Humanizing Care, in the modern sense, also means putting technology at the service of the person. This Atlas clearly shows that attention to detail and meticulous description of the design phases are developed with the ultimate goal of spreading knowledge so that anyone who wishes can replicate the Real and Virtual care experiences for their patients. Dr. Alessandro Tel, the creator of this extraordinary project, a profound connoisseur and user of virtual planning software and 3D printing, along with the other Authors, guides the reader in a didactic presentation that makes the text a true guide to the most modern and sophisticated techniques of Virtual Planning and Surgery.

The growing role of new technologies in healthcare and their use cannot be separated from human intelligence, which will see in this volume the highest expression of surgical virtuosity expressed by the human hand. In the health chain, which must ensure the comprehensive care of the patient, it is now essential to train and benefit from multiple professional figures, beyond doctors and nurses, for true teamwork: IT specialists, robotics experts, AI, Virtual Reality, Augmented Reality, immersive navigation, intraoperative navigation, (data analysis experts, health statisticians, quality control experts, management engineers, clinical engineers, physicists, sociologists, psychologists, biotechnologists, legal experts, project managers), in order to develop aspects of 5P medicine (Personalized, Predictive, Preventive, Participatory, Populational) related to technology, such as Personalized and Precision Surgery.

The new healthcare professional must have the ability to use technologies creatively, not only to improve therapeutic and organizational effectiveness but also to increase the time available for patient relationships, facilitating communication and interactions. Technologies such as virtual surgical planning support verbal descriptions with realistic images, enhancing patient understanding and making consent truly informed. This approach transforms the traditional parental doctor-to-patient model with a purely informative one, creating a more participatory and aware relationship with our patients.

Therefore, building a defined vision of techno-humanization means allowing health professionals to facilitate the integration of skills, generating interconnections between different disciplines that aspire to create a new model of prevention, diagnosis, and care.

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1 Introduction to Virtual Surgical Planning Software

1.1 Definition and Purpose of VSP Software

Virtual Surgical Planning (VSP) is a technique that utilizes computer-based systems to digitize clinical data for diagnosis, design of surgical procedures, treatment planning, and outcome prediction. The process begins with data acquisition, primarily obtained from radiological imaging. This data is then transformed into a three-dimensional (3D) model within a virtual environment, serving as the focal point for analysis. VSP's development was driven by advancements in Computer-Aided Design (CAD) and Computer-Aided Manufacturing (CAM), which originated in mechanical engineering but were later adapted for medical use. Today, VSP is widely employed in craniomaxillofacial (CMF), orthopedic, and reconstructive surgeries. It has been shown to enhance surgical precision, assist in outcome prediction, and improve patient communication, resulting in safer surgeries and better-informed patients.

VSP encompasses essential features such as 3D model visualization, manipulation tools, and simulation capabilities, all contributing to its widespread adoption [1]. Its flexibility allows it to assist surgeons at multiple stages and integrate seamlessly with surgical practices and other technologies like 3D printing, advanced manufacturing techniques, and surgical navigation systems. The success of VSP is evident across many surgical departments, facilitated by the automation of processes from imaging acquisition to 3D rendering. This advancement has gained approval from regulatory bodies, notably the Food and Drug Administration (FDA) in the United States and the European Medicines Agency (EMA) in Europe, following the Medical Device Regulation (MDR).

1.2 Historical Background

The introduction of computed tomography (CT) in the 1970s marked a revolutionary shift in medical imaging by providing detailed cross-sectional images of the human body. Building on this advancement, Vannier et al. [2] developed the first computed three-dimensional (3D) reconstructions from CT data, significantly enhancing diagnostic capabilities and surgical planning compared to conventional two-dimensional (2D) images.

These innovations were quickly leveraged to create physical 3D models using computer numerically controlled (CNC) milling machines programmed with reconstructed CT scan slices. However, reproducing complex geometries was challenging due to the low resolution along the z-axis in early CT scans. This limitation was overcome through advancements in both imaging and manufacturing technologies. The introduction of spiral CT improved image resolution, while the advent of rapid prototyping technologies—such as selective laser sintering (SLS), stereolithography (SLA), and 3D printing—enabled the production of models with intricate internal contours [3]. Unlike CNC milling, these additive manufacturing systems were more compatible with digital data and allowed for accurate replication of complex anatomical structures.

In the early 1990s, these technological advancements were introduced into surgical departments, providing enhanced anatomical references for complex structures [3]. Shortly thereafter, fully computer-based virtual surgical planning systems emerged, which could be directly translated into navigation systems for orthopedic surgery and

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A. Tel, M. Robiony (eds.), *Atlas of Virtual Surgical Planning and 3D Printing for Cranio-Maxillo-Facial Surgery*,
https://doi.org/10.1007/978-3-031-94495-6_1

traumatology [4]. This comprehensive integration significantly improved surgical precision and reduced errors. Companies like Medtronic and Brainlab began releasing commercial neurosurgical planning systems that combined preoperative imaging with intraoperative guidance, marking a significant milestone in neurosurgical practice.

The early 2000s witnessed another technological leap with the incorporation of virtual reality (VR) and augmented reality (AR) technologies into the applied research field. Additionally, the development of 3D surface and texture scanning complemented volumetric CT data by fully rendering soft tissues, allowing for better prediction of postoperative aesthetic outcomes. As these implementations underwent extensive research and in silico trials, the simulation capabilities of virtual surgical planning techniques became more standardized [5]. Tools for performing virtual surgeries with custom implant designs and improved integration with widely available platforms and data formats—most notably DICOM—became extensively used and tested across multiple surgical fields.

1.3 Evolution of VSP Software

The first generation of virtual surgical planning (VSP) software emerged to assist surgeons in designing patient-specific prosthetics, primarily in orthopedics. Due to the complexity of these systems and their interfaces—often adapted from general-purpose CAD software—they were typically operated by engineers or specialized personnel.

- *Advancements in the 1990s*
  In the mid-1990s, significant advancements in computational power and the introduction of 3D acceleration in consumer graphics processing units (GPUs) enabled more extensive implementations of VSP software. This period witnessed the emergence of specialized software companies in the medical and surgical fields:
  - Materialise: Founded in 1990 to provide 3D-printed parts, Materialise released Mimics in 1992. Mimics was a platform that converted medical images into 3D models, integrating seamlessly into the company's main services.
  - Brainlab: Established in 1989 as a surgical planning and navigation software company, Brainlab released its first product 3 years later. The company's software facilitated the integration of CT and MRI data into digital workflows.

Research-oriented departments rapidly adopted these technologies, exploring applications such as elastography, volumetric modeling algorithms, surgical and radiation treatment planning, and image-guided diagnostics [6].

- *Innovations in the Early 2000s*
  The early 2000s were marked by:
  - Research Advancements: Engineering departments implemented VSP solutions incorporating virtual reality (VR) and augmented reality (AR) for surgical training simulators and interactive planning optimization [7].
  - Industry Commitments: A focus on providing safe and standardized software led to significant milestones. Materialise achieved FDA 510(k) premarket clearance for the SimPlant System in 2004, making it the first software for preoperative simulation and evaluation of surgical treatment—specifically dental implant placement—to receive such approval.
  - The following decade saw many other VSP tools receive clearance, leading to increased adoption by surgeons, particularly in CMF and orthopedic reconstructive surgeries. Key technical features at this stage included:

    Quantitative Measurements: Highly accurate measurements validated by numerous reports.

    3D Object Manipulation: Ability to separate and manipulate 3D objects for virtual osteotomies. Six Degrees of Freedom Movement: Comprehensive movement control of bone elements.
- *Transition to Patient-Specific Modeling*
  Advancements in imaging technologies such as cone beam CT (CBCT), 3D laser scanners, and 3D optical systems allowed for detailed capture of soft tissue textures and colors [8]. VSP software integrated these multimodal data sources to:
  - Build Realistic Digital Models: Enhanced models that accurately represent patient anatomy.
  - Simulate Soft Tissue Deformation: Improved predictions of how soft tissues respond to bone movements and implant insertions.

This period marked a transition to patient-specific modeling, making high-fidelity models widely available. The expansion of 3D printing—both in-house and through external companies—confirmed VSP software as a crucial tool for designing surgical guides and custom implants, reducing the need for extensive engineering support due to built-in software features.

- *Technological Innovations in the Last Decade*
  Recent years have seen the following improvements:
  - Artificial Intelligence (AI) and Computer Vision: Development of AI models to automate segmentation

tasks and detect anomalies, facilitating the identification of pathological lesions [9].
- Refined Biomechanical Modeling: Utilization of finite element analysis (FEA) to create optimized simulations that incorporate geometric, anatomical, and tissue property data, along with surgical manipulations [1]. This advancement allows for better risk assessment of potential complications.
- Cloud Computing: Migration of software to cloud platforms has enabled surgeons to access planning tools without specialized equipment. This shift has also improved research collaboration through secure, multidisciplinary data sharing.

These features are now standard in VSP software packages. Modern VSP tools, however, greatly benefit, compared to previous solutions, from improved user interfaces (UIs) and user experience (UX). Many groups have contributed to the development of surgeon-friendly solutions, which has ensured the success of VSP platforms.

1.4 Importance of VSP in CMF Surgery

CMF surgery, alongside orthopedics, has significantly benefited from Virtual Surgical Planning (VSP), with its applications widely explored [10]. Before VSP's advent, cephalometry and two-dimensional imaging techniques—such as panoramic radiographs and cephalograms—were the preferred solutions, complemented by dental cast models mounted on adjustable articulators for predicting and planning occlusion. The introduction of reliable three-dimensional virtual reconstruction and VSP tools has been recognized for their superiority, establishing VSP as the new standard of care. This innovation has been effectively complemented by manufacturing advancements, evolving from additive manufacturing to 3D printing and now expanding into bioprinting [11, 12].

Several domains have confirmed VSP's superiority over traditional surgical methods, notably: (I) decreased risks and complications; (II) reduced reliance on surgeons' expertise, serving as a tool that accelerates the learning curve for trainees; (III) increased surgical precision, resulting in improved anatomical alignment and occlusal relationships; (IV) reduced intraoperative time by shifting decision-making to the preoperative phase; and (V) enhanced aesthetic and functional outcomes. The shift toward patient-centric care and personalized surgical methods has thus been successful in all these areas. Finally, (VI) the ability to involve patients in surgical planning through accessible 3D models, as opposed to complex 2D imaging, has improved patient satisfaction rates by enabling doctors to better manage expectations [11].

2 Key Components of VSP Software

2.1 Imaging Integration

Data acquisition is the critical first step in Virtual Surgical Planning (VSP). It requires careful standardization and optimization to minimize patient exposure to radiation while maintaining accuracy and precision. Various imaging techniques provide both 2D and 3D data, and their combination enables a clearer understanding of the relative position and orientation of the surgical site, including bone and soft tissue relationships.

- *CT/CBCT/MRI Scanning*
  - CT (Computed Tomography) and CBCT (Cone Beam Computed Tomography) are widely used in clinical imaging for VSP. They generate tomographic images that can be reconstructed into a 3D model from digital data. While both techniques expose patients to ionizing radiation, CBCT is favored for CMF applications because of its lower radiation levels and localized scanning, making it more suitable for focused areas like the jaw or sinuses. However, CBCT offers reduced precision compared to traditional CT, particularly in imaging soft tissues, as it primarily excels at capturing hard tissues like bones and teeth.
  - MRI (Magnetic Resonance Imaging), unlike CT and CBCT, does not use ionizing radiation and is preferable for visualizing soft tissues. MRI sequences such as T1, T2, and FLAIR offer varying levels of contrast depending on the tissues of interest. However, its sensitivity to patient motion, which can cause image blurring, limits its utility in some cases.
- *3D Scanning*
- 3D scanners capture the external surface anatomy with high accuracy, making them ideal for applications like facial reconstruction, orthognathic surgery, and prosthetic design. These devices are non-invasive, radiation-free, and capable of producing detailed models quickly, even in clinical settings. Various types of 3D scanning technologies are available:
  - Laser Scanning: Utilizes a laser beam to map surface contours with high precision.
  - Structured Light Scanning: Projects a grid or light pattern onto the surface, capturing deformations via cameras to create a 3D model. It is ideal for larger or less complex surfaces.
  - Photogrammetry: Uses multiple 2D images from different angles to create a 3D model. This is the simplest

and most cost-effective method, commonly used in CMF surgery. Standard photo angles include lateral profiles, 45-degree views, and frontal views, all taken with the patient in a natural head position.

2.2 Imaging Formats and Data Standards

- DICOM (Digital Imaging and Communication in Medicine) is the standard format for radiological imaging in VSP. It encodes not only the imaging data but also acquisition parameters and settings, ensuring compatibility across different VSP software.
- 3D Scanners typically store data in STL (Standard Tessellation Language) or OBJ (Object File) formats, which represent surface geometries either as polygonal meshes or point clouds. Some software uses proprietary formats, limiting compatibility with other platforms, which can be a drawback when integrating different systems [13].

2.3 3D Modeling and Visualization Tools

The 3D modeling process in VSP begins with the importation of 2D medical images, followed by anatomical segmentation using algorithms such as thresholding and region growing. Subsequently, surface and volume rendering techniques are applied to generate a 3D model. Various methods are then employed to create a mesh—a representation that accurately describes the surface topology of bones and soft tissues. A mesh is composed of (Fig. 1):

- Vertices: Points in 3D space that serve as the corners or intersections of the mesh
- Edges: Straight lines connecting two vertices
- Faces: Flat surfaces formed when multiple edges connect in a closed loop, typically triangular or quadrilateral in shape

Once the 3D model is fully rendered, advanced visualization tools allow clinicians and engineers to explore different organs and correlate them with the corresponding 2D images, regardless of the imaging modality used.

2.4 Image Import and Segmentation Tools

Medical images, commonly stored in the DICOM format, are imported into VSP software. The first critical step after importation is denoising the images to enhance quality, as noise—unwanted random variations in pixel intensity—can degrade image quality and adversely affect subsequent 3D reconstruction and planning.

- *Denoising Techniques* [14]:
  1. Local Filtering (Fig. 2):
     - Linear Filters: Mean filtering, Gaussian filtering, Wiener filtering.
     - Nonlinear Filters: Median filtering, adaptive median filtering, bilateral filtering.
  2. Non-local Means (NLM) Filtering (Fig. 3):
     - Considers the similarity between patches of pixels across the entire image, providing effective noise reduction while preserving details.
  3. Deep Learning-Based Filtering:
     - Utilizes neural networks trained to distinguish between noise and meaningful signal, offering superior performance in noise reduction and feature preservation.

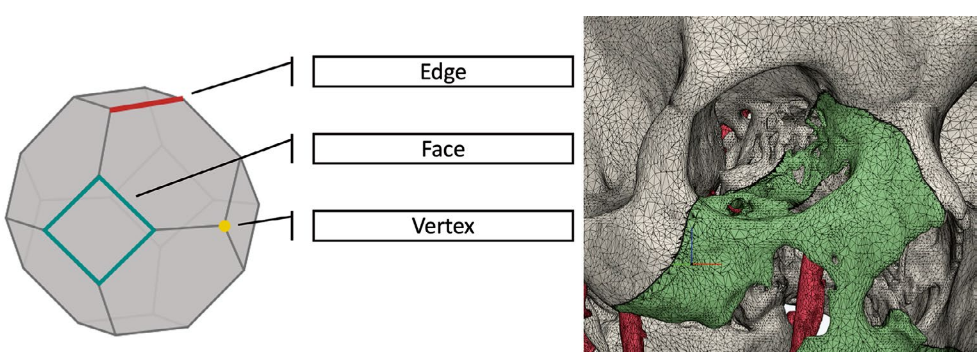

Fig. 1 Schematic representation of a 3D polyhedral model and of an anatomical STL file illustrating the fundamental components of a mesh structure. Right panel illustrates a complex maxillectomy mesh with the poly-wireframe displayed. Notably, curves need a substantial amount of triangulation to be defined

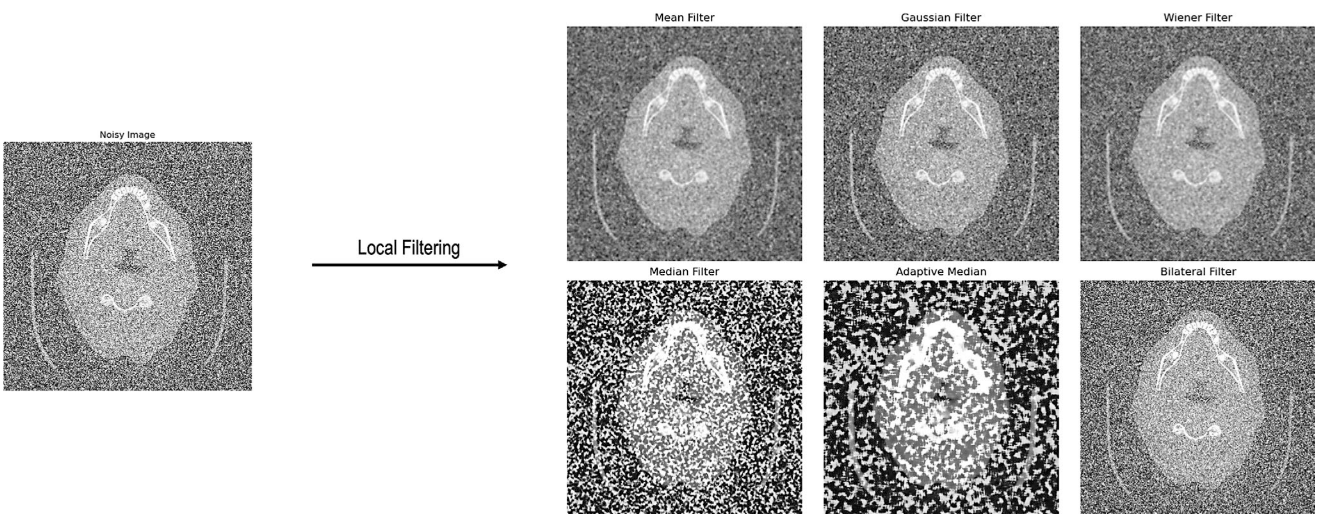

Fig. 2 Comparison of local filtering techniques applied to a noisy medical image (CT scan slice, on the left), including Mean, Gaussian, Wiener, Median, Adaptive Median, and Bilateral filters. Each method demonstrates varying noise reduction and detail preservation

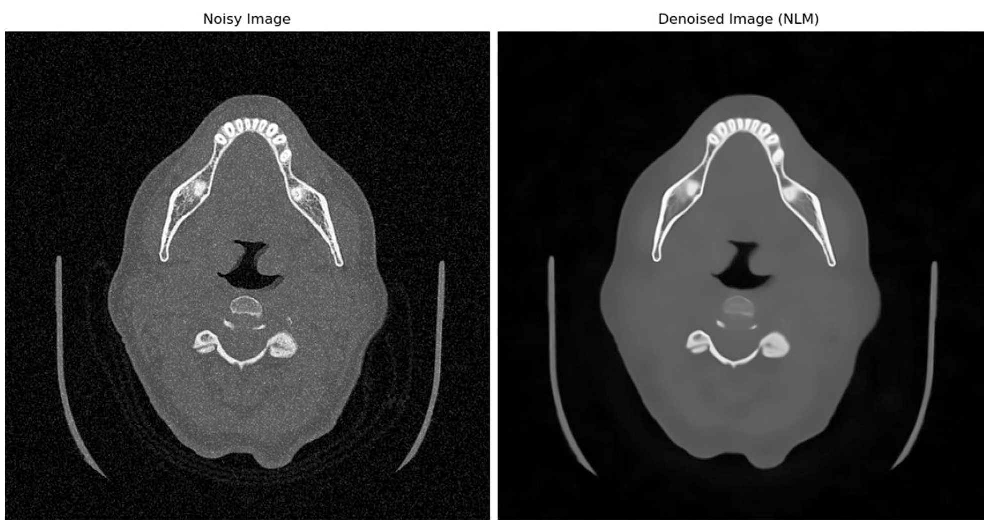

Fig. 3 Comparison of a noisy CT image (left) and its denoised counterpart using the Non-Local Means (NLM) algorithm (right), demonstrating significant noise reduction while preserving anatomical details

Non-local means filtering and deep learning-based denoising are increasingly popular due to their balance between noise reduction and preservation of anatomical details, particularly in high-resolution datasets used for complex procedures. After denoising, image enhancement techniques are applied to further improve the visibility and quality of anatomical structures.

While these are often automated, most software provides manual tools for fine-tuning. The main image enhancement techniques (Fig. 4) include [15]:

1. Contrast Enhancement:
   – Histogram Equalization: Adjusts the contrast by redistributing pixel intensity values.
   – Gamma Correction: Alters the luminance of the image to improve the visibility of specific structures.
2. Edge Enhancement:
   – Highlights critical anatomical boundaries to optimize accuracy in 3D reconstruction.
3. Intensity Windowing:
   – Adjusts the range of displayed intensity values to enhance specific features, commonly used to differentiate between bone and soft tissue.
4. Sharpening Filters:
   – High-Pass Filtering and Laplacian Sharpening: Enhance fine details and anatomical edges by increasing the contrast between neighboring pixels.

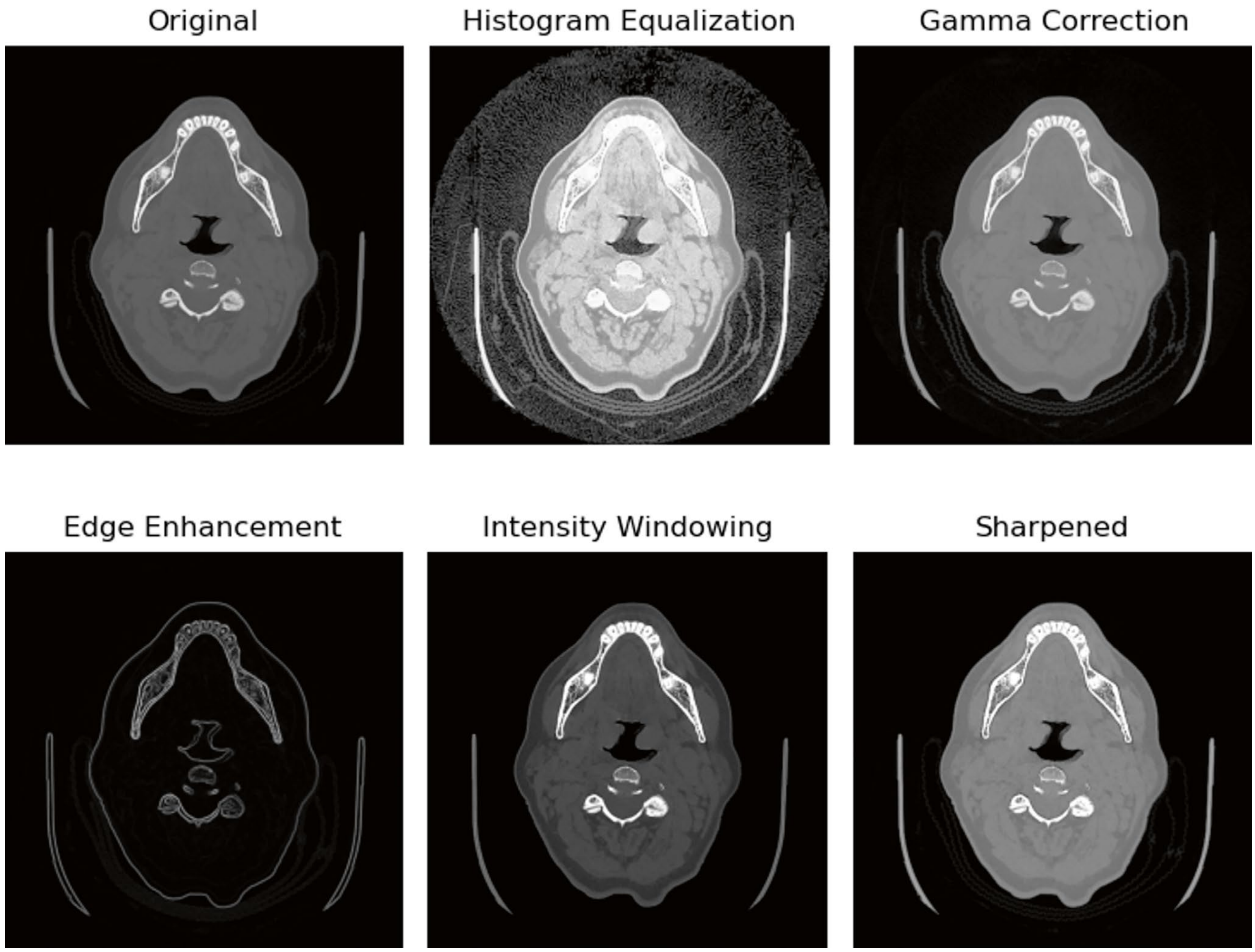

Fig. 4 Visualization of image enhancement techniques applied to a CT image, including Histogram Equalization, Gamma Correction, Edge Enhancement, Intensity Windowing, and Sharpening. Each method emphasizes specific features to improve contrast, detail visibility, or edge clarity compared to the original image

Following enhancement, image segmentation partitions the images into distinct regions with similar properties such as intensity, texture, or contrast. Precise segmentation is essential for accurate registration and anatomical labeling. Segmentation Methods [16, 17]:

1. Manual Segmentation:
   – Performed entirely by clinicians or engineers, providing high accuracy but is time-consuming.
2. Semi-automatic Segmentation:
   – Combines automated algorithms with manual input for initialization and correction, balancing efficiency and accuracy.
3. Automatic Segmentation:
   – Fully automated using algorithms, including deep learning methods that may be supervised (using annotated datasets), semi-supervised, or unsupervised [18].

Automatic segmentation is more effective for tissues with high contrast, such as bone and air-filled lungs. While it offers speed and efficiency, semi-automatic methods are often preferred clinically due to the need for expert oversight. Common segmentation algorithms (Fig. 5) are:

1. Thresholding:
   – Segments images based on intensity values, using thresholds derived from the image histogram. It does not consider spatial information, making it susceptible to noise.
2. Region Growing:
   – Expands regions by appending neighboring pixels that meet certain criteria, such as similar intensity. It utilizes spatial information but requires accurate denoising to function effectively.

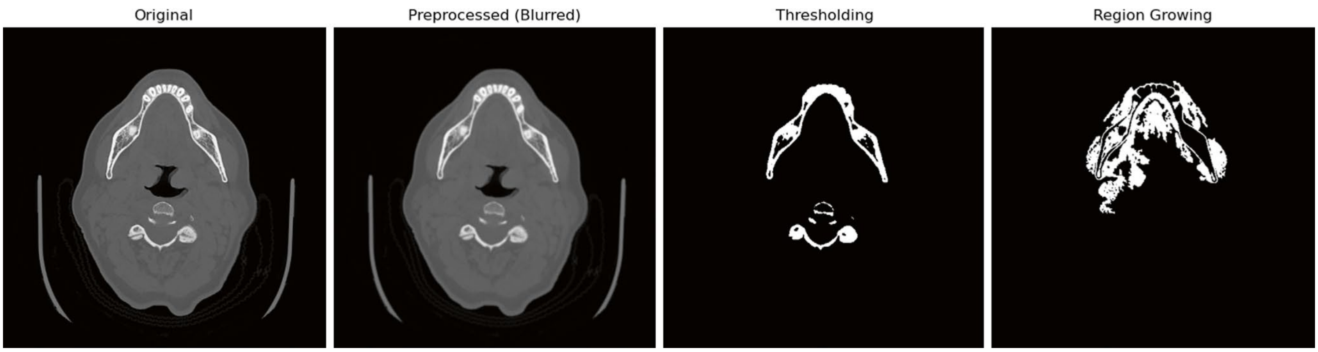

Fig. 5 Segmentation workflow applied to a CT image. The original image is preprocessed with blurring to reduce noise and smooth intensity variations, improving segmentation accuracy. Thresholding is used to separate regions based on intensity values, producing a binary mask. Region-growing segmentation groups connected pixels with similar intensities. Outputs highlight the distinct segmentation capabilities of each method

Combining thresholding with region-based methods enhances segmentation accuracy by leveraging both intensity and spatial information [17].

2.5 3D Model Generation and Mesh Optimization

From the denoised and segmented 2D images, a 3D model is constructed to enhance visualization of anatomical features and facilitate surgical planning. The transition to 3D visualization has significantly improved diagnostic accuracy and procedural planning. Many algorithms have been developed to extract a 3D representation from 2D imaging, and many of these are now incorporated in modern VSP software [19]. Volumetric rendering techniques are essential for visualizing the entire volume of medical imaging data without explicitly converting it into surface representations or polygonal meshes. Direct volume rendering (DVR) is a key method employed for this purpose. DVR allows for the direct visualization of volumetric data by mapping data values to optical properties like color and opacity, providing detailed views of internal structures. Techniques such as ray casting, which projects rays through the data volume to accumulate color and opacity values, are frequently utilized in VSP software.

While DVR is excellent for visualization, it falls short when manipulation of the 3D model is required—such as editing, measurement, or exporting to computer-aided design (CAD) applications—because it does not produce a surface or mesh representation that these applications can process. To address this limitation, algorithms like the Marching Cubes algorithm are employed to extract a polygonal mesh of an isosurface from the volumetric data. An isosurface represents a surface within the volume where the data value equals a constant (e.g., a specific tissue density threshold). The Marching Cubes algorithm examines the values at the corners of each voxel—the three-dimensional equivalents of pixels—and generates triangles to define the surface of the isosurface. This process efficiently produces a mesh suitable for real-time interaction, which is crucial in VSP applications (Fig. 6).

Once the 3D surface is generated, smoothing techniques are applied to reduce artifacts and enhance anatomical realism [20]. Laplacian smoothing is a commonly used method that adjusts the position of each vertex based on the average position of its neighboring vertices, effectively reducing noise and irregularities in the mesh (Fig. 7).

Other frequently applied smoothing techniques include recursive Gaussian smoothing, Taubin smoothing, and bilateral smoothing. Each method treats the mesh differently, and many software programs offer user-selectable options to choose the most appropriate technique for preserving small features and boundaries (Fig. 8). Smoothing is often essential when preparing models for 3D printing or simulation, where surface imperfections could adversely affect outcomes.

Following smoothing, mesh optimization techniques are employed to simplify the 3D-generated mesh, a critical step that enhances computational efficiency and allows for faster real-time interaction without compromising essential anatomical details. Decimation, or mesh simplification, reduces the number of polygons in a mesh using techniques such as edge collapse, where edges between neighboring vertices are collapsed, and methods based on quadric error metrics, which aim to preserve the overall anatomical structure and sharp edges while reducing complexity [21].

In contrast, when greater detail preservation is required—for instance, in areas like blood vessels or complex articular surfaces—the opposite process of decimation, known as subdivision, is applied. Subdivision enhances detail by subdi-

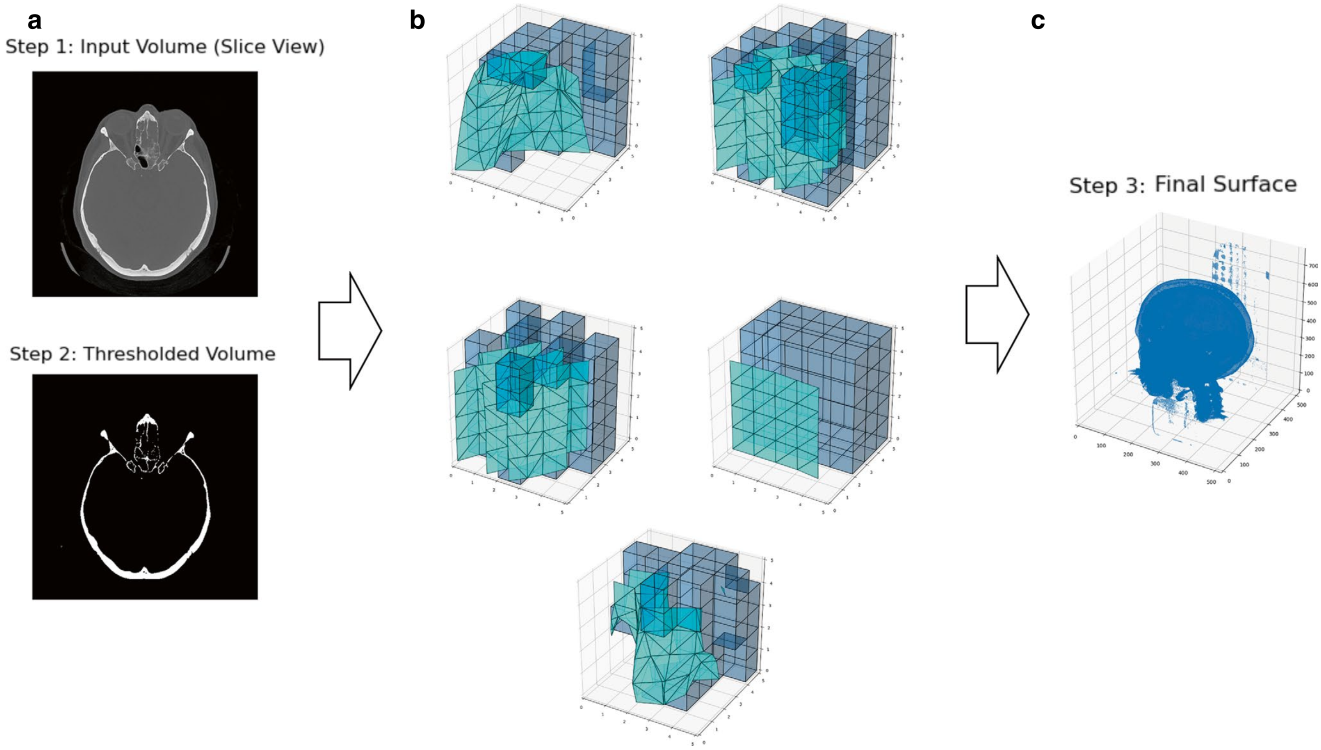

Fig. 6 Pipeline for 3D surface reconstruction from volumetric medical imaging. (**a**) Step 1 shows the input volume in slice view. Step 2 illustrates the thresholded volume, isolating regions of interest. (**b**) Intermediate steps in surface generation with the Marching Cubes algorithm, visualized with voxel grids and mesh triangulation. (**c**) Step 3 depicts the final 3D surface model of the anatomical structure

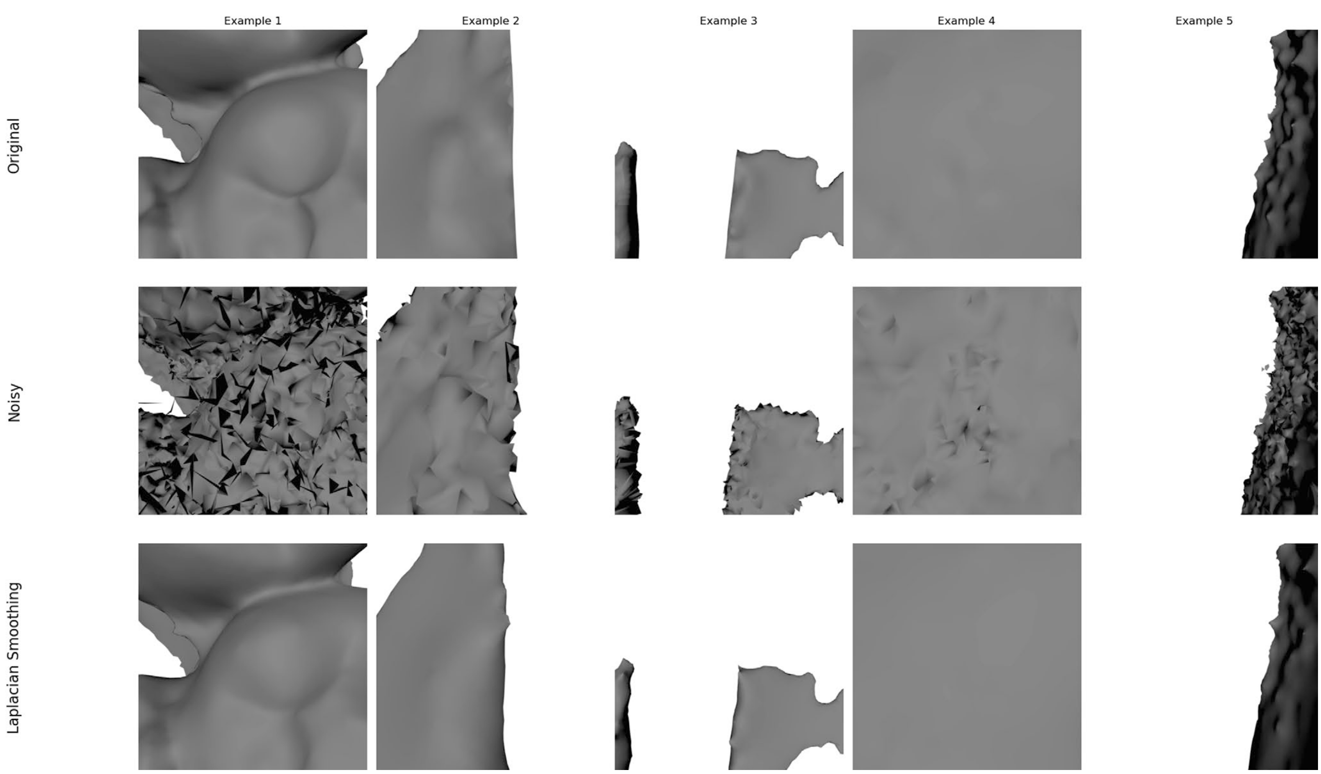

Fig. 7 3D skull model detailed views showcasing the application of Laplacian smoothing to enhance anatomical realism. Noise was introduced to the original surface, creating artifacts and irregularities. Laplacian smoothing was applied, repositioning each vertex based on the average position of its neighbors, effectively reducing noise and restoring surface smoothness. Examples 1 to 5 illustrate the process across various regions of the skull

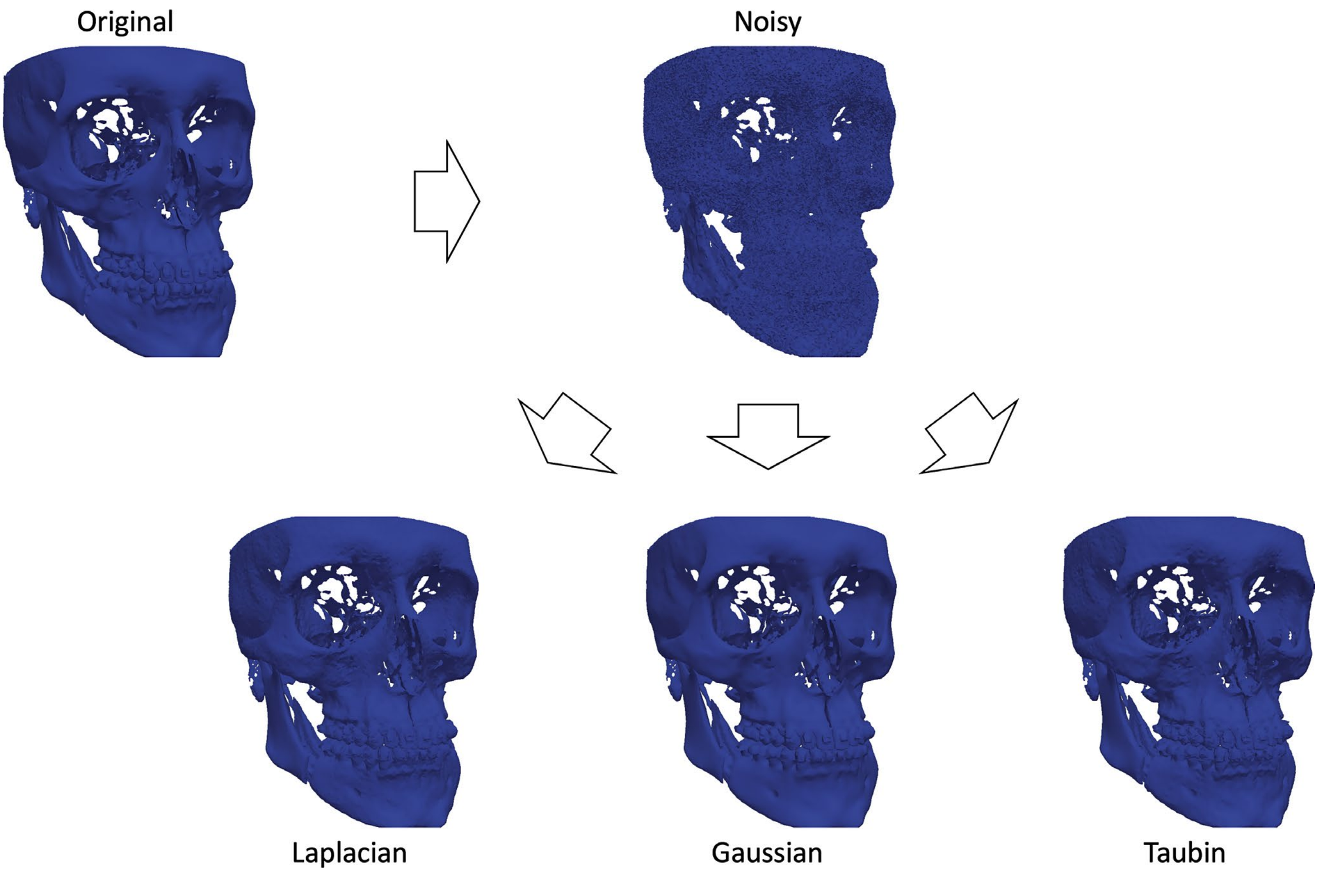

Fig. 8 Comparison of smoothing techniques applied to a noisy 3D skull model. The original model was artificially degraded with noise, followed by three smoothing approaches: Laplacian smoothing, Gaussian smoothing, and Taubin smoothing

viding and adding polygons to the mesh. Techniques such as the Catmull-Clark subdivision method are used to refine the mesh, providing increased detail and smoothness [22]. This process is particularly important for accurately representing intricate anatomical structures in surgical planning.

2.6 Multimodal 3D Registration

In VSP, software often requires the registration and alignment of three-dimensional models derived from various medical imaging modalities—such as CT, CBCT, MRI, and 3D surface scanners—to accurately represent a patient's anatomy by leveraging the strengths of each modality. Image registration involves determining the correct mapping that relates positions in one image to the corresponding positions in another. Several methods are employed to combine these multimodal datasets, classified into rigid, non-rigid, and hybrid approaches based on the type of alignment needed [23].

Rigid registration assumes that the surfaces are related by a rigid transformation (i.e., rotation and translation) without any structural deformation, which is often applicable to bone segments. An extension of rigid registration is the affine method, which allows for scaling and shearing transformations in addition to rotation and translation. Non-rigid registration, in contrast, permits free-form deformations to accommodate structural differences between images but requires longer processing times to identify corresponding features across different imaging modalities.

To achieve complete registration, algorithms must first identify similarities between images, create a transformation model with a set of numerical parameters that define a particular instance of the transformation, and then proceed with the optimization of the overlapping images. In the typical workflow of VSP software, the registration process begins with a preprocessing step. Here, images are resampled, and intensity values are normalized to facilitate comparisons between different imaging modalities. An initial transformation is then estimated to roughly align the datasets, either by manual selection of anatomical landmarks or, more commonly, by automatically detecting prominent features such as bone edges and vascular structures. Subsequently, similarity metrics are defined to measure the correspondence between the morphed (moving) image and the fixed (reference) image. A wide range of metrics has been developed,

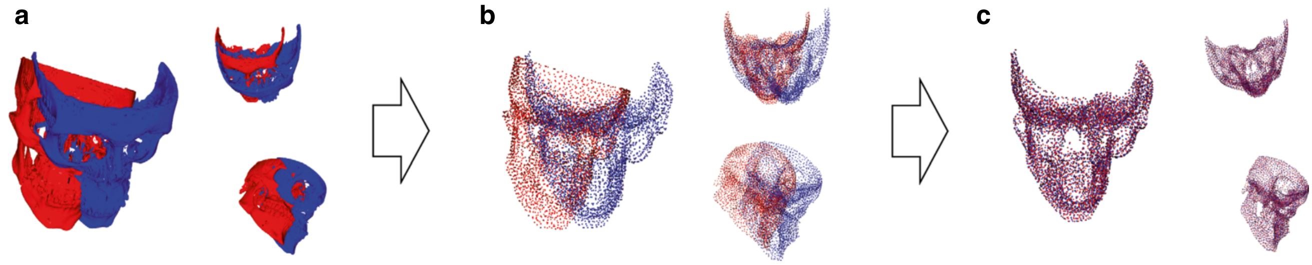

Fig. 9 Iterative Closest Point (ICP) algorithm applied to 3D anatomical models. (**a**) Initial surfaces (red and blue) before alignment. (**b**) Point cloud representation of the initial objects. (**c**) Final superimposed model after ICP convergence, showing minimized distances between corresponding points

with mutual information being preferred for registering images from different modalities. The transformation model is then applied and iteratively updated to improve alignment.

The most common registration techniques are [24]:

1. Rigid methods:
   – Iterative Closest Point (ICP): This method works by finding corresponding points between surfaces and iteratively minimizing the distance between these points through rotations and translations (Fig. 9). Various improved versions of ICP have been developed, and they perform optimally on bone 3D models.
   – Mutual Information (MI) Based Registration: This technique aligns images based on statistical dependencies rather than direct intensity similarities, making it suitable for combining CT's bone detail with MRI's superior soft tissue contrast.
2. Non-rigid methods [25]:
   – B-Spline Deformation: The anatomy is divided into a grid of control points in both the source and target images. A spline function defines correspondences between these points and extends them to the areas away from the control points. Commonly used in brain and abdominal organ alignment, it preserves local detail while adapting to changes in shape and is more computationally efficient compared to other spline techniques.
   – Demons Algorithm: Named for its ability to "push" and "pull" pixels across images until they align, this method is used in applications like brain imaging and tumor monitoring, where tissues may have shifted due to growth or other factors.

After registration is complete, an optimizer adjusts the transformation parameters to further improve image similarity until convergence is achieved. Finally, validation techniques are employed to ensure that the registration algorithm has correctly matched the input data, with an average error acceptable for the specific application in VSP.

2.7 Visualization Tools

After 3D model generation and registration have been performed, VSP software provides visualization tools to transform the 3D model into interactive views that allow surgeons to explore the anatomy from different perspectives. Some of these tools also provide a multi-view of the reconstructed model alongside the original DICOM images, with the plane identification to match the slice reference in the 3D model. Visualization is mostly used for diagnostic purposes, as little to no manipulation of the anatomies happens at this stage. For each of the available tools, a list of features and applications will be reported.

1. Multiplanar Reconstruction (MPR)

   MPR is a fundamental visualization technique that allows the viewing of medical imaging data in multiple planes (Fig. 10). Starting from a set of axial (horizontal) slices typically obtained from CT or MRI scans, MPR enables the reconstruction of images in other orthogonal planes: sagittal (vertical slices from left to right) and coronal (vertical slices from front to back). It also supports oblique and curved planar reconstructions [26]. Concurrent visualization of all these planes enhances spatial understanding of anatomical structures. Users can then scroll through slices in one plane, and the other planes will automatically update the view. It is widely used in most CMF applications, especially for the evaluation of fractures in facial trauma, localization of neoplasms, to assess skeletal discrepancies in orthognathic surgery, and to determine optimal implant sites with regards to bone density and proximity to vital structures.

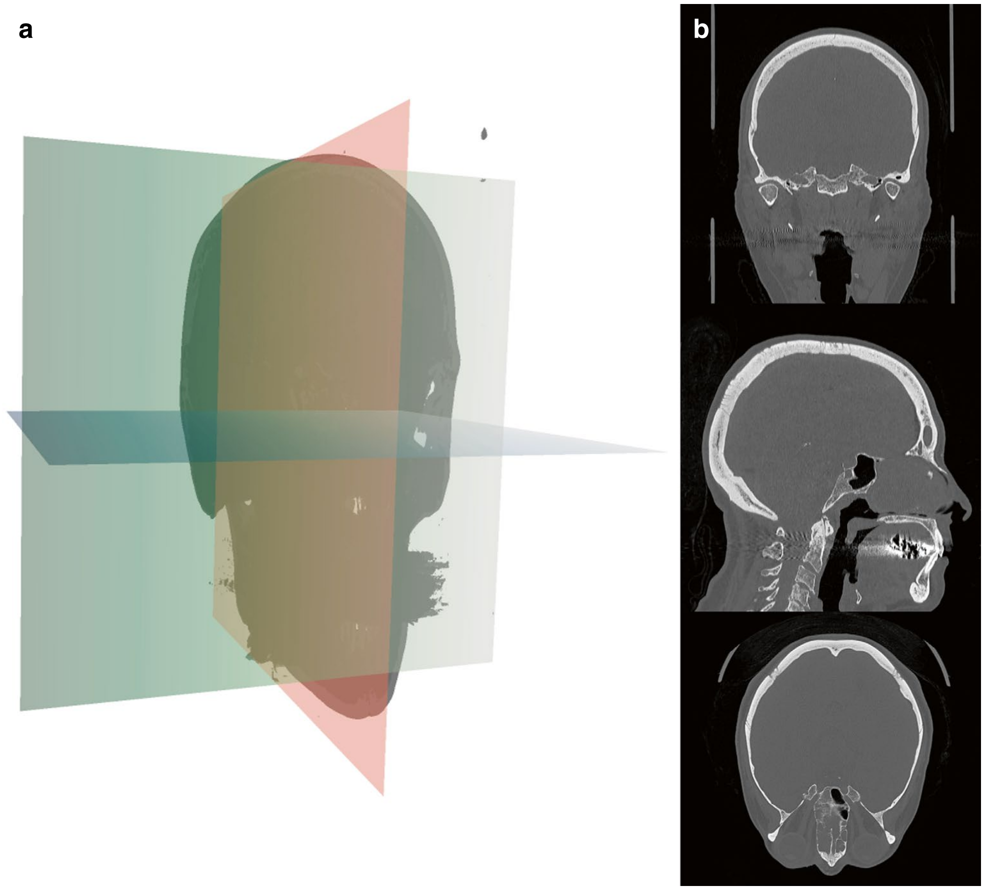

Fig. 10 Multiplanar reconstruction (MPR) of a CT scan for 3D anatomical visualization. (**a**) Representation of orthogonal planes (axial, sagittal, and coronal) intersecting the skull model in 3D space. (**b**) Corresponding 2D views along axial, sagittal, and coronal planes derived from the volumetric data

2. Transparency and Clipping

   Transparency and clipping tools enhance the visualization of internal structures by adjusting the opacity of overlying tissues or by virtually removing sections of the 3D model. They allow slicing at any angle, offering customized views tailored to the anatomical area of interest. It is relevant to correctly visualize impacted third molars or canines within the jawbone and to assist in visualizing the fit and positioning of bone grafts or alloplastic materials in reconstructive procedures.
3. Color Coding

   Color coding assigns specific colors to different anatomical structures or tissues within the 3D model, enhancing differentiation and recognition of smaller structures, such as nerves, and pathologic regions. It integrates with on-screen legend and labels for quick identification of anatomies, hence optimizing the understanding of complex anatomical relationships and better communication with research collaborators and patients.
4. Virtual Endoscopy and Fly-Through Navigation

   Virtual endoscopy simulates the experience of navigating within hollow anatomical structures using 3D imaging data, while fly-through navigation allows movement through any part of the anatomy. It has been used for preoperative exploration of the maxillary sinuses, a transantral approach to the inferior orbit [27], and airway assessment in patients with obstructive sleep apnea.
5. Annotations and Measurements

   Annotations and measurement tools allow users to mark points of interest, add textual notes, and perform quantitative assessments directly on the 3D model. Both linear and curved measurements can be performed to cover also nonlinear paths and surfaces. It is possible to determine angles between bones, implants, and other anatomical features, as well as computation of the volume of lesions and structures. Cephalometric analysis commonly performed in orthodontic and orthognathic surgery planning can be applied to the 3D model, and surgical guides can be created with precise measurements that inform their design and production.
6. Shading and Lighting Techniques

   Shading and lighting techniques simulate how light interacts with surfaces, enhancing the visual realism of 3D models and improving depth perception. Realistic shading helps visualize postoperative soft tissue contours, important in aesthetic surgeries and patient consultations, and it highlights bone surface irregularities. This has been further improved with the advent of vertex shading, which assigns each mesh vertex its corresponding isovalue from the density map of a CT or MR. The aim is to represent polygonal anatomical structures with realistic color features.

7. Texture Mapping and Cinematic Rendering

   Texture mapping overlays 2D image data onto the surfaces of 3D models, adding detailed surface characteristics and enhancing visual realism. Cinematic rendering produces photorealistic images by simulating complex light-tissue interactions. It is possible to apply textures representing skin, muscles, bones, or organ surfaces that can help to predict potential scarring and facial reconstruction results, easing the discussions with patients regarding cosmetic outcomes.

8. Virtual Surgical Simulation

   3D model generation and tools that enhance anatomical visualization are essential components of VSP. However, they represent only the initial steps toward full manipulation and comprehensive simulation of surgical procedures. VSP software integrates a variety of tools and methods that enable surgeons to plan, practice, and optimize surgeries within a risk-free virtual environment. These tools enhance the surgeon's ability to visualize patient-specific anatomy, simulate surgical interventions, and predict postoperative outcomes. Their development is based on specific engineering methods, which serve as a common foundation for many of these tools.

2.8 Computational Modeling and Simulation

Computational modeling and simulation methods have led to the development of three main tools [28]:

1. Virtual osteotomy planning
2. Soft tissue simulation
3. Deformable modeling for soft tissue reconstruction

These tools use computational techniques to simulate the physical behavior of biological tissues under a variety of conditions. FEA and deformable modeling enable the prediction of soft tissue responses to skeletal changes, simulate tissue deformation during reconstructive procedures, and model the forces applied to bone segments after implant placement.

- Dynamic Osteotomy Simulation: This set of tools allows surgeons to simulate osteotomies in a 3D environment with real-time feedback on the impact of changes in bone structure. It is crucial for planning complex cuts and predicting postoperative alignment. For example, simulating a Le Fort I osteotomy to correct maxillary hypoplasia, allowing for precise planning of bone segment movements.
- Soft Tissue Prediction: These tools simulate the effects of skeletal adjustments on soft tissue outcomes, enhancing preoperative planning in aesthetic and reconstructive surgeries. For example, predicting facial contour changes after mandibular advancement in orthognathic surgery.
- Deformable Anatomical Modeling: This method simulates deformations in soft tissue and bone to reflect the dynamic nature of anatomical structures. It is often used in temporomandibular joint (TMJ) surgeries and complex trauma cases. For example, modeling soft tissue response in TMJ replacement surgery to optimize joint function and facial symmetry.

2.9 CAD/CAM Methods

CAD/CAM technologies are employed to design and fabricate patient-specific implants and surgical guides. Using CAD software, custom devices are created based on the patient's anatomical data and then manufactured using additive manufacturing techniques. The tools include:

1. Collision Detection and Constraint Modeling [29]: These tools identify potential interferences between anatomical structures or surgical instruments during virtual procedures, assisting in the evaluation of surgical pathways. For example, detecting potential collisions between surgical instruments and vital structures during mandibular reconstruction.
2. Patient-Specific Implant Simulation [30]: This tool facilitates the design and virtual fitting of implants tailored to individual patient anatomy. It integrates with additive manufacturing protocols to enable seamless transition from virtual design to 3D printing of implants. For example, designing a custom titanium mandibular implant for reconstruction after tumor resection.
3. Virtual Fixation and Splint Simulation [12]: These tools assist in planning the placement of fixation devices and surgical splints. They help determine the optimal placement of screws and plates for bone stabilization and predict dental alignment outcomes to ensure functional and aesthetic results. For example, planning the placement of miniplates and screws in a bilateral sagittal split osteotomy for mandibular setback.
4. Surgical Guide Creation [13]: This feature enables the design of precise surgical guides based on preoperative plans, helping surgeons accurately translate virtual simulations into physical templates. Guides can be fully cus-