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Augmented reality in oral and maxillofacial surgery

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1 Introduction

Augmented reality (AR) is a technology which links the real and virtual world, extending the user's reality with virtual information. With the advancement of mobile computing, AR applications have been implemented in a wide range of fields, such as gaming and industry. Medicine has always been an area of great potential for AR, with a first system introduced as early as 1986 by Roberts et al. [1], and several works following in the early 1990s [2–4]. The appeal of medical AR goes back to the notion of "X-ray" vision, the ability to effectively see through objects. In medicine, where an inside view of the patient's body is usually readily available through medical imaging, such as X-ray, computed tomography (CT), or magnetic resonance imaging (MRI), this information can be merged into the same physical space as the patient to permit *in situ visualization*.

This new visualization paradigm offers several benefits over the traditional method of viewing medical imaging data on a separate 2D monitor. First, AR visualization eliminates the need for physicians to mentally transform imaging data to the patient. This is beneficial in many scenarios, such as physical examination of the patient or treatment planning but is especially helpful during image-guided interventions. In current practice, navigation information is displayed on one or several monitors placed around the surgical site, which is a challenging task itself due to constraints resulting from insufficient space or line-of-sight requirements. The physician is consequently forced to divide his attention between navigation and the patient, while coordinating the manipulation of surgical tools. By using in situ visualization, this attention disruption becomes unnecessary, resulting in improved hand-eye coordination for the physician and therefore, facilitating the surgeon's performance in terms of accuracy and time efficiency [5]. A comparison between traditional image guidance and guidance using AR is illustrated in Fig. 5.1. A second important

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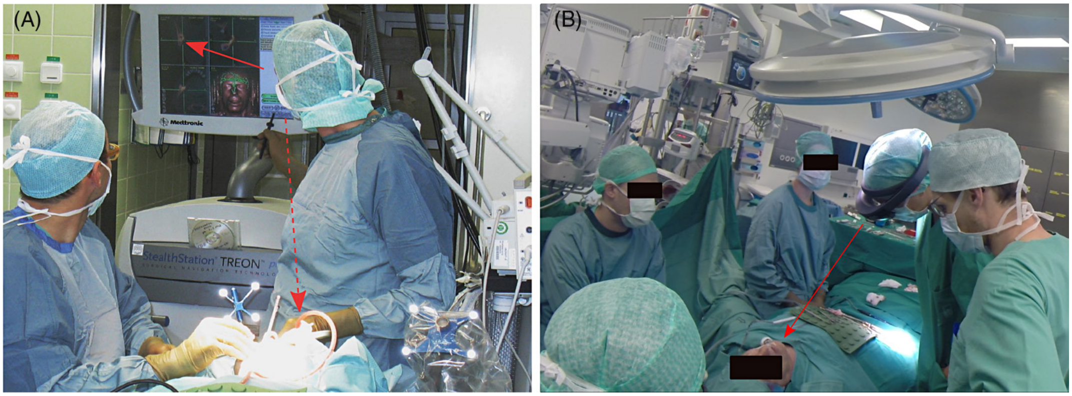

FIGURE 5.1 Comparison between traditional image-guided surgery and augmented reality (AR) guided surgery. (A) With conventional navigation systems, the surgeon is forced to divide his attention between navigation information and the surgical site. (B) AR systems supporting in-situ visualization allow surgeons to focus on the patient only, while viewing navigation information directly overlaid with the patient in their view.

benefit of medical AR is an improved perception of imaging data in support of the physician's decision-making process. Modern AR displays enable stereoscopic visualization of volumetric data, resulting in a true three-dimensional (3D) view. This implicitly results in perceptual cues such as binocular disparity and motion parallax, which lead to a stronger spatial understanding of structures [6]. Furthermore, automatically aligning the viewpoint of real and virtual objects aids in 3D inspection of data, by making the adjustment of the viewpoint more natural [5].

Oral and cranio-maxillofacial surgery (OCMS) was among the first specialities investigated in the context of medical AR, pioneered in 1995 by Wagner et al. [4]. This was presumably caused by the fact that OCMS is a surgical speciality working with a particularly complex anatomy, were image guidance has a high potential. The oral and cranial region is home to delicate structures like the larynx, oral cavity and a rich nervous system, which, if damaged during surgery or treatment, might leave the patient unable to speak, swallow or seriously disfigured [7]. Only highly accurate procedures can guarantee a surgical outcome, which is both functionally and aesthetically adequate and preserves the patient's quality of life as much as possible. Therefore, AR has found its application in OCMS implantology, orthognathic surgery, trauma, and oncology [8].

2 Augmented reality: concepts and technology

2.1 Definition of augmented reality

A term often used interchangeable with augmented reality is mixed reality (MR). According to the popular definition of the "virtuality continuum" by Milgram and Kishino [9] (Fig. 5.2), MR describes all combinations of real and virtual between real environment and virtual reality (VR). While VR completely immerses the user within a virtual world, AR contains mainly real elements, enhanced with some virtual content. However, a simple

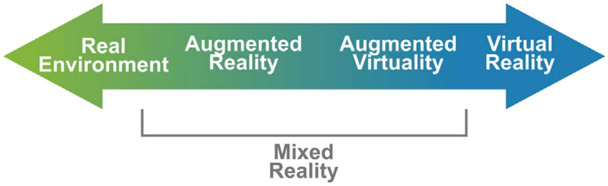

FIGURE 5.2 Virtuality continuum by Milgram and Kishino [9]. Mixed reality describes all combinations between the real environment (a direct view of reality) and virtual reality (an immersion in a fully digital environment). Augmented reality usually refers to the overlay of virtual objects over the real-world environment, while augmented virtuality describes real objects, projected, and controlled in a virtual world.

blend of virtual and real objects does not yet constitute an AR system. According to Azuma [10], AR is defined by the following characteristics: it (1) combines real and virtual, (2) is interactive in real-time, and (3) is registered in 3D. Traditional special effects in movies or TV overlays in news or sports broadcasts don't fall into this characterization of AR, since they are not interactive or not registered three-dimensionally, respectively.

2.2 Augmented reality displays

In principle, three concepts for visual AR displays can be distinguished. **Video see-through** (VST) displays capture the observed scene with a camera and combine the resulting image digitally with virtual information. They have the advantage of a flexible, arbitrary merging between virtual and real images, which allows a depiction of fully opaque virtual objects with correct colours. Furthermore, by delaying the real view, relative lag between reality and virtuality can be minimized [5]. On the downside, VST displays are limited in their resolution and image quality by the capturing optics, both for real and virtual content. **Optical see-through** (OST) displays, on the other hand, do not require a camera to capture the real world. Instead, virtual imagery is directly overlaid with reality using an optical combiner. Compared to VST, OST displays have the advantage of not blocking the user's vision, not falsifying the real view by non-ideal capturing optics of a camera [11], and the visualization quality of real content is not limited by the resolution of the viewing camera or display. However, for correct alignment of virtual content with the reality, the relation of the user's eyes to the display must be known to achieve a synchronization between real and virtual viewing parameters. This is typically accomplished by display calibration, often involving manual calibration steps [12]. A limitation of OST displays is that virtual content is usually perceived as an overlay over real content. Accurate perception of structures located within real objects is difficult to achieve, since the reality cannot be manipulated, contrary to VST modalities. Finally, **spatial** displays use a projector to cast images directly onto real world objects, which they usually capture using a camera. Even though modern projectors have high resolution, refresh rates, and often support stereo projection, image quality is rather low compared to state-of-the art OST or VST displays. This shortcoming is amplified when projecting onto irregular surfaces or using the system in environments with bright natural lighting. Furthermore, spatial displays suffer from the same constraint on depth perception as OST displays do. Fig. 5.3 provides an overview over display types in AR.

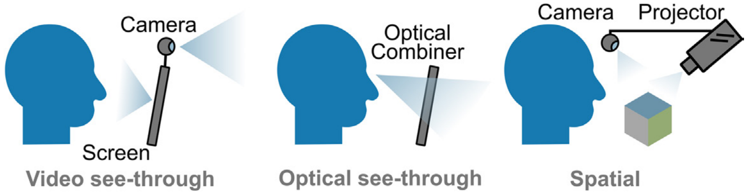

FIGURE 5.3 Different AR display types. Video see-through displays capture the reality with a camera and digitally combine real and virtual images before displaying them on a screen. Optical see-through displays, on the other hand, overlay virtual content directly with reality using an optical combiner. Finally, spatial displays project images directly onto real objects, which are usually captured by a camera.

According to Schmalstieg and Höllerer [13], AR displays can further be categorized according to the distance between eyes and display. In head space, **head-mounted displays** (HMDs) show information directly in front of the user's eyes. Such wearable displays allow a natural synchronization of real world, virtual content and the user's perspective and actions, while keeping the hands of the user free [14]. VST-HMDs, OST-HMDs, and projector-based HMDs have been proposed in the past. Moving further away from the eyes to the body space, **hand-held displays**, in particular smartphones and tablets, are prevalent AR devices. Since an estimation of the relation between eyes and display is increasingly more difficult with a larger distance, VST or, in some cases, spatial systems are more common in this space. Lastly, **world space displays** are stationary placed within the environment, independent of the user. They can enable VST AR using monitors and cameras, OST AR by employing fixed optical combiners or virtual content projected on real objects using non-movable projector.

2.3 Registration and tracking

While the display takes care of *combining* real and virtual content, registration is needed for *aligning* real and virtual coordinate systems and therefore, correlating computer-generated content with the real scene. For applications where some sort of X-ray vision is desired, accurate 3D registration is important to not ruin the perception of real and virtual world coexisting. For medical applications, demands are even higher—a misalignment between a virtual interventional target and the patient may cause the entire procedure to fail, leading to a possibly serious medical accident [15].

Accurate registration in the user's perspective relies on continuous tracking of the viewing camera within the environment. Tracking is integral in any AR system to synchronize the viewpoint of virtual content with the viewpoint of the real scene. For full tracking, both position and orientation need to be determined, resulting in six degrees of freedom (6DOF) describing the pose of the device.

2.3.1 Tracking paradigms and sensors

One can distinguish between **outside-in** and **inside-out** approaches for tracking, depending on the location of the tracking sensors. For outside-in methods, external tracking

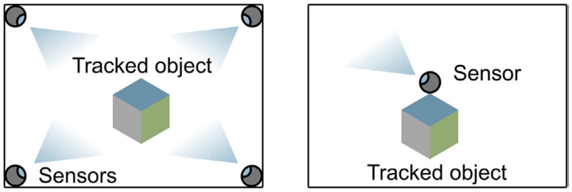

FIGURE 5.4 Tracking paradigms in AR. In (A) outside-in tracking, the sensors a stationary mounted in the environment and observe the tracked object within a fixed volume. Meanwhile, (B) inside-out tracking places the sensors on the tracked object itself. The sensor localizes itself by relating itself to stationary features, either artificial or natural, within the environment.

infrastructure (e.g., a camera) needs to be stationary mounted and the position and orientation of the tracked object, which can move within a limited tracked volume, in relation to the sensor, can be calculated. In inside-out tracking, the sensor is located on or within the device, which then moves around the environment, tracking itself. Static references need to be observable by the tracker, such that the pose of the device in relation to them can be determined, however, the tracking sensors are mobile. Inside-out approaches have recently exploited the fact that AR devices are equipped with increasingly powerful hardware, promoting the integration of advanced computer vision algorithms for detection and tracking of the environment from images captured by a high-resolution camera, integrated into the device. The difference between these two paradigms is visualized in Fig. 5.4. When selecting a tracking modality, one is often confronted with a trade-off between accuracy, usability and reliability [16]. While outside-in approaches are considered to be more accurate and reliable, they come at the cost of additional system components and line of sight constraints. Inside-out approaches work in an unprepared environment, but their accuracy and reliability often does not meet the requirements of high precision applications, such as medicine [5].

In principle, tracking can be accomplished with different kinds of sensors, such as mechanical, haptic devices, electromagnetic fields, or global positioning systems (GPS). However, vision-based sensors, such as visible light cameras or infrared (IR) sensors are by far the most active area of research and will therefore be the focus of the following chapter [17].

2.3.2 Marker-based systems

Optical registration and tracking can be accomplished with marker-based approaches, which rely on artificial indicators rigidly attached to real world objects. A fast and cheap method is to track known image patterns (fiducials) with standard red-green-blue (RGB) visible light cameras. However, such approaches are sensitive to uneven, non-controllable lighting conditions. The tracking of retro-reflective spheres with infrared (IR) cameras has been shown to be a more robust alternative [16]. This principle is used by many commercial tracking and motion capturing solutions, such as OptiTrack (Natural Point, Inc., Corvallis, Oregon, USA) or Vicon (Vicon Motion Systems Ltd, UK), which operate in an outside-in fashion. Marker-based approaches have the advantage of providing a solution for both tracking and registration in one go. For an accurate marker-based registration, markers and real objects are usually rigidly calibrated to each other, so that tracking of the markers allows a precise, 6DOF pose estimation of the real object to which the markers are attached. Stationary markers can also serve as easy to detect references for inside-out tracking. The obvious disadvantage of marker-based systems is that they require a meticulously prepared environment, were markers and real-world counterparts need to be calibrated, line-of-sight constraints must be adhered to, and lighting conditions must be adjusted.

2.3.3 Marker-free systems

Markerless registration and tracking is an approach which exploits natural features observable by the tracking device within the environment. One of the most noteworthy techniques for markerless, model-free tracking is simultaneous localization and mapping (SLAM) [18]. As the name suggests, SLAM algorithms build a map of the environment from information gathered from a variety of sensors within a device and simultaneously locate this device within this map. Other markerless tracking approaches are based on models or templates, where a 3D model of parts of the observed scene is available and compared with the camera images to estimate it's 6DOF pose as a 3D to 2D matching problem [13,17]. As an alternative, some AR systems integrate 3D surface information of the scene directly, in example by capturing the scene with stereo cameras, structured light or time-of-flight (TOF) depth sensors. The so acquired surfaces can directly be registered with a 3D model of the target. However, these additional sensors must be dynamically calibrated with the remaining system components, which generally results in complicated setups.

Finally, registration can be performed manually or semi-manually. For example, the pose of the real object to be annotated with augmented content can be digitized by capturing some known points on its surface with a tracked tool. Then, the virtual model can be registered to it using a point-based registration. Alternatively, the pose of a virtual object can be adjusted in a purely manual way, by using controls supported by the AR application, such as touch buttons or gestures. The major drawback of manual approaches is that the registration is not dynamic—in case the real object moves, coherence is lost, and the procedure must be repeated. This is why such registration strategies are often combined with marker-based systems, were manual user input is only required for initial calibration, and real-time tracking is thereafter accomplished with the aid of fiducials.

2.4 Visualization and visual coherence

Even after real and virtual objects have been correctly aligned, there are still some important factors influencing the perception of the virtual content in AR, which can be related to visualization. To obtain an actual impression of location and characteristics of virtual objects, they need to be blended with the reality in a visually coherent, non-obstructive way.

A naïve opaque overlay of virtual graphics may occlude important information in the real scene and even semi-transparent overlays might be distracting and falsifying real information. Furthermore, basic image fusion techniques such as overlays suffer from their lack of depth cues, which is especially problematic for X-ray visualization, where the user should percept augmented content as lying within real objects.

One particularly important depth cue is **occlusion** [19]. In a basic overlay, only virtual content can occlude the real scene, and not vice versa, which might lead to the impression of virtual objects floating on top of the environment. A deeper understanding of the observed scene is required to properly handle occlusions. For example, phantom rendering, first introduced by Breen et al. [20], and similar techniques register an invisible model of the real occluder to the object and use it to inhibit the rendering of virtual objects where they would be occluded by reality. The idea of phantom rendering can be extended by texturing phantom objects using the information captured by the camera and fusing real and virtual information in these overlapping regions in a way that enhances the inference of spatial relations. Widespread techniques in that regard are cutaways, Focus-and-Context (F + C) visualization, and ghosting. Cutaways can easily be realized by cutting a hole into the phantom object and displaying this hole with the virtual object within. In F + C, the virtual focus objects are partially occluded by key features, such as edges, from real context objects [21]. Ghosting, on the other hand, renders the phantom object transparently on top of the virtual object. In the process, the transparency of the occluder is determined by its important salient video image features, such as their curvature [22].

While occlusion offers information about the ordering of objects within the scene, it does not provide information about the distance of objects. **Motion parallax** and **stereo disparity** are cues that deliver information about this relative and absolute distance. With stereoscopic head-mounted displays, both of these cues can be intuitively realized.

Illumination and **shadowing** are other important factors in visual coherence. Aside from providing a sense of depth, these cues are also important for correctly perceiving the shape of objects. By approximating the light sources in the reality, for example using light probes, virtual objects can be illuminated accordingly, and virtual shadows can be correctly cast on real objects.

2.5 Current augmented reality hardware

Advances in mobile displays, graphics processing units (GPUs) and tracking technology have recently resulted in a large choice of enabling technologies for AR, apart from standard monitor and camera setups. First and foremost, low cost smartphones and tablet computers have made VST AR accessible to a broad range of users and developers. Smartphones can be integrated into affordable head mounted devices containing simple optics, such as the Google Cardboard (Google, Mountain View, CA, United States) or the Samsung Gear VR (Samsung, Seoul, South Korea), to create a more immersive experience. Easy to use development platforms such as ARCore (Google, Mountain View, CA, United States) and ARKit (Apple Inc., Cupertino, CA, United States) provide out-of-the-box solutions for environmental understanding and device tracking. Due to limited computing power, reliability and accuracy, such setups are, however, more suitable for entertainment purposes than for serious applications with high precision requirements.

Tethered VST-HMDs, which require a connection to a PC, overcome these limitations at the expense of reduced mobility and higher cost for the consumer. Noteworthy examples of such displays include the HTC Vive (HTC Corporation, New Taipei City, China) or the Oculus Rift (Oculus VR, Menlo Park, CA). For accurate tracking, these devices use a combination of sensors, such as inertial measurement units (IMU) and outside-in cameras.

OST display solutions have only recently been commercialized, with the Google Glass (Google, Mountain View, CA, United States) released in 2013 being one of the most prominent examples. Currently, the Microsoft HoloLens (Microsoft Corporation, Redmond, WA, United States), released in 2016, is the most popular hardware choice in the category of OST-HMDs. The HoloLens uses several sensor types (TOF sensor, visible light cameras, IMU) for inside-out tracking. Virtual images are projected onto a pair of transparent combiner lenses, allowing for a true, stereoscopic 3D visualization of content.

3 Augmented reality in medicine: current practice and challenges

3.1 Applications of AR in medicine

Medical AR has become a very broad topic, with applications ranging from medical education to image guided surgery, and employment in a wide variety of medical fields. According to recent surveys by Eckert et al. [23] and Chen et al. [15], the largest body of research focuses on clinical applications, with the majority of research going toward surgery or intervention, followed by applications in therapy and rehabilitation. A considerable amount of studies also explores AR in medical education and training. Examples for these diverse fields of applications are displayed in Fig. 5.5.

3.1.1 Education and training

In an educational context, AR can aid learners by visualizing complicated spatial relationships, animating complex phenomena, and facilitating interactive learning through real-time interaction and feedback [24]. Furthermore, new technologies, such as AR, potentially enhance the attractiveness and appeal of traditional educational interfaces such as books or lectures, increasing the students' motivation to learn [25]. A prime example of AR-supported education in medicine is anatomy learning, where textbook images or anatomical models can be annotated with virtual information and made interactive. AR-supported anatomy learning has been shown to reduce the cognitive load for students [26] and increase their motivation to study [27]. Commercial applications for AR supported anatomy learning, such as the Human Anatomy Atlas by VisibleBody (Argosy Publishing Inc, Newton, MA, United States) or Complete Anatomy by 3D4Medical (Elsevier,

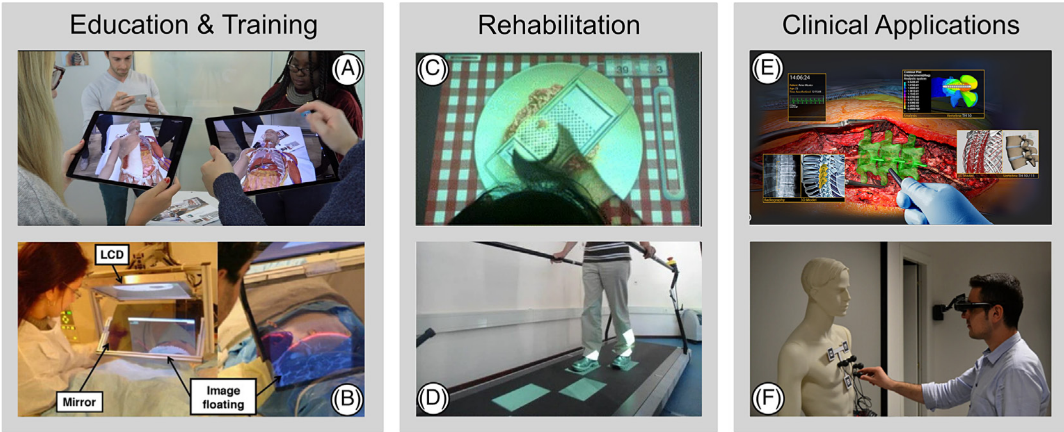

FIGURE 5.5 Examples for the different fields of applications of medical AR. (A) A handheld, video see-through AR system used for anatomy learning. (B) The Perk Station is employed for training percutaneous surgical procedures using a world-localized optical see-through system. (C) A projector-based AR application is used to aid stroke patients in regaining their ability to perform day-to-day tasks. (D) A similar application is employed for helping patients in walking adaptability therapy. (E) A mock-up showing AR assisted, image-guided spine surgery. (F) Using a head-worn AR display for aiding untrained people in performing electrocardiography. *Part A: (Image courtesy of 3D4Medical by Elsevier); Part B: Image adopted from Ref. [32]; Part C: Image adopted from Ref. [37], published under CC BY 4.0 license; Part D: Image adopted from Ref. [36], published under CC BY 4.0 license; Part E: Image adopted from Ref. [45]; Part F: Image adapted from [56], published under CC BY 4.0 license.*

Amsterdam, Netherlands), as shown in Fig. 5.5A, are now internationally used by universities and clinics.

AR also has a place in medical training, where the overall goal is not the studying of theoretical concepts, but the acquisition of technical skills. By using specialized phantoms or simulators, medical students and residents can improve their ability to perform tasks with a high perceptual, cognitive, and sensorimotor workload, without the instrumentation of the patient [28]. Such training systems can be enhanced using AR, by providing image guidance or instant feedback to the trainee. Several commercial training tools using AR technology exist and have been evaluated in the literature [29], in example the ProMIS system for laparoscopic tasks (Haptica, Inc., Dublin, Ireland), or the CAE Vimedix (CAE Healthcare, Inc., Montreal, Canada) for training ultrasound examinations. Experimental systems have, in example, also been applied to train the insertion of needles [30–32], as seen in Fig. 5.5B, and neurosurgical procedures [32]. These studies show that AR in medical training can improve the accuracy and speed of carrying out a simulated task, however, how well skills acquired in these mixed environments translate to skills needed to perform actual clinical interventions still remains questionable.

3.1.2 Rehabilitation

In rehabilitation, medical AR can help patients in the recovery from mental or physical conditions, either in their homes or in specialized rehabilitation centers. An area of particularly high research interest is the rehabilitation of deficiencies of the musculoskeletal system, of which stroke patients commonly suffer from [33–37]. Examples of such systems are shown in Fig. 5.5C and D. These studies show that AR interfaces have the potential to make repetitive tasks and activities, which usually must be performed during rehab, more engaging. Furthermore, AR systems allow a more objective evaluation of the therapy progress, also remotely. Aside from sensorimotor defects, successful implementations of AR rehab systems have been reported for the management of chronic pain [38,39]. AR applications for rehabilitation are facilitated by the fact that affordable, mobile technologies, such as smartphones or tablets, can easily be deployed in the patients' homes and additionally enable remote monitoring of activities and progress.

3.1.3 Clinical applications

Most AR systems for usage in hospitals and clinics focus on applications within the operating room (OR). The overreaching goal of these applications is usually the enhancement of conventional image-guided surgical navigation. Image-guided surgery (IGS) has helped surgeons to perform safer, less invasive interventions for almost 30 years [40], by aiding physicians in localizing and reaching target regions more quickly and accurately, while reducing the risk of harming critical structures during the procedure. In IGS, a preprocessed dataset of the patient (e.g., containing imaging data and planning information) is accurately registered to him or her within the OR, and a navigation system is used to track instruments in relation to this data. Commercial surgical navigation systems, in example manufactured by Brainlab (Brainlab AG, Feldkirchen, Germany) or Medtronic (Medtronic, Minneapolis, MN, United States), provide imaging, planning, and tracking information on a separate monitor. It is evident that AR interfaces have the potential to greatly simplify such procedures by providing in situ visualization, for example, fusing navigation information directly with the patient. This allows the surgeons to focus their attention on the patient and the surgical site alone, and they do not have to mentally map information between two different sites. Several experimental AR systems to support complex interventions have been experimentally trailed, in example for tumor resection [41–44], pedicle screw placement [45–47] (as shown exemplary in Fig. 5.5E), and surgical drilling [48,49]. Even though IGS is the most common procedure supported by medical AR, it is also the most challenging. Navigated surgical procedures usually have highest demands in terms of accuracy and reliability. Furthermore, cumbersome and bulky setups or distracting visualizations have to be avoided to assure acceptance and usability. The currently very restricted usage of AR within the OR shows that most developmental AR systems fail to deliver some of these requirements so far. However, medical technology companies are slowly starting to open up to the integration of AR into their navigation systems.

Interventions outside of the OR have also been subject of interest for AR research. In example, support for radiation therapy [50], the placement of catheters [51,52] or other needle interventions [53] have been explored. Furthermore, AR has the potential to aid novice health care workers or untrained personnel in performing and interpreting complex examinations such as ultrasound [54,55] or electrocardiography [56] (Fig. 5.5F).

Clinical application of AR in these scenarios is usually less critical than within the OR, since they are more tolerant of errors caused by device or system failures. Nonetheless, for procedures where guidance is not absolutely necessary, the benefits of AR must outweigh the cost of additional hardware components and work steps AR systems usually come with. Therefore, their contribution to the clinical routine has yet to be validated [15].

3.2 Medical AR displays

The type of display used for medical AR applications does not only determine the way augmented data is presented to the user, but also has a major influence on precision and practicality of a system. An exemplary overview of medical display choices is shown in Fig. 5.6.

3.2.1 World space displays

World localized VST displays in the form of stationary monitors with additional tracked cameras have long been the most widely used technology in medical AR [23]. Aside from using a conventional camera to capture the scene, live images from tracked medical devices can be augmented directly. A notable example is the Camera Augmented Mobile C-arm (CamC) introduced in 1999 by Navab et al. [57]. Their first system allows the overlay of X-ray images from a mobile C-arm and optical images from a camera in real-time. CamC has since been extended by numerous capabilities and is one of the few AR systems,

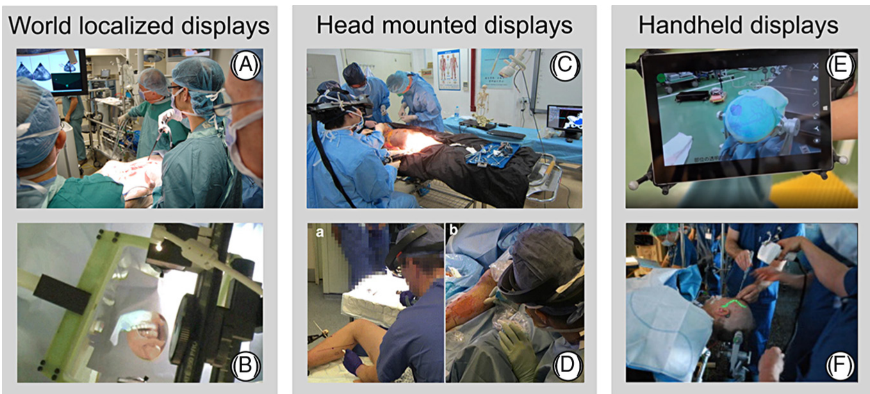

FIGURE 5.6 Different types of medical AR displays. (A) A laparoscopic surgery supported by a conventional world localized AR system using a 2D monitor. The laparoscopic video is augmented with pre-surgical planning data but still, the surgeons must look away from the patient for navigation. (B) An optical see-through, world localized display shows a surface rendering of an anatomical structure directly overlaid with the patient. (C) A tethered head-worn display is used during orthopaedic surgery. (D) The HoloLens, an optical see-through HMD, is emerging as a popular display choice for medical applications, as shown here for vascular surgery. (E) A handheld tablet computer is used for pre-operative visualization of a brain tumor, and (F) A handheld projector, developed by Gavaghan et al. [80], displays navigation information directly on the patient's skin surface. *Part A: Image adapted from Ref. [61]; Part B: Image adopted from Ref. [135], published under CC BY 4.0 license; Part C: Image adopted from Ref. [15]; Part D: Image adopted from Ref. [71], published under CC BY 4.0 license; Part E: Image adopted from Ref. [79]; Part F: Image courtesy of Kate Gerber, University of Bern.*

which have successfully translated into clinical practice [48]. In another example, the Intraoperative Brain Imaging System (IBIS) by Drouin et al. [58] allows the augmentation of traditional navigation information with ultrasound images captured by a tracked probe and a live video from the surgical site, fusing all information within one view [59]. In particular, minimally invasive procedures, such as laparoscopy or endoscopy have been an active focus of AR research, as the loss of direct vision inherent to these interventions can be partially compensated by augmenting the camera images with pre-interventional planning. For examples, the reader is referred to reviews by Bernhardt et al. [23] or Linte et al. [61]. AR-supported laparoscopy tools are also commercially available, for example, the NeoChord system (NeoChord, Minnetonka, MN, United States). However, all these setups have the common limitation of not offering immersive in situ visualization. Virtual data, even though fused with the reality captured by a camera, is displayed on external monitors, and therefore, is still diverting the physician's attention away from the patient. Moreover, conventional monitors do not support stereoscopic vision, reducing the visualization possibilities to 2D. An example is given in Fig. 5.6A.

World localized OST solutions do not have this limitation. Such so called AR windows typically use half-silvered mirrors for an overlay of imaging with the live patient. For example, an integral videography (IV) device for medical applications, as shown in Fig. 5.6B), was developed by Liao et al. [62]. IV systems reconstruct points stereoscopically in space using a micro convex lens array. Recent applications of IV overlay devices are reported by Ma et al. [47,63], where CT imaging is fused with the patient in support of pedicle screw and dental implant placement. Such systems usually suffer from inferior image quality in comparison to other displays and require bulky stationary infrastructure directly between physician and patient, possibly blocking the interventional site.

Similarly, projector-based systems enable situ visualization directly on the patient, but without a device amidst patient and doctor. An advantage of projector-based displays is that virtual content can be seen by multiple people at once, allowing for easy collaboration. However, projector-based AR suffers from limitations in terms of image quality, and generally only works in darker environments, which is often not realizable in a medical context. Furthermore, projecting data on irregular, deformable tissue, such as a patient's outer anatomy, is challenging since it requires dynamic adjustment of the data to avoid distortions.

3.2.2 Head mounted displays

Compared to world space displays, HMDs have the advantage of not cluttering the complex medical environment with too many additional components and not blocking the physician's access to the patient in any way. Head-worn operating binoculars, a special case of OST-HMDs, were amongst the first medical AR displays explored by Roberts et al. in the late 1980s [1]. Their system enabled the superimposition of planning data with the optical imagery as seen through the binoculars. The augmentation of the surgeon's view through operating binoculars or microscopes has since found its way into commercial surgical microscopes, such as the Zeiss Kinevo (Carl Zeiss AG, Oberkochen, Germany) or the Leica ARveo (Leica Camera AG, Wetzlar, Germany). Such systems are now routinely used, especially in the fields of neurosurgery, dentistry, and otorhinolaryngology, just to name a few. Augmented operating microscopes, therefore, present an example of a successful integration of AR into the clinical routine. Nonetheless, their field of application is limited to microsurgical procedures.

One of the first VST-HMDs, designed specifically for medical purposes, was the "Reality Augmentation for Medical Procedures" (RAMP) system introduced by Sauer et al. in the early 2000s [64,65]. Aside from two stereoscopic color cameras, the RAMP VST-HMD included a separate IR camera, which was able to detect retro-reflective markers for inside-out tracking and registration. Originally proposed for needle guidance, RAMP has found its way into many experimental applications in the medical domain and was used to study perceptual and visualization difficulties in medical AR [66–68].

With the recent improvements in mobile computing, consumer-grade HMDs have gained considerable popularity in the medical domain. State-of-the-art VST displays, such as the Oculus Rift, are still used in medicine [69], however, the focus has shifted towards OST-HMDs. This shift was largely caused by the introduction of the HoloLens in 2016. Since then, numerous experimental systems for the HoloLens have been described in a large range of medical specialties. Examples include orthopedics [46,70], angiology [51,71] (see also Fig. 5.6D), neurosurgery [72,73], pathology [74], and critical care [75], just to name a few. Furthermore, the HoloLens found its application in commercial medical solutions such as OpenSight (Novarad, American Fork, UT, United States), which has recently been FDA approved [76]. OST-HMDs are usually preferred to VST-HMDs in medical scenarios, since the physician wearing it is not completely separated from his or her real surroundings and thus, can still safely navigate within the environment in case of device failures. In a safety critical environment, such as the operating room, this is of utmost importance. Unfortunately, current OST-HMDs still provide insufficient precision and latency for many interesting clinical applications such as IGS [15]. Furthermore, limited rendering capabilities result in restrictions to the level of detail of virtual content, which is also detrimental for medical applications, were small details can have a large impact on decision-making. Promising hardware such as the HoloLens 2 or specifically developed displays for the medical sector, such as Augmedics xvision (Augmedics, Arlington Heights, IL, United States), might overcome these limitations in the future, affirming the status of OST-HMDs as the new gold standard for medical AR.

3.2.3 Handheld displays

Handheld AR systems are less popular in the medical domain, since they occupy the hands of the user, impeding the physician's interaction with the patient or with interventional tools. Therefore, it's applications are focused on training and education [77], the evaluation of surgical outcomes [78] or pre-operative visualization [79], mostly using tablet computers as displays, as exemplary shown in Fig. 5.6E). A handheld, portable projector system for medical applications was developed by Gavaghan et al. [80] (Fig. 5.6F), and a similar system was employed for neurosurgical navigation by Tabrizi et al. [81].

3.3 Registration and tracking in medical AR

The choice of registration and tracking technique plays a fundamental role in medical AR. Obviously, many medical procedures, such as image-guided interventions, have very high demands in terms of accuracy and are not tolerant to lag or loss of tracking. For convincing in situ visualization, accurate image-to-patient registration is absolutely necessary to profit from its potential benefits. At the same time, the tracking modality should be simple enough to not add undue technical complexity to already complicated workflows.

Marker-based AR systems are still dominating in current research, as they are more straightforward to implement and usually more precise than marker-less systems. Outside-in tracking of retro-reflective IR markers is a very popular technique applicable to both registration and tracking. It integrates well with all display types, as demonstrated in example for IV displays [47], world space monitor setups [58], handheld devices [79] and HMDs [82]. The obvious advantage of this method is that the same technology for tracking is used in the majority of commercial navigation systems, such as the Brainlab Curve or the Medtronic Stealth Station. Since such systems are already well integrated in the clinical routine, repurposing them for AR might ease the translation of such systems from research to the clinic. A drawback of this tracking modality is, however, that a constant line of sight between the tracking camera and the tracked objects needs to be maintained. Especially for complex setups with multiple tracked targets (e.g., the patient, the AR device, and surgical instruments), this constraint restricts the freedom of movement of the physician. Surgical navigation systems using electromagnetic tracking instead of IR do not suffer from this limitation but have proven to be less reliable due to interferences from ferromagnetic or conductive objects within the OR.

Inside-out tracking of markers alleviates the line-of-sight constraint by eliminating the need to track the AR device. Most often, it is performed by tracking planar fiducials using standard visible light cameras integrated in mobile devices such as smartphones and tablets [83,84] or HMDs [45,75,85,86]. A shortcoming of all marker-based approaches for registration is that the attachment of a marker or fiducial to the patient usually requires an invasive procedure, since they need to be fixed on rigid tissue such as bone to avoid unwanted shifts caused by tissue deformation. To enable in situ visualization, the markers need to be also visible in the virtual imaging data, and their position in relation to the patient's anatomy needs to be calibrated manually. This requires time and human as well as technical resources while limiting usability, therefore making the usage of such systems only justifiable for complex surgical procedures, were accurate image-guided navigation is absolutely necessary.

An alternative to using fiducial markers for registration is the utilization of natural anatomical landmarks. During anatomy education, medical students learn to identify a large variety of such landmarks in all parts of the body and in corresponding medical imaging, which allows for a point-based matching to achieve registration. However, since the automatic detection of such points is difficult, this registration strategy usually requires manual input, in example by digitizing the landmarks through touching them with tracked tools [51,87–89]. A progression of this technique are surface-based registration methods, where instead of a few points, parts of the patients' skin surface are captured and registered to the skin surface extracted from pre-interventional imaging through standard surface registration algorithms, such as Iterative Closest Point (ICP) [90]. Brainlab has commercialized this technique with their z-touch, a laser pointer which can be used to capture the patients' outer anatomy. In research, other setups to capture the 3D representation of the patient have been explored, for example, TOF depth sensors [91–93] or stereo cameras [94–96]. A common drawback of surface-based methods is that they only provide a solution for registration, not racking. The devices which capture the 3D representation and the AR device need to be calibrated to a common reference frame to achieve a dynamic overlay, which usually, again, requires the introduction of markers and/or navigation systems. This results in a quite substantial technical setup, which furthermore requires manual calibration steps, which is an important impeding factor when it comes to clinical usability and acceptance.

All approaches described earlier perform rigid registration, that is, estimate the 6DOF pose of the real object (e.g., the patient) to transform the virtual content accordingly. In the medical domain, the target anatomy can only be considered as rigid in some areas, while in others, one is usually confronted with soft tissue. This tissue is subject to deformation and movement from physiological sources such as breathing and heartbeat, the interventional or surgical procedure itself, or gravity. Tissue deformation needs to be considered in image-to-patient registration for many applications, especially endoscopic and laparoscopic interventions [60]. Non-rigid registration algorithms usually rely on intraoperatively captured data, either for using it directly for augmentation [59], or for updating a 3D patient model with the acquired data [97]. However, more research in the area of real-time online 3D modeling is needed to fully address this challenge [15].

3.4 Visualization of medical data in AR

The overarching goal of an AR visualization of medical data is to support the physicians' decision-making process, without overwhelming them. Clinicians are usually accustomed to conventional radiographs presented on 2D monitors, where medical data is visualized in 2D, in the form of orthogonal slices through the image volume (axial, sagittal, and coronal planes), or, sometimes, oblique reformats, so called multi-planar reformations. In the case of AR visualization, they are confronted with a more complex 3D situation. Furthermore, the visualization of virtual content must not occlude the real view too much and should not distract from the patient.

To preserve the clinically established 2D view, slice rendering has also been employed in medical AR systems [98,99]. This technique has, of course, the drawback that data is only shown in selected planes. Hence, given an AR display, 3D visualization is becoming more widely used, mostly in the form of 3D surface rendering. For surface rendering, tissue has to be segmented and converted to polygons prior to visualization, making it more complicated to establish a workflow. These polygons can be visualized as dense surfaces, but other representations, such as wireframes or contours, can be derived from them. In contrast, direct volume rendering offers superior image quality and does not require surface extraction before visualization [68]. However, performance requirements of volume rendering can still not be easily addressed with mobile hardware, such as HMDs.

Aside from the form of data representation, the technique to fuse real and virtual plays a large role in the visualization of medical data in AR. In a complex medical context, the implementation of advanced visualization effects such as lightning and shadows might not be feasible, but depth cues from correct occlusion handling and context-aware visualization can have a large influence on the perception of medical data [68]. Depth perception is especially important to infer information about spatial relations between anatomic and pathologic landmarks, obtain a size estimate of or a path to target structures. Phantom rendering-based occlusion handling for medical AR was already described in very early work by State et al. [2,100], where cutaway visualization is used for AR-supported, ultrasound-guided needle biopsies. Pauly et al. [101] developed a learning-based method for identifying objects in the surgical scene and medical imaging data and building a fused image based on the physician's preferences, as seen in Fig. 5.7A. Bichlmeier et al. described the first F + C visualization specifically for medical applications [67], which is shown in Fig. 5.7B). They enumerate several conditions for effective in situ visualization, including a non-restricted view of the target anatomy, concealing occluding anatomy and focusing on the region of interest, and an integration of virtual content, which allows an intuitive perception of spatial relations. Their approach was later extended for volume rendering using stereoscopic visualization on an HMD [68] (Fig. 5.7C). The same group also studied the concept of "Magic Mirrors" for medical AR visualization, a technique which allows the physician to use a virtual mirror to look at target anatomy from different perspectives [102]. Lerotic et al. [103] proposed an "inverse realism" technique similar to F + C, by superimposing strong features of the AR occluded surface with the virtual content, displayed in Fig. 5.7D). Hansen et al. [104] utilized illustrative contour rendering techniques to create a sense of perspective on a 2D display.

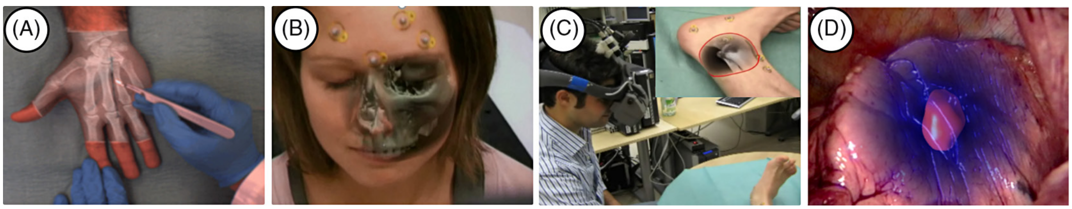

FIGURE 5.7 Different strategies for improving depth perception in medical AR. (A) By identifying relevant objects in the scene and combining them in a meaningful way, occlusions can be handled correctly [101]. (B) Focus and context visualization as introduced by Bichlmeier et al. [67]. (C) The technique was also implemented on a head worn display [68]. (D) Inverse realism accentuates strong features of the real object, while still focusing on the virtual content to obtain depth cues [103].

3.5 Requirements and challenges

In this chapter, we have shown that the feasibility of AR within a medical environment has been studied by a considerable number of research projects. However, it is also evident that few AR systems have successfully been implemented in actual clinical practice, and even fewer systems are commercially available. Demanding requirements and unique challenges still preclude the adoption of AR systems in medicine.

3.5.1 Accuracy and reliability of tracking and registration

Even though remarkable technological advances were made in the past years, the implementation of medical AR systems still faces major technical challenges. In particular, the demands in accuracy and reliability of calibration, registration and tracking are still not straightforward to address. While medical applications have the advantage of usually being carried out in a relatively small, closed, and controlled environment, they still have unique demands in terms of lightning and arrangement of devices, which can have an adverse influence on visual tracking. Consequently, within a clinical setting, one is often confronted with a trade-off between accuracy, invasiveness, and usability [5].

Surgical navigation systems already deliver sub-millimeter precision and real-time interactivity, and therefore, many research projects focus on integrating AR solutions with these already well-established devices. However, a typical AR system requires the addition of several components, such as image capturing devices and displays, which have to seamlessly integrate with the tracking technology. Evidently, each system component contributes to the overall error and latency. This chain of components influencing each other also convolutes the calculation of the overall error and reliability of the system. It is desirable to perform an online computation of the current system error, so the physician is always aware of the accuracy of the information currently presented to him [5]. Aside from that, multi-component systems might require lengthy set up times and manual calibration procedures, which require additional time and human resources. It is, therefore, desirable to develop systems requiring minimal components and minimal technical knowledge to set up, while still preserving the tracking and registration accuracy delivered by high-end devices.

Although advances in mobile computing have made wearable and handheld devices more powerful, current state-of-the-art hardware is often still not able to meet the high demands medical AR has in tracking and registration. The HoloLens, which we have already shown to be one of the most popular devices for medical AR right now, still has deficiencies in terms of robustness and latency of its built-in SLAM tracking [105,106] or in the stability of registered virtual content [107]. Even after accurate registration, virtual content can be misaligned because of these shortcomings, hampering the implementation of the HoloLens within the OR for a real clinical application.

3.5.2 Visualization and representation

While the effective, natural visualization of medical data in AR was quite actively studied in the past, recently, research focus has shifted again towards tracking and registration issues. Nevertheless, the visualization problem has not yet been fully solved.

We summarized a number of strategies to overcome the problem of incorrect depth perception in medical AR. However, most of the discussed visualization techniques can only be applied to VST displays in a straightforward way, because they usually require a manipulation of the reality, as captured as images by a video camera. Since for OST and projector displays the appearance of the real scene cannot be altered, producing depth cues or realistic lightning and shadows through visualization techniques is much more difficult. In this regard, more research into display technology itself might be necessary to achieve the desired effects

But not only the “how” is important when thinking about medical data visualization, also the “what” and “when” should be prime concerns, as pointed out by Kersten-Oertel et al. [108]. To determine what content is required by the physicians in the current situation, without overwhelming them with redundant information, some sort of context aware augmentation is necessary [109]. Ideally, an AR system would automatically recognize the situation the physician is in and adapt the virtual content accordingly. Current advances in machine learning, especially deep neural networks for action recognition and object detection, will be invaluable aids to realize such systems in the future.

3.5.3 Acceptance and usability in the clinic

The acceptance, usability, and interoperability of medical AR systems within the clinic are, unfortunately, often overlooked by researchers, even though they are arguably among the most important factors in clinical translation [110].

Proposed systems often come with overburdened setups, lengthy calibration, and unintuitive user interfaces and data representations, which cause health care professionals to reject those new technologies. The actual clinical benefit and utility are often insufficiently addressed in research projects. Most studies focus on a validation of their system in terms of objective measurements, such as accuracy or latency, usually performed ex vivo or on phantoms. However, such metrics alone do not guarantee a clinical benefit to the physician or to the patient. A closer collaboration between engineers and medical staff is required to transition medical AR systems from proof-of-concept prototypes to medical devices, by taking into account clinical needs and constrains enforced by the clinical routine [111].

4 Augmented reality in oral and cranio-maxillofacial surgery

4.1 Traditional CAS procedures and their limitations

The concept of computer-assisted surgeries in the head and neck area were first described in the late 1980s [112]. Since then, surgical navigation systems have been implemented in the clinical routine in different subspecialties of OCMS, such as trauma surgery, foreign body removal, tumor resection, reconstructive surgery and orthognathic surgery [113]. The oral and cranio-maxillofacial complex houses delicate anatomy and critical organs, such as the brain, eyes, larynx, and oral cavity. Surgical interventions in this region have, therefore, high demands in precision, to guarantee an outcome for the patient, which is both functionally and aesthetically optimal. With a technical system accuracy in the

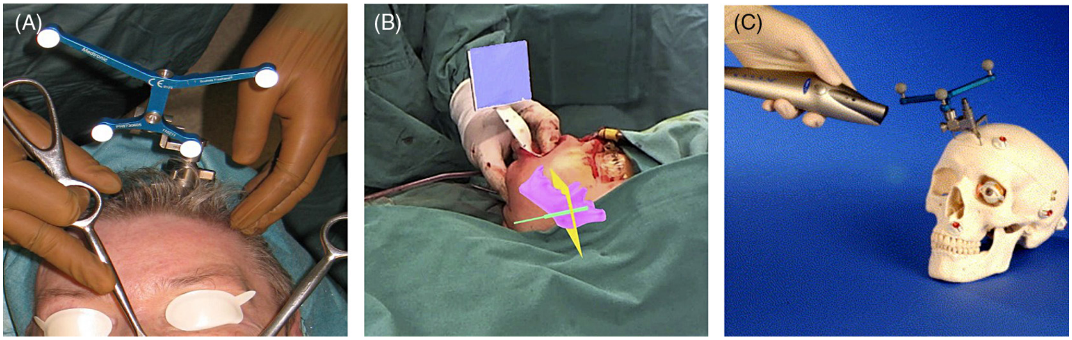

FIGURE 5.8 Image-to-patient registration strategies in OCMS. (A) In traditional navigated OCMS, a skull-fixed marker, here using retro-reflective spheres for tracking with an infrared sensor, are used for registration. (B) Alternatively, using patient-specific occlusal splints for non-invasive marker fixation has been proposed. (C) Markerless registration, for example, using a laser scanner to capture the outer anatomy of the patient has also been suggested. However, to track the movement of the patient, a marker is still required. *Part B: Image adapted from Ref. [141]; Part C: Image adapted from Refs. [117].*

sub-millimeter range and an average intra-operative error of maximal two millimeters [113], current navigation systems can satisfy this demanding criteria, making OCMS more precise and predictable and leading to a more optimized workflow for the surgeon, and an improved outcome for the patient. In terms of tracking technology, both optical and electromagnetic navigation systems are still commonly used in OCMS clinics [114].

The benefits of IGS do, however, come at a cost. Conventional navigation increases the complexity of a surgery. The first challenge is image-to-patient registration. Most often, navigated OCMS requires the fixation of fiducial markers to the skull as seen in Fig. 5.8A, which is invasive. Alternatively, the non-invasive usage of an occlusal dental splint to hold reference markers has been proposed [115], see Fig. 5.8B, which is, however, much more prone to error due to the movable temporomandibular joints and the small operating field. Additionally, as patient-specific dental casts have to be prepared for the surgery, it increases planning and preparation time. After marker placement, specialized pre-operative scans must be acquired, which will later be referenced with the patient in the OR and used for image guidance. This process requires time and human resources and therefore, must be planned several days in advance. At the same time, in case of CT scanning which is the most commonly used imaging modality in OCMS [116], increases radiation dose for the patient in a critical area. Marker-less methods, for example, using a laser scanner to digitize the patients skin surface as in Fig. 5.8C, have been evaluated as an alternative [117], but require the patient to remain stationary and are, therefore, only applicable to selected applications. Since AR systems usually require the addition of displays and capturing devices to the setup, making them even more complex, registration is still an interesting area of research in IGS in general and AR-guided IGS in particular. Reliable, precise registration and tracking of the patient, which does not involve invasiveness and limits manual interaction to a minimum, would be most desirable.

Another limitation arises from the fact that IGS systems usually render medical imaging and planning data in 2D on an external monitor, while the anatomical structures and surgical interactions themselves are three-dimensional. This forces the surgeon to divide his attention between navigation system and operation site, and furthermore requires complex hand-eye coordination, which can only be acquired during years of training. In situ visualization using AR technology could alleviate this problem by transferring imaging data directly in the same reference space as the patient, improving the spatial perception of targeted anatomies and the coordination of 3D interactions.

4.2 History and state of the art of AR in OCMS

The work in AR for OCMS was pioneered by the group of Wagner et al. from the University of Vienna in the mid-1990s. They used the ARTMA Virtual Patient system (ARTMA Biomedical, Vienna, Austria), an AR system based on a VST-HMD for capturing and augmenting the surgical scene, and a tracking system based on electromagnetic sensors, fixed on the craniofacial bone or an occlusal splint, for image-to-patient registration and tracking. The ARTMA system supported several means of visualizing medical data, such as surface renderings of anatomical structures, task-oriented geometrical primitives, and numerical information. They published several case studies of different OCMS procedures, including foreign body removal and dental implant placement [118], intra-oral tumor resection [4], osteotomy [119], and temporomandibular joint movement measurement [120]. Furthermore, they tested the feasibility of their system for teleassistance and telenavigation [121]. While their system was reported to increase the perceived safety of the procedures by surgeons and, in some cases, reduced the operative time, pre-operative planning, and preparation time was increased significantly. Although they did not provide measures about system accuracy, they state that the tracking and registration methodology did not meet the requirements in precision and reliability for some procedures, and their system can, therefore, only be used for selected cases.

Birkfeller et al. [122] designed both an augmented, head-mounted operating microscope called Varioscope AR, as well as a navigation system specifically designed for implantology [123], which is based on optical tracking of active infrared light-emitting diodes (LEDs). They combined their devices to create an AR system for the support of skull-base surgery [124], by attaching LED markers to the HMD, the patient, and tracked tools. In their study, they showed that surgeons were able to localize target structures with high accuracy when supported with a rendering of pre-operative planning data. A challenge their system is confronted with is the relatively low refresh rate of 15–50 Hz and the precondition of a complicated, manual calibration procedure. Nonetheless, since they integrated their system into an already well-accepted device, they report superior clinical agreement of physicians as to comparable systems.

Around the same time, Salb et al. developed Intraoperative Presentation of Surgical Planning and Simulation Results (INPRES) [125], using a stereoscopic, see-through HMD, at the Universities of Karlsruhe and Heidelberg. Similar to previously described systems, it is based on the combination of an HMD, at that time the commercially available Sony Glasstron LDI (Sony Corporation, Tokyo, Japan) and an optical infrared tracking system for outside-in tracking. Image-to-patient registration is realized by digitizing landmarks, marked by titanium screws implanted in the patient's head or on a dental splint, using a tracked pointing device. Although their system showed promising results in terms of tracking and registration accuracy, they report some limitations in terms of hardware, especially concerning the resolution and image quality of the HMD. Manual display calibration and registration are other drawbacks of their approach.

The same group of collaborators between Karlsruhe and Heidelberg later presented an alternative system, which was the first to use surface-based registration for AR in OCMS [126,127]. More precisely, a structured light-based surface scanner was used to capture the patient's outer anatomy prior to intervention, and this 3D model was registered with pre-operative CT or MRI for an initial registration. Still, skull-attached IR markers and a corresponding navigation system were used to track the patient's movement during surgery. One advantage of this registration scheme is that a pre-operative scan showing the IR fiducials is not necessary, therefore, they need to be placed only during the primary surgery and radiation dose for the patient is confined. Instead of displaying data on an HMD, a projector-based display modality was used to show task-oriented geometrical primitives, such as osteotomy lines and tumor margins. The group reported on the successful application of their system in selected cases of tumor resection and reconstructive surgery in the oral-craniomaxillofacial complex and quantify the system error with around one mm. A notable limitation is the deformation of projected images on non-rigid, irregular soft tissue during the surgery.

Mischkowski et al. first described the clinical use of X-Scope (Brainlab, Heimstetten, Germany), which their group co-developed, in 2006 [128]. X-Scope is based on a handheld VST, integrated with an IR-based navigation system for tracking. Registration is accomplished point-based through anatomical landmarks and a tracked pointer. The system supports the visualization of surface renderings and was used in orthognathic surgery, specifically the translocation of bony segments, in five cases. With an average deviation of 9.7 mm between real and virtual objects, X-Scope was not precise enough for IGS, however, authors attribute usability as a control device to their system. The same setup was used for 46 orthognathic interventions by Zinser et al., reported in comparison to several conventional techniques in 2013 [129,130]. They also experimented with stereotactic image-to-patient registration but found that skull-fixed fiducials were more reliable. System accuracy was improved to around 1.7 mm. Overall, by usage of the AR system, operating time was 60 min longer than conventionally, but the technique using AR navigation was described to be superior to conventional protocols for specific clinical requirements, leading to favorable outcomes for the patients.

At the University of Tokyo, an IV-based display modality using a half-silvered mirror for medical augmented reality was developed [131]. This display was first integrated into an AR system for oral surgery by Tran et al. [132], where it was combined with an optical navigation system for instrument and patient tracking. They experimented with the overlay of geometric information, such as surgical paths and instrument positions, as well as textual information for situations where small differences are difficult to perceive trough pure visualization. Their system was evaluated in a hole-drilling task on a phantom and submillimeter accuracy between planning and outcome was reported. Geometric primitives were rendered 10 frames per second (fps). The stationary setup between physician and patient might, however, limit the workspace of the surgeons, and the response time of the system was still an area of improvement. The same setup was later used by Suenaga et al. [49] for displaying surface renderings of the maxillary and mandibular jaw on a human volunteer.

The same group from the University of Tokyo developed a tracking methodology based on a stereo camera setup for markerless image-to-patient registration in dental implantology [133]. Their principle is based on tracking the 3D contour of the patients' teeth and matching it to a pre-operatively acquired teeth model using an ICP algorithm. Wang and Suenaga combined this tracking and registration paradigm with the previously described IV display [134,135]. Further improvements in terms of rendering and implementation were realized, resulting in an average system accuracy of 0.9–1.1 mm and a rendering frame rate of 50–60 fps. This system is the first AR system for OCMS which performs marker-free, real-time registration, and tracking. Per contra, since the teeth contours of the patient must be fully visible for this tracking strategy, its applications are limited to dental surgery. Later, Wang et al. adapted their tracking and registration paradigm based on the teeth contour to work with monoscopic cameras, using a method by Ulrich et al. [136] for initial registration and an ICP for refinement, and implemented both the stereoscopic and monoscopic version in a VST AR application for implantology [137,138].

Zhu et al. based their registration strategy for AR in orthognathic surgery on a non-invasively placed occlusal dental splint fixed on the mandible [139]. They used an image-based marker, trackable with the ARToolKit software (ARToolworks, Seattle, WA, United States) and a standard visible light camera. The system supported 15 interventions by displaying pre-operatively planned osteotomy lines and a surface model of the mandible in relation to the patient anatomy. Unfortunately, they do not report on the used display modality or system performance. The setup was subsequently used for surgical navigation in orbital hypertelorism surgery [140], were they report an average deviation of 2.2 mm between pre-operative design and actual osteotomy outcome. Qu et al., from the same university, describe a similar approach for the treatment of hemifacial microsomia in 10 cases [141], but achieve a smaller deviation of around 1.4 mm between the pre-operative plan and actual outcome. They conclude that AR can aid in mandibular distraction osteogenesis to generate an aesthetic outcome for the patient. Nonetheless, they also report on deficiencies of the system in terms of user friendliness. Han et al. also report the application of this system in synostotic plagiocephaly surgery of seven patients in 2019 and report sufficient accordance between the pre-surgical plan and the surgical outcome [142].

In 2016 and 2017, this group reported the integration of their dental splint-based registration strategy with a head worn AR display, performing drilling tasks during mandibular angle split osteotomies, a robot-assisted surgery [143,144], and to display inferior alveolar nerve bundles during orthognathic surgeries [145]. All these works have the common drawback of being heavily reliant of the manufacture and rigid fixation of an occlusal splint, which is reliant on stable occlusal relations and excludes edentulous patients from a treatment with these systems, and prolongs preparation time for the interventions.

Another projector-based AR system was introduced in 2012 by Gavaghan et al. [146]. Their contribution is the usage of a portable projector device, which should reduce overhead and intrusiveness, while increasing workspace flexibility, compared to stationary projector systems. Once again, an IR-based tracking system is used to establish a correspondence between target and projector, as well as target and imaging data by using a point matching-based registration strategy. They used their overlay device to project a tumor, the facial nerve, and the mandible onto the patient for guidance during mandible tumor resection. An accuracy evaluation revealed a mean projection accuracy of 1.3 mm, while a refresh rate of 50–60 Hz could be maintained for surface rendering of anatomical structures.

A markerless VST system, using a stationary stereo camera setup, together with a movable camera, and a conventional monitor as a display, was introduced by Lee et al. in 2012 [94]. Similar to other surface-based registration strategies, they reconstruct the patients' skin surface from matching stereo frames and use an ICP-based algorithm to register it with pre-interventional imaging. After initial registration, the patient needs to remain stationary. The movable camera is tracked using an ARToolKit marker. The proposed system is capable of rendering surface data and orthogonal CT planes with an average target registration error of 3.3 mm. Later, they replaced the stereo camera in their system with a TOF depth sensor, the Kinect (Microsoft Corporation, Redmond, WA, United States) [99]. However, the system accuracy did not improve significantly, and a clinical application of the system has not yet been demonstrated.

In 2014, a VST-HMD-based system for LeFort 1 orthognathic surgery was introduced by Badiali et al. [147]. As a registration and tracking strategy, they implemented an inside-out paradigm with a set of visible markers implanted into the skull of a phantom and point-based registration. Therefore, they do not require external infrastructure for tracking. Overall, a mean system error of 1.7 mm was determined in vitro using a phantom.

Another VST-HMD application, this time for implantology, was proposed by Lin et al. [148]. Similar to other groups, they use an occlusal splint with an ARToolkit marker, tracked inside-out with a conventional visible light camera mounted on top of the headset, as a registration strategy. They projected pre-operational planning data for dental implant surgery within the field of view of the surgeons and achieved a sub-millimeter accuracy between planning data and outcome in an in vitro experiment.

Profeta et al. experimented with the application of AR to guide freehand Single Photon Emission Computed Tomography (SPECT) in sentinel lymph node biopsy of head and neck cancer patients [149]. A conventional monitor and camera setup, as well as outside-in IR-based optical tracking for co-referencing the SPECT probe and patient, were used to overlay textual elements and 3D surface renderings showing SPECT hotspots on the patient. The same principles were later evaluated for navigated surgery of head and neck tumors [150].

A case report of the usage of an augmented operating microscope for intra-orbital tumor resection was reported by Scolozzi and Bijlenga in 2017 [151]. An IR-based navigation system was used to track the microscope, and the microscope itself served as a reference coordinate system correlating the surgical site and the pre-operative plan. A surface rendering of the tumor was overlaid within the microscope to grant a better insight into its deep extension.

Wang et al. performed a cadaver study using AR to guide temporomandibular joint arthrocentesis [152]. A projector-camera system and an image-based registration method based on the homography between camera and projector were employed. The entire system is stationary, thus no inside-out or outside-in tracking was implemented. Another drawback is the manual calibration procedure between camera and projector image, which is time intensive and error prone. It is unclear whether the reported accuracy of an average of 3.5 mm is sufficient for a clinical application of the system.

Recently, Ahn et al. presented a system for Le Fort 1 osteotomy using a stationary monitor based VST modality. Their system uses image markers, an intermediate splint for attaching a marker cube to the patient and a stereo camera for outside-in optical tracking. By using this stereo setup, they were able to achieve high system accuracy with registration errors below 0.5 mm, making it comparable to commercial navigation solutions. However, since their visualization is still based on a monitor, it does not alleviate the problem of the surgeon having to divert his attention between surgical site and navigation information.

Pietruski et al. described a proof of concept study of an OST-HMD based system for mandibular resection in 2019 [153]. They use the well-established, outside-in tracked configuration with an IR tracking camera and rigidly fixed markers on the HMD and the patient. In their study, they performed an in vitro comparison between AR-guided osteotomies and the conventional procedure using cutting guides, and found that both varieties lead to similar outcomes, however, improved hand-eye coordination and orientation within the operating field were reported by surgeons using the AR system.

Finally, our group, in cooperation between the Medical and Technical Universities of Graz, started to develop an AR system for OCMS in 2018. We were the first to use the HoloLens for supporting OCMS for the immersive visualization of imaging data from head and neck cancer patients. Our main idea is to develop an AR system which is comfortable for both the patient and the surgeon, thus neither requiring invasive markers, nor excessive hardware infrastructure or complicated manual calibrations. Pepe et al. described an initial approach using facial landmark detection to determine the orientation and the HoloLens' built-in spatial mapping module and ray casting to estimate the 3D position of the patient, in order to overlay pre-interventional imaging data accurately with him [154,155]. However, due to the coarseness of the spatial map built by the HoloLens, the registration error was high, especially in the back-front dimension, and the procedure required some manual adjustments of the imaging data. In a second approach by Gsaxner et al., we therefore utilize the HoloLens' TOF depth sensor to reconstruct a more accurate, finer representation of the patients face, and relate it with information from its self-localization capabilities for improved image-to-patient registration [44]. Our current system supports rendering of surface meshes and orthogonal 2D imaging data, to support clinicians in target localization during surgery planning (a video is available under [156]). To facilitate the development of AR solutions for OCMS, we furthermore published our dataset including PET-CT scans and 3D models of 12 head and neck cancer patients, which can be used for low-cost phantom creation and the implementation and evaluation of AR systems [157].

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