Diplomarbeit

The use of augmented and virtual reality in clinical oral & maxillofacial surgery

A review of literature

eingereicht von

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zur Erlangung des akademischen Grades

Doktor der Zahnheilkunde

(Dr. med. dent.)

an der

Medizinischen Universität Graz

ausgeführt an der

Universitätsklinik für Zahnmedizin und Mundgesundheit

Klinische Abteilung für Mund-, Kiefer- und Gesichtschirurgie

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Graz, 13.08.2020

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Abstract

Background: In the last two decades three-dimensional (3D) visualization technologies have become part of our daily life. In the field of oral and maxillofacial surgery 3D visualization technologies such as augmented reality (AR) and virtual reality (VR) are of great interest, because these technologies offer the opportunity to visualize complex anatomical conditions in three dimensions and in real time directly on the patient. AR and VR are assumed to have great potential to better understand complex physiological and pathological conditions pre- and intraoperatively and increase diagnostic accuracy and treatment outcome. Although many works have been published in the literature that outline various novel highly promising AR and VR applications in oral and maxillofacial surgery, none of them provides so far a clear consensus, a clear description of limitations or levels of evidence about their real clinical potential. Therefore, the aim of this work was to review the literature in order to evaluate the clinical potential and to provide an overall level of evidence of the existing research to date regarding AR and VR in oral and maxillofacial surgery.

Methods: A literature search on PubMed, Mendeley and the Web of Science was conducted. For the electronic data research, the following keywords were used: “virtual reality maxillofacial” and “augmented reality maxillofacial”. Only already published or accepted papers were used. After applying predefined inclusion and exclusion criteria, the remaining papers were reviewed in order to give a state-of-the-art overview of the clinical potential of AR and VR in oral and maxillofacial surgery.

Results: 56 original papers and 3 reviews were found with the keywords “augmented reality maxillofacial.” The main focus for AR papers was related to “protection of the infra alveolar nerve” (n=2), “orthognathic” (n=7), “reconstruction” (n=6), “tumor resection” (n=8), “dental implants” (n=4) and “system accuracy” (n=11). The search with the keywords “virtual reality maxillofacial” showed 89 original studies and 5 reviews. The main focus for VR papers was related to “teaching” (n=11), “planning” (n=8) and “virtual reality in preoperative anxiety patients” (n=2). After the selection process 36 papers on augmented reality and 26 papers on VR were included in this review. The level of evidence found in the literature showed evidence grades between Ib and V for VR technologies and IIIa and V for AR technologies There was no evidence level found for AR applications

higher than IIIa and for VR applications higher than Ib. Comparative clinical studies are completely missing so far.

Discussion: VR has great potential in clinical education and 3D surgical planning. Intraoperative use of VR can lead to lower stress level of the patient.

AR is mainly used in an intraoperative setting. In particular, superimposing surgical plans and important anatomical structures are of great interest. Due to the higher accuracy achieved by using hard tissues as reference for registration, augmented reality is so far especially convenient for surgeries concerning hard tissue structures like bone or teeth. Although more original papers were found related to AR, a higher level of evidence was found for VR applications.

Conclusion: Although the use of VR and AR applications show great potential in clinical oral and maxillofacial surgery, so far no functional stable technology could yet have been established for the clinical practice. The level of evidence in the published literature was found to remain low, especially for AR applications, which mainly seem to be used in early stage pilot projects regarding a clinical use. Therefore, studies with higher levels of evidence, comparative assessments and practical implementations, especially for AR applications, are necessary, in order to further develop and establish these technologies in the clinical routine.

Zusammenfassung

Hintergrund: In den letzten zwei Jahrzehnten haben 3D Technologien in vielen Bereichen unseres täglichen Lebens Einzug gehalten. Auch in vielen Feldern der Medizin werden 3D Darstellungen in der Diagnostik und der Therapie verwendet. Wie in vielen chirurgischen Bereichen besteht jedoch in der Mund-, Kiefer- und Gesichtschirurgie ein besonderes Interesse an Technologien, wie AR und VR. Diese ermöglichen es komplexe anatomische Zusammenhänge, dreidimensional und in Echtzeit, präzise auf die Patienten und Patientinnen zu projizieren. AR und VR könnten es ermöglichen komplexe physiologische, wie auch pathologische Zusammenhänge prä- wie auch intraoperativ besser zu verstehen und somit zu einer verbesserten Diagnostik und einem verbesserten Outcome führen. Obwohl bereits viele Arbeiten publiziert wurden, welche die möglichen Vorteile dieser Technologien für die Mund- Kiefer- und Gesichtschirurgie beleuchten, wurde bis jetzt noch keine Zusammenschau der Limitationen bzw. des Evidenzniveaus, der klinischen Anwendung von AR und VR durchgeführt. Daher soll diese Literaturrecherche das klinische Potential dieser Technologien, sowie das Evidenzniveau der existierenden Literatur evaluieren.

Methode: In dieser Studie wurde eine Literaturrecherche durchgeführt. Es wurden die Datenbanken von PubMed, Mendeley und das Web of Science mit den Schlagwörter „augmented reality maxillofacial“ und „virtual reality maxillofacial“ durchsucht. Nach Anwendung der Ein- und Ausschlusskriterien wurde die verbliebene Literatur herangezogen um das klinische Potential von AR und VR in der klinischen Mund-, Kiefer- und Gesichtschirurgie zu beurteilen.

Ergebnisse: Die Literatursuche ergab 56 Originalarbeiten und 3 Reviews zu den Schlagworten „augmented reality maxillofacial“. Die Schwerpunkte lagen auf den Gebieten “protection of the infra alveolar nerve” (n=2), “orthognathic” (n=7), “reconstruction” (n=6), “tumor resection” (n=8), “dental implants” (n=4) und “system accuracy” (n=11).

95 Originalarbeiten und 5 Reviews wurden zu den Schlagworten „virtual reality maxillofacial“ gefunden. Die Forschungsschwerpunkte lagen hierbei auf “teaching” (n=11), “planning” (n=8) und “VR in preoperative anxiety patients” (n=2).

Nach dem Selektionsprozess wurden 36 Studien (VR) bzw. 26 Studien (AR) für diese Arbeit herangezogen.

Das Evidenzniveau lag zwischen Ib und V bei VR und zwischen IIIa und V bei AR.

Diskussion: VR hat nach derzeitigem Stand großes Potential in Bereichen der klinischen Ausbildung, sowie in der 3D OP-Planung. Die intraoperative Anwendung von VR kann zu einem niedrigeren Stresslevel beim Patienten bzw. der Patientin führen.
AR findet vor allem intraoperativ Anwendung. Die genaue OP-Planung und/oder ein genaues 3D Modell der Patientenanatomie, kann auf das OP Gebiet projiziert werden. Aufgrund der hohen Präzision der Projektionen durch die Verbindung mit harten Geweben, findet AR derzeit besonders bei Operationen an knöchernen Strukturen Anwendung. Trotz der höheren Anzahl an Publikationen zu AR, zeigt die Studienlage zu VR Anwendungen eine höhere Evidenz.
Conclusio: Obwohl AR und VR großes Potential in der klinischen Mund-, Kiefer- und Gesichtschirurgie zeigen, konnten sich diese noch nicht in der klinischen Routine etablieren. Das Evidenzniveau der durchgeführten Studien war niedrig. Besonders Anwendungen der AR, welche sich aktuell meist in der Pilotphase befinden, werden derzeit entwickelt und in ersten Experimenten getestet. Sie sind Gegenstand derzeitiger Forschungen für den klinischen Einsatz. Weitere Studien mit höherer Evidenz, vergleichende Studien und die praktische Anwendung, vor allem der AR sind notwendig um diese Technologien weiter zu entwickeln und in der klinische Routine zu etablieren.

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Glossary and Acronyms

2D *2*-dimensional

3D *3-dimensional*

APAIS amsterdam preoperative anxiety and information scale

AR *augmented reality*

CAD/CAM *computer-aided design/computer aided manufacturing*

CAVE *computer activated virtual enviroment*

CAVOS *computer-assisted 3D virtual osteotomy system for orthognathic surgery*

CT *computer tomography*

HC *heart coherence*

HMD *head mounted device/display*

ICP *interactive closest point*

MRI *magnetic resonance imaging*

PC *personal computer*

PET-CT *positron emission-computer tomography*

RCT *randomized controlled trial*

RP *rapid prototyping*

SPECT *single photon emission computed tomography*

STL *stereolithography*

VAS *visual analog scale*

VR *virtual reality*

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1 Introduction

1.1 Purpose of this thesis

In the last two decades 3D visualization technologies have increasingly become part of our daily life. Due to this rapid development, the possibilities of highly advanced software and visualization programs are of great interest to surgeons all over the world. Especially in the area of oral and maxillofacial surgery, where complex surgical cases are being treated, 3D visualization seems to be a promising tool for future diagnostic and treatment support. (Zhao, Patel and Cohen, 2012) Based on datasets of 3D imaging, such as MRI, CT or PET-CT, 3D-pictures of the area of interest can be generated and visualized in different ways.

The visualization by means of virtual reality (VR) is well known today in popular areas such as gaming and entertainment. Another option is to integrate the virtual picture in a real life environment. (Chicchi Giglioli *et al.*, 2015) (Badiali *et al.*, 2014) With special glasses like Microsoft HoloLens® it is possible to visualize the specific CT or MRI scans directly on the patient. The user can see the virtual picture directly on the patient's face at the same time. Virtuality and reality become one and enhance the user's perception. Therefore this technology is called augmented reality. (Chicchi Giglioli *et al.*, 2015)

This technology gives the opportunity to visualize the site in order to make a diagnosis and/or to carry out the steps for preoperative planning 3-dimensionally, which seems to have a highly promising potential for clinical use. This is especially true for complex anatomical regions and areas of limited intraoperative view such as inside the facial skull, where advanced visualization technologies can be used to support diagnosis, treatment plans and surgical procedures for increased accuracy and safety.

Since the beginning of medical imaging with the first X-rays, physicians have had to deal with the problem of needing to transfer the information from a 2-dimensional picture onto a 3D patient just by-picturing it mentally**.** Furthermore, they have to look away from the patient in order to focus on a diagnostic image displayed on a separate workstation. (Meola *et al.*, 2017) This issue is referred to as a "switching focus problem." By bringing the desired information in 3D directly

on the patient, AR is able to effectively bridge this gap. (Sielhorst, Feuerstein and Navab, 2008; Meulstee *et al.*, 2019)

Both technologies, AR and VR, are not yet integrated in the clinical routine, but are currently subject of intensive research in various medical disciplines. (Dixon *et al.*, 2013) There are certain requirements which need to be fulfilled in order for them to be integrated into clinical routine. The technology needs to be mobile, functionally stable, easy to handle and require specific software support such as functioning face detection algorithms and sufficient hardware power. The latter is often not available in the needed amount in many clinical centers and specific software packages are still subject to research. (Khor *et al.*, 2016) Especially in the last years, many works have been published in the literature that outline various novel highly promising AR and VR applications in different fields of oral and maxillofacial surgery, (Chen and Hu, 2018; Kwon, Park and Han, 2018; Bosc *et al.*, 2019; Joda *et al.*, 2019) however without providing a clear consensus, limitations or level of evidence about the real clinical potential of these technologies.

Therefore, the aim of this work is to review the literature in order to evaluate the clinical potential and to provide an overall level of evidence of the existing research to date regarding AR and VR in oral and maxillofacial surgery.
To the best of the author's knowledge, this is the first review of literature concerning the evaluation of AR and VR technologies in oral and maxillofacial surgery.

1.2 Structure of this thesis

In the beginning of this thesis, an introduction is given to illustrate the differences between AR and VR. Furthermore, the history and the technical principles of both technologies are explained.

In the second part, a state-of-the-art overview of both technologies in the clinical field of oral and maxillofacial surgery is presented. The overview and resulting facts are based on a review of literature. The literature review was based on an electronic search in the scientific databases PubMed, Mendeley and the Web of Science.

In the final part of this thesis, the results of the literature search are discussed in order to evaluate the clinical potential of the two technologies. Finally, a summary and a future outlook are given.

2 Mixed reality continuum

Virtual images and reality can be combined in varying degrees. The range between reality and virtual reality is called “mixed reality.” This term goes back to Milgram’s and Kishino’s study in 1994, which described mixed reality as a “merging of real and virtual worlds somewhere along the “virtuality continuum” which connects completely real environments to completely virtual ones.”(Milgram, 1994)

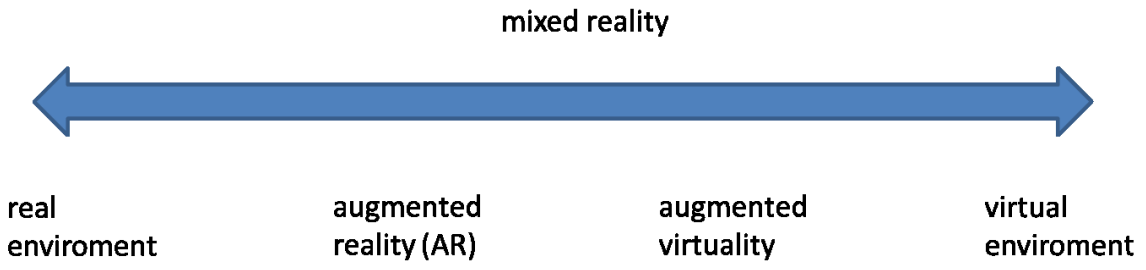

Figure 1 Virtuality continuum
(Milgram, 1994)

3 Virtual reality (VR)

3.1 Definition and main principle

VR places a user inside a completely computer-generated environment. VR has become increasingly popular for movies, games and other media. Nowadays computer graphics have reached a high-level point where the images cannot be differentiated from the real world. The virtual reality is completely detached from reality itself by replacing the normal sensory input of reality through computer generated stimuli. This is achieved with head-mounted displays (HMD) directly in front of the user's eyes. Therefore a user can completely immerse herself in the virtual world without any restrictions. (Egger *et al.*, 2017) Immersion and interaction are the key features of VR. (Kwon, Park and Han, 2018)

3.2 Technique

3.2.1 Creating a three-dimensional vision

The reason why humans can see in 3D is our binocular vision system. Our eyes are 6-7cm apart. Every eye registers a slightly different picture than the other one. Based on this so-called binocular parallax, the human brain generates a kind of depth map of the seen object. This is the key to visual stereoscopic vision or stereopsis. (Cutolo and Ferrari, 2017)

VR hardware can be divided into input and output devices. Input devices collect data from the real world, such as the position and movement of the user, while output devices bring the virtual world to the user by giving visual, auditory and haptic stimuli to the users' senses. (Casasanto and Jasmin, 2018) Nowadays VR devices often provide input and output data and are therefore often referred to as hybrid devices. (Anthes *et al.*, 2016)

3.2.2 Output devices

Output devices bring stimuli to the user to create a nearly perfect illusion of reality. Visual, auditory and haptic input can be given by different kinds of hardware. Since this area is continually evolving and changing, it is impossible to give a

comprehensive overview of all the different hardware add-ons to VR. For this reason, only the most common technologies will be mentioned here.

3.2.2.1 Head mounted display (HMD)

The most common feature in output devices is the visual display in form of a head-mounted display (HMD). Like the name suggests, two displays are worn on the head, one in front of each eye, thus creating a 3D effect.
(Casasanto and Jasmin, 2018) HMDs can be wired to a computer, which gives the opportunity to launch more complex tasks and a higher resolution due to a higher processing power.
Mobile HMDs are not attached to an external PC. The whole processing takes place in the HMD, which makes the latter heavier and limits its computing power. (Anthes *et al.*, 2016) Examples for currently popular HMDs for VR are Valve Index (Valve™), Oculus Rift S (Oculus™) and HTC Vive Pro (HTC™).
Another option to create a virtual room is the so-called CAVE system (Computer-Activated Virtual Environment). The virtual images are projected on the walls, floor and ceiling of a room. The user wears 3D glasses like in a cinema.
For audio stimuli; headphones or an external sound system can be used to give a 3D sound experience to the user. (Casasanto and Jasmin, 2018)

3.2.3 Input devices

Input devices collect data from the real world in order to adapt the VR as realistically as possible.

3.2.3.1 Controllers

The most common input devices are controllers. Controllers collect information input by buttons and joysticks. The user holds one controller in each hand. Like widely-known controllers for computer games, controllers can be wired or wireless. Some controllers even give haptic feedback to the user by means of vibration or other stimuli, known as “reactive grip.” (Anthes *et al.*, 2016)

3.2.3.2 Navigation

When the user wants to move through virtual space, an input device which detects the orders in which direction the user wants to move is needed. Furthermore, such navigation methods have to be intuitive, with no learning time needed. Several methods have been introduced, depending on the VR setup. Using a fully immersive setup requires more complex methods than using VR in front of a computer and strolling through cyberspace through the use of a mouse or joystick. (Fuhrmann, Schmalstieg and Gervautz, 1998) (Anthes *et al.*, 2016)
Commonly used methods of navigation are:

- **Walking:** The actual walking of the user is tracked and his/her movement in reality is transferred to the virtual space. This technique is limited to actual room size and range of the tracking systems.
- **Gaze-directed:** The system moves in the direction in which the user is looking. This represents a very intuitive navigation method.
- **Pointing:** The user can move through the virtual space by pointing in the direction where he/she wants to go.
- **Cross-Hair:** The direction of movement is determined by a virtual line between the head and hand of the user.
- **Controller:** Physical controllers like joystick, mouse or similar devices

(Fuhrmann, Schmalstieg and Gervautz, 1998)

4 Augmented reality (AR)

4.1 Definition and main principle

The most commonly used definition of AR was postulated by Azuma in 1997:
"[…] AR allows the user to see the real world, with virtual objects superimposed upon or composited with the real world. Therefore, AR supplements reality, rather than completely replacing it. Ideally, it would appear to the user that the virtual and real objects coexisted in the same space[…]"(Azuma, 1997)
In addition, three main characteristics for an AR were defined:

1. Combines real and virtual
2. Interactive in real time
3. Registered in 3D

(Azuma, 1997)

Based on this common definition, AR is not limited to a specific way of combining technology. Various applications have been introduced to superimpose virtual images in the real world. The best known is the head-mounted device (HMD). (Badiali *et al.*, 2014) The two others are the display on monitors or the projection directly on the patient with a beamer. (Gavaghan *et al.*, 2012)

4.2 History

In 1968 Ivan Sutherland introduced the first head-mounted three-dimensional display. Sutherland could display 3D wireframe objects. Solid or "opaque" objects could not be displayed at the time because computers didn't have enough processing power to solve the "hidden line problem," which describes the difficulty to compute which objects are hidden by others. (Sutherland, 1968)
In the early 1990s Boeing researcher Thomas P. Caudell coined the term of augmented reality. He used a see-through head-mounted display in order to superimpose diagrams or templates on aircraft parts in the factory. The idea was to optimize the precision of production. (Caudell and Mizell, 1992)
At the same time, Louis Rosenberg developed for the US Air Force a perceptual system called "virtual fixture," whereby a robot arm was connected to an upper

body exoskeleton. When the operator in the exoskeleton moved his/her arm, the robot arm moved the same way. Sensory and visual feedback was given to the user by the exoskeleton and a vision system. This vision system was the first functioning AR system ever built. (Rosenberg, 1992) (Rosenberg, 1993)

At the millennium, AR started to infiltrate our daily life. In 1998 the first yellow line was drawn in the broadcast of a football game. A computer-generated virtual line was projected onto a live football game in order to help the viewer have a better overview of the match. (Schmalstieg and Höllerer, 2016)

Today AR technologies are integrated in daily life. This can be seen in “fun” applications used by a large number of people. To name just a few examples: Pokémon Go™, where virtual monsters are projected in our environment, or cat ears and many other fun features that can be generated in selfies on Instagram™ with special filters.

4.3 Technique

In AR a virtual picture needs to be correctly superimposed in the real world. More precisely, virtual contents are projected 3-dimensionally directly in the real environment. This needs more elaborate technical requirements and higher specialized software techniques (tracking software) than merely creating a VR environment.

4.3.1 Visual display

Three different approaches to visualize AR can be distinguished. The first to mention is the video see-through. A camera records reality live. AR footage is added in the video feed and shown to the user. The user sees reality on a screen enhanced with the virtual data.

The second method is optical see-through. The viewer sees reality with his/her own eyes and AR data is superimposed with semitransparent mirrors and lenses.

The third is direct projection of virtual data on a real object, a method known as projective display. (Krevelen and Poelman, 2010)

4.3.1.1 Video see-through

Video see-through is the cheapest way to visualize AR. It is also described as easier to implement than other kinds of displays. Given that reality is recorded by the cameras, it is easier to modify these data with virtual objects. (Rolland, Holloway and Fuchs, 1994)

However, this method has a major disadvantage that is frequently described. The camera-mediated view is not as good as reality in terms of quality and visual perception. (Cutolo and Ferrari, 2017)

Other disadvantages are the limited field of view and a sense of disorientation experienced by users because the positions of the cameras are not the same as of the users' own eyes. (Bimber and Raskar, 2006)

For example: When the cameras are mounted on the forehead, the cameras record from the point of view of the forehead and not from that of the user's eyes.

4.3.1.2 Optical see-through

Optical see-through systems integrate the virtual images in the visual field of the user. The real world is seen with the own eyes and virtual elements are superimposed on this view. The most common kind of optical see-through system is the visualization with a head-mounted device. The virtual information appears in the view of the user by means of transparent mirrors. This technique offers the advantage that the user can still see even if the device is not working anymore, which makes this system very interesting for medical and military use. (Krevelen and Poelman, 2010)

Another method is the retinal scanning display. It projects the virtual information directly on the retina of the user with a low power laser. Therefore, the resolution of the virtual image is not limited. (Silverman *et al.*, 2003)

4.3.2 Projective display

In this method the virtual information is directly projected on the real object. Reality becomes the screen for the virtual information. This method is already used in neurosurgery and laparoscopic surgery.

The disadvantage of this technology is that the surgeon's point of view is not the same as that of the projector. This means that the degree of accuracy is limited. (Bernhardt *et al.*, 2017) (Gavaghan *et al.*, 2012)

4.3.3 Integral imaging

Most of the techniques mentioned above need supplementary glasses in order to evoke a 3D effect for the observer. Looking at stereoscopic images for a longer period of time may cause fatigue.

Integral imaging uses an array of tiny lenses for obtaining and displaying the 3D image of an object. A set of images of the object of interest is obtained by the use of an array of lenses and a 2D image sensor. To create a 3D hologram the collected 2D images are displayed on a screen behind the microlens array. The rays emitted by the screen converge through the microlens array and create the 3D hologram. (Jang, Oh and Javidi, 2004; Liao *et al.*, 2004) (Murugesan *et al.*, 2018)

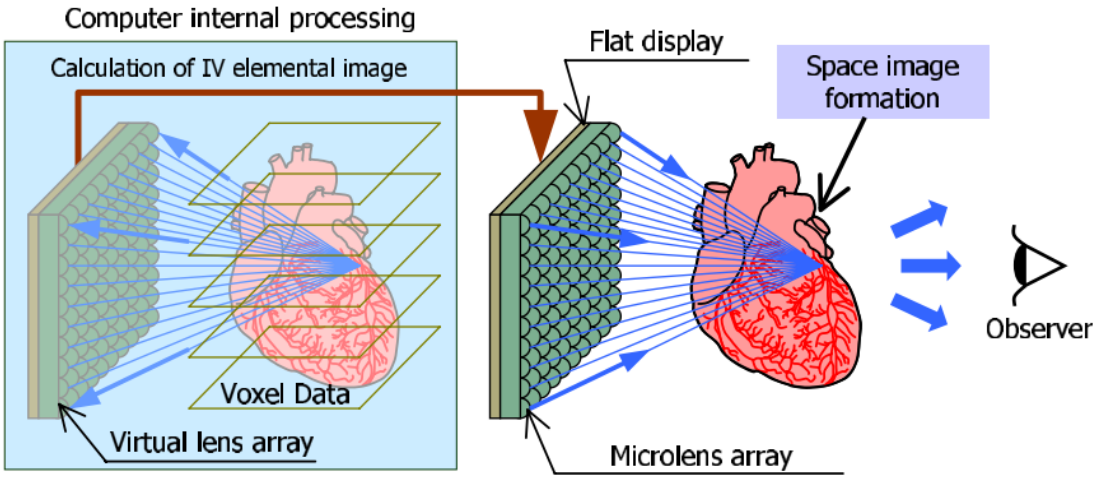

Figure 2 Principle of integral imaging
(Liao *et al.*, 2004)

4.3.4 Tracking

A major challenge for AR systems is to maintain an accurate overlay of virtual information on a real object for a long period of time. This is especially demanding when the real object is being modified while the AR system is working. An error in accuracy can result either from camera motion during filming and/or deformation of the real object. Due to these circumstances, it is necessary to adjust in real time the virtual picture to the changed conditions. The systems need to "know" where they are and where to project the virtual information. Therefore, a tracking of the camera and a tracking of the scene are essential to maintain the accuracy of AR. Today three tracking techniques are popular in AR: Optical tracking, magnetic tracking and markerless tracking. (Bernhardt *et al.*, 2017)

4.3.4.1 Optical tracking

Optical tracking systems are based on at least two cameras. Dedicated markers are attached to the element of interest and are detected by the cameras. These fiducial markers are placed on structures which remain still during the procedure. Therefore the position of the element or of the camera can be calculated by measuring the distances between the camera and the marker. (Vávra *et al.*, 2017) Most systems use infrared reflecting markers.

4.3.4.2 Magnetic tracking

In magnetic tracking systems a rapidly changing magnetic field is generated at the surgical site. The sensors are placed in the surgical site and therefore in the magnetic field. Because the magnetic field changes rapidly, a current is induced in every single sensor. Depending on the voltage measured in the sensors, every sensor can be determined in the magnetic field.

A key advantage of this technique is that the sensors are much smaller than those for optical tracking. Moreover, a magnetic field does not need a direct line of sight and is therefore suited for tracking inside the patient, as in laparoscopic surgery. (Bernhardt *et al.*, 2017)

On the other hand, with an average accuracy of 1.0 mm, magnetic tracking is not as accurate as optical tracking. Magnetic tracking is very prone to distortion of the

magnetic field, for example of metallic objects, which can lead to dramatic tracking errors. (Franz *et al.*, 2014)
Magnetic and optical tracking technologies both rely on markers that are attached to the patient. This creates several disadvantages:

1. The fixation of the marker to the patient takes time and effort. (e.g. producing a splint)
2. The fixed marker devices need some space. This fact limits movements around the patient, especially if the system were used within an interventional procedure.
3. If the designed position of the marker varies from its actual position, the error affects the accuracy of tracking.
4. Markers have to be “visible” for the AR system. Therefore, they have to extend from the patient. Due to low stiffness and a long error propagation path, accuracy can be significantly compromised.

(Wang, Shen and Yang, 2019)

Markerless tracking methods are attracting more and more attention in the surgical field in order to avoid these disadvantages.

4.3.5 Creating a marker less augmented reality

A markerless AR which can be used for diagnostic or therapeutic reasons is currently a topic of intensive research. The markerless approach is a high-level calibration method that does not need any additional external devices such as optical or magnetic systems. In practice, functional stable face detection software for AR devices is needed for a complete markerless calibration in the maxillofacial region. Such software has recently been developed by the medical and the technical universities of Graz (Pepe *et al.*, 2019) and will be clinically evaluated in the near future.
As mentioned above, the AR system needs to “know” the exact location of the user and the patient in order to superimpose the virtual image exactly in the right spot. With markerless tracking the camera and the visual system need to know

themselves their spatial position. The key is to make many pictures from nearly every point of view and save them.

When the camera in the real environment is moving, it collects live pictures and compares them with the saved ones. If the pictures are exactly alike, the camera “knows” its position in relation to the patient. Then the 3D virtual image can be integrated exactly into the real environment.

To carry this out in a practical clinical set up, certain steps are necessary to integrate the virtual medical data correctly in the real medical environment. The steps can then be divided into a preoperative environment, an intra-operative environment and a pose refinement. (Murugesan *et al.*, 2018)

4.3.5.1 Preoperative environment

Before the surgery takes place, a CT scan is performed and the data is segmented.

Segmentation is a process in which different areas in one picture are differentiated by different criteria. Criteria can be pixel, borders and regions. This process enables medical imaging to distinguish between anatomical structures. (Wallner *et al.*, 2019) This makes it possible to create a virtual 3D model of a structure. (Wake *et al.*, 2019)

During the ensuing “offline phase” an aspect graph is generated. A virtual camera takes different views of the model from different viewpoints. In order to compare these views with the 2D projection, these pictures need to be organized in “clusters.” Images that have mutual similarities higher than a predefined threshold are thus clustered into “aspects.” These aspects are downsampled and the clustering process is repeated. In this way, a “similarity- based hierarchical aspect graph” is created. (Wang *et al.*, 2017)

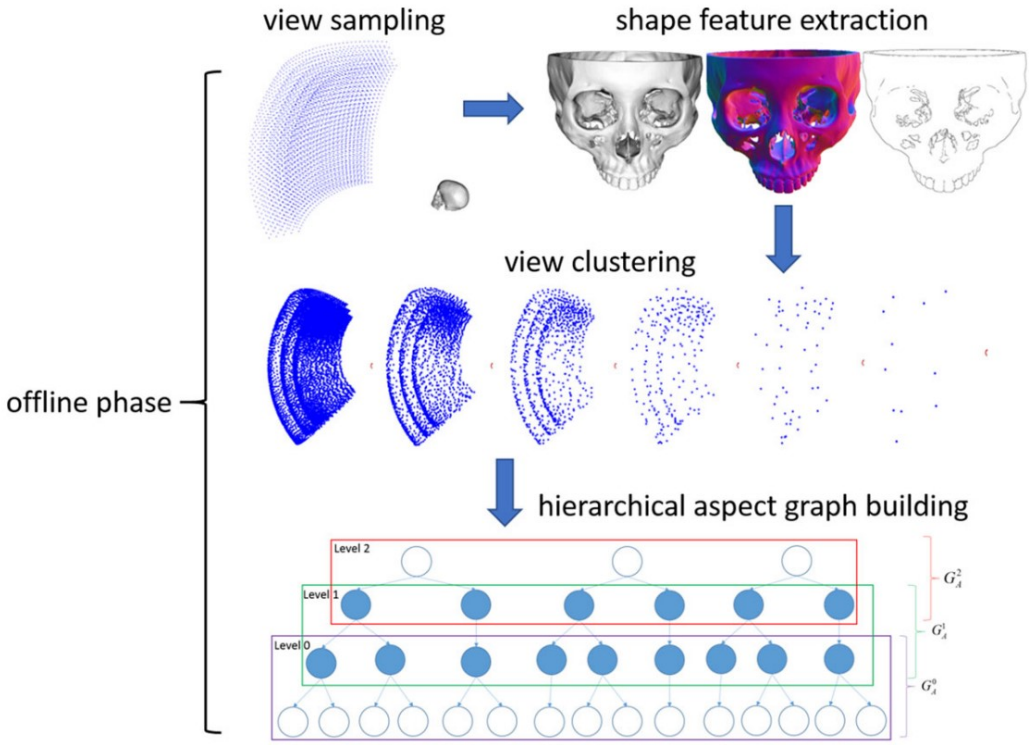

Figure 3 Creating a similarity- based hierarchical aspect graph
(Wang *et al.*, 2017)

4.3.5.2 Intra-operative environment

During surgery, the surgical scene is recorded with a 4K camera. Every recorded view is searched for in the top level of the aspect graph. When a predefined threshold of similarity is found it is stored in an extra file. This file is called a candidate list. The process is repeated at the next lower level and the matches are tracked down the hierarchical pyramid until the bottom level is reached. By knowing the best match on the bottom level with the highest similarity, the position of the virtual camera is located. Therefore the spatial position of the 3D model in relation to the real camera can be determined. (Wang *et al.*, 2017; Murugesan *et al.*, 2018)

4.3.5.3 Pose refinement

Pose refinement is done by an iterative closest point (ICP) algorithm. With this algorithm the segmented images are imposed onto the live video of the surgical site which creates an AR video of the scene. (Murugesan *et al.*, 2018)

5 Methods

For this thesis the aforementioned scientific databases were electronically reviewed for literature on AR and VR in oral and maxillofacial surgery. For the electronic data research, the following keywords were used: “virtual reality maxillofacial” and “augmented reality maxillofacial”. Only already published or accepted papers were used.
Due to the nature of the technologies, the fields of applications of AR and VR are different. Therefore, a separate literature review was conducted for each of the technologies. The review was performed according to the following inclusion and exclusion criteria.

Inclusion criteria were:

- The study had to include the use of AR or VR applications in oral and maxillofacial surgery in a clinical or pre-clinical setting
- The study had to discuss a field of application for oral and maxillofacial surgery in adults and/or children
- The study had to deal directly with the technology of AR or VR

Exclusion criteria:

- Studies related to technologies other than AR or VR
- Studies without direct application in oral and maxillofacial surgery
- Studies without a fully available text
- Studies written in a language other than English
- Letters and abstracts

Although the technologies “augmented reality” and “virtual reality” seem to be an increasing research topic in scientific oral and maxillofacial surgery, these concepts are often confused with each other, or with computer-assisted surgery, 3D planning, etc. Therefore, all papers were excluded which were not directly related to AR and/or VR according to their typical definition.
Only articles meeting the above-mentioned inclusion and exclusion criteria and published until January 2020 were considered.

All studies included in this thesis were reviewed and assigned to a level of evidence according to the specifications of the Oxford Centre for Evidence-based Medicine (March 2009) (Jeremy Howick March, 2009)

Level of evidence	Type of evidence
Ia	Systematic review (with homogenity) of randomized controlled studies (RCT)
Ib	Individual RCT (with narrow confidence intervals)
Ic	All or none study
IIa	Systematic review (with homogenity) of cohort studies
IIb	Individual cohort study (including low quality RCT)
IIc	"Outcomes" research; Ecological studies
IIIa	Systematic review (with homogeneity) of case-control studies
IIIb	Individual Case-control study
IV	Case series (and poor-quality cohort and case-control study
V	Expert opinion without explicit critical appraisal or based on physiology bench research or "first principles"

Table 1 Definition of level of evidence
(Burns, Rohrich and Chung, 2011)

To give a good clinical overview and illustrate the value of AR and VR in clinical oral and maxillofacial surgery, the resulting publications were sorted into different branches or subfields that were found to repeatedly make use of the two technologies.
For AR these are: "protection of the infra alveolar nerve" "orthognathic", "reconstruction", "tumor resection", "dental implants" and "system accuracy".
For VR, the studies were classified into the following categories: "teaching," "planning," "VR in preoperative anxiety patients" and "intraoperative use of VR."

6 Results

Until January 2020 the literature search on PubMed, Mendeley and the Web of Science identified a total of 146 publications. 51 papers were found with the keywords “augmented reality maxillofacial.” The search with the keywords “virtual reality maxillofacial” showed 95 studies.

From the 51 papers found with the keywords “augmented reality maxillofacial,” 16 were excluded since they did not fulfill the inclusion criteria.

From the 95 papers with the keywords “virtual reality maxillofacial,” 26 were included in the study. Although immersion and interaction are the key features of VR (Kwon, Park and Han, 2018), many papers using the term “virtual reality” did not match this typical definition. 45 papers had to be excluded because of misleading labelling of VR. From the 45 excluded papers, 14 were on the topic of AR and were included in the 51 papers with the keywords “augmented reality maxillofacial.” The oldest paper was found to be published in 1995; the most recent one was published in 2019.

Figure 4 and Figure 5 show the complete data selection process and the steps followed in this work.

After the selection process, all remaining papers were assigned to a level of evidence from the Oxford Centre for Evidence-based Medicine (March 2009). The detailed distribution is shown in Table 4. The majority of all papers showed an evidence level of IV and V. Evidence grade category I, such as systematic reviews of RCTs or other study designs with a high level of evidence could only be found within the literature concerning VR. The most common study designs were case reports (level V) and case series studies (level IV). The published reviews gave an overview of different clinical approaches or technical variations published summing up case reports or expert opinions.

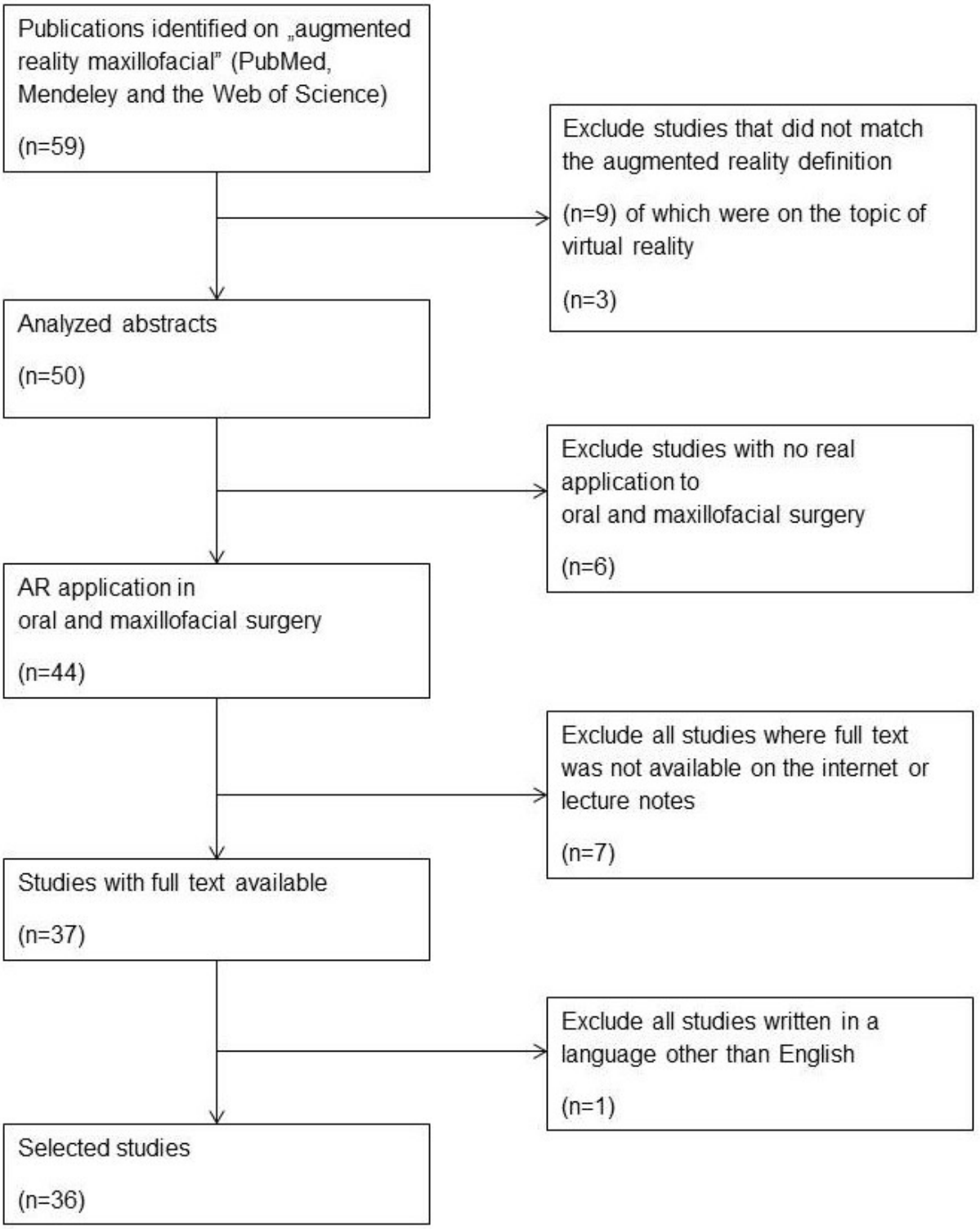

Figure 4 Selection process of literature found with the keywords "augmented reality maxillofacial"

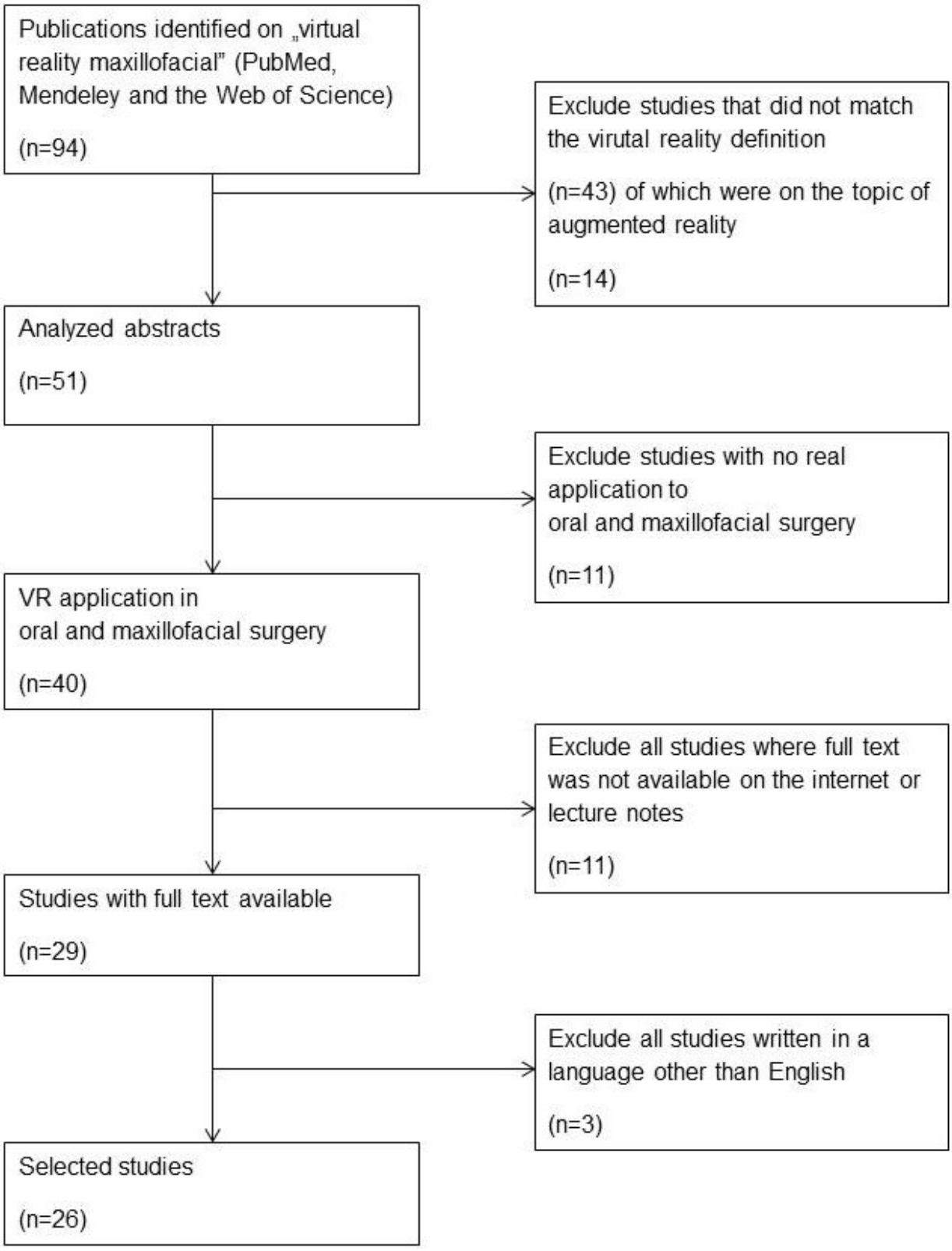

Figure 5 Selection process of literature found with the keywords "virtual reality maxillofacial"

Author	Year	Title	Typical field of research
Ahn et al.	2019	Tracking Accuracy of a Stereo Camera-Based Augmented Reality Navigation System for Orthognathic Surgery	Orthognathic
Ayoub et al.	2019	The application of virtual reality and augmented reality in Oral & Maxillofacial Surgery	Review
Battaglia et al.	2019	Combination of CAD/CAM and Augmented Reality in Free Fibula Bone Harvest.	Trauma
Essig et al.	2011	Virtual 3D tumor marking-exact intraoperative coordinate mapping improve post-operative radiotherapy	System accuracy, tumor
Ewers et al.	2005	Basic research and 12 years of clinical experience in computer-assisted navigation technology: A review	Implantology
Ewers et al.	2005	Seven years of clinical experience with teleconsultation in craniomaxillofacial surgery	Orthognathic
Farronato et al.	2019	Current state of the art in the use of augmented reality in dentistry: A systematic review of the literature	Review
Gavaghan et al.	2012	Evaluation of a portable image overlay projector for the visualisation of surgical navigation data: Phantom studies	System accuracy, inferior alveolar nerve
Gsaxner et al.	2019	Facial model collection for medical augmented reality in oncologic cranio-maxillofacial surgery	Tumor
Hassfeld et al.	2003	Computer-based approaches for maxillofacial interventions	Implantology

Kwon et al.	2018	Augmented reality in dentistry: a current perspective	Review
Marmulla et al.	2005	New augmented reality concepts for craniofacial surgical procedures	Tumor
Marmulla et al.	2005	An augmented reality system for image-guided surgery. This article is derived from a previous article published in the journal International Congress Series	Tumor
Mischkowski et al.	2006	Application of an augmented reality tool for maxillary positioning in orthognathic surgery - A feasibility study	System accuracy, Orthognathic
Murugesan et al.	2018	A novel rotational matrix and translation vector algorithm: geometric accuracy for augmented reality in oral and maxillofacial surgeries	System accuracy
Nijmeh et al.	2005	Image-guided navigation in oral and maxillofacial surgery	Tumor
Pellegrino et al.	2019	Augmented reality for dental implantology: A pilot clinical report of two cases	Implantology
Pietruski et al.	2019	Supporting fibula free flap harvest with augmented reality: A proof-of-concept study	Trauma
Profeta et al.	2016	Augmented reality visualization in head and neck surgery: an overview of recent findings in sentinel node biopsy and future perspectives	Tumor
Schreurs et al.	2018	Implant-oriented navigation in orbital reconstruction. Part 1: technique and accuracy study	Trauma
Scolozzi et al.	2017	Removal of recurrent intraorbital tumour using a system of augmented reality	Tumor

Suenaga et al.	2015	Vision-based markerless registration using stereo vision and an augmented reality surgical navigation system: a pilot study.	System accuracy
Tepper et al.	2017	Mixed reality with hololens: Where virtual reality meets augmented reality in the operating room	Trauma
Wagner et al.	1999	Clinical Experience with Interactive Teleconsultation and Teleassistance in Craniomaxillofacial Surgical Procedures	Trauma
Wagner et al.	1996	Image-guided surgery.	Implantology
Wagner et al.	1997	Virtual reality for orthognathic surgery: The augmented reality environment concept	Orthognathic
Wagner et al.	1995	Virtual image guided navigation in tumor surgery - technical innovation	Tumor
Wang et al.	2019	Augmented reality for temporomandibular joint arthrocentesis: a cadaver study	Orthognathic
Wang et al.	2019	A practical marker-less image registration method for augmented reality oral and maxillofacial surgery	System accuracy
Wang et al.	2017	Video see-through augmented reality for oral and maxillofacial surgery	System accuracy
Wang et al.	2015	Real-time computer-generated integral imaging and 3D image calibration for augmented reality surgical navigation	System accuracy
Watzinger et al.	1997	Computer-aided navigation in secondary reconstruction of post-traumatic deformities of the zygoma	Trauma

Won et al.	2017	Application of augmented reality for inferior alveolar nerve block anesthesia: A technical note.	Inferior alveolar nerve
Yao et al.	2020	Augmented Reality Technology Could Be an Alternative Method to Treat Craniomaxillofacial Foreign Bodies: A Comparative Study Between Augmented Reality Technology and Navigation Technology	System accuracy
Zhu et al.	2017	A novel augmented reality system for displaying inferior alveolar nerve bundles in maxillofacial surgery	System accuracy, orthognathic
Zinser et al.	2013	Computer-assisted orthognathic surgery: Waferless maxillary positioning, versatility, and accuracy of an image-guided visualisation display	System accuracy, orthognathic

Table 2 Included literature on AR

Author	Year	Title	Typical field of research
Arikatla et al.	2016	High Fidelity Virtual Reality Orthognathic Surgery Simulator	Education
Ayoub et al.	2019	The application of virtual reality and augmented reality in Oral & Maxillofacial Surgery	Review
Bartella et al.	2019	Virtual reality in preoperative imaging in maxillofacial surgery: implementation of “the next level”?	Planning
Casap et al.	2011	Evaluation of a navigation system for dental implantation as a tool to train novice dental practitioners	Education
Chen et al.	2018	A patient-specific haptic drilling simulator based on virtual reality for dental implant surgery	Education
Chen et al.	2018	A review of haptic simulator for oral and maxillofacial surgery based on virtual reality	Review
Farronato et al.	2019	Current state of the art in the use of augmented reality in dentistry: A systematic review of the literature	Review
Ganry et al.	2018	Using virtual reality to control preoperative anxiety in ambulatory surgery patients: A pilot study in maxillofacial and plastic surgery	Anxiety
Hassfeld et al.	2003	Computer-based approaches for maxillofacial interventions	Review
Joda et al.	2019	Augmented and virtual reality in dental medicine: A systematic review	Review

Li et al.	2019	Combined application of virtual surgery and 3D printing technology in postoperative reconstruction of head and neck cancers	Planning
Maliha et al.	2018	Haptic, Physical, and Web-Based Simulators: Are They Underused in Maxillofacial Surgery Training?	Education
Matsuo et al.	2018	Virtual reality head-mounted display for endoscopically-assisted implant surgery	Planning, intraoperative use of VR
Medellín-Castillo et al.	2016	The evaluation of a novel haptic-enabled virtual reality approach for computer-aided cephalometry	Planning
Miki et al.	2016	Development of a virtual reality training system for endoscope-assisted submandibular gland removal	Education
Pulijala et al.	2018	An innovative virtual reality training tool for orthognathic surgery	Education
Pulijala et al.	2018	Effectiveness of Immersive Virtual Reality in Surgical Training—A Randomized Control Trial	Education
Robiony et al.	2007	Virtual Reality Surgical Planning for Maxillofacial Distraction Osteogenesis: The Role of Reverse Engineering Rapid Prototyping and Cooperative Work	Planning
Sohmura et al.	2004	Prototype of simulation of orthognathic surgery using a virtual reality haptic device	Education
von Sternberg et al.	2007	Learning by doing virtually	Education
Wierinck et al.	2006	Effect of tutorial input in addition to augmented feedback on manual dexterity training and its retention	Education

Wierinck et al.	2007	Expert performance on a virtual reality simulation system.	Education
Xia et al.	2001	Three-dimensional virtual-reality surgical planning and soft-tissue prediction for orthognathic surgery.	Planning
Xia et al.	2000	Computer-assisted three-dimensional surgical planning and simulation: 3D virtual osteotomy.	Planning
Yamashita et al.	2020	Clinical Effect of Virtual Reality to Relieve Anxiety During Impacted Mandibular Third Molar Extraction Under Local Anesthesia	Anxiety
Yua et al.	2012	Preliminarily Measurement and Analysis of Sawing Forces in Fresh Cadaver Mandible Using Reciprocating Saw for Reality-Based Haptic Feedback	Planning

Table 3 Included literature on VR

Level of evidence	AR (n)	%	VR (n)	%
Ia	0	0%	0	0%
Ib	0	0%	2	8%
Ic	0	0%	0	0%
IIa	0	0%	0	0%
IIb	0	0%	5	19%
IIc	0	0%	0	0%
IIIa	4	11%	5	19%
IIIb	0	0%	0	0%
IV	15	42%	7	27%
V	17	47%	7	27%
Total	36	100%	26	100%

Table 4 Distribution of level of evidence

7 Discussion

7.1 Virtual reality applications in oral and maxillofacial surgery

7.1.1 Teaching

In surgery constant repetition of a procedure is required in order to acquire the technical knowledge and the skills to perform well. This is especially true for trainees who have to learn whole surgeries from scratch. 25-40% of novice surgeons do not feel comfortable performing a major surgical procedure. With a lack of self-confidence and a sense of “feeling overwhelmed” with a situation, the risk of error rises. (Pulijala *et al.*, 2018b) The ability to evaluate the own performance also increases according to the degree of experience (von Sternberg *et al.*, 2007) Classical training methods are animal and phantom training. Phantom training cannot simulate the haptic of the tissue, whereas the extent of animal training is limited by costs and facility capacities. (Miki *et al.*, 2016) Due to these reasons, VR has been the focus of several research studies in the past in nearly all kinds of surgical fields.

The first paper which described VR as a surgical training tool is by von Sternberg et al. in 2007. It introduced a VR training system (VOXEL-MAN) designed to train students to perform an apicectomy. After VR training, the students had to perform an apicectomy of a pig jaw. Students who had learned to perform surgery using the VOXEL-MAN achieved significantly better results in preserving neighboring structures and reducing the volume of defects.

Furthermore, self-evaluation of VR-trained students correlated significantly better with the evaluation made of them by their trainers, who were experienced oral and maxillofacial surgeons. (von Sternberg *et al.*, 2007)

VR training for procedures involving hard tissues like apicectomies, dental implantation (Casap *et al.*, 2011; Chen, Sun and Liao, 2018) and tooth preparation (Wierinck, Puttemans and van Steenberghe, 2006; Wierinck *et al.*, 2007) were the first to be described as sufficiently good training procedures due to the fact that interaction with hard tissues is easier to simulate. Therefore surgical procedures involving bony structures, like orthognathic surgeries, are the focus of VR training tools. (Sohmura *et al.*, 2004; Arikatla *et al.*, 2016; Chen and Hu, 2018)

Generating haptic feedback with soft tissues is more difficult. Miki et al. introduced a VR simulator for simulating endoscopic submandibular gland removal. In this virtual model, three structures were generated from data collected from actual surgeries. Each structure (submandibular gland, blood vessel and three layers of connective tissue) was assigned a value of elasticity and hardness. (Miki *et al.*, 2016) Novice surgeons performed significantly better on the simulator after practicing ten times on this device. The study failed to evaluate if VR- trained surgeons obtained statistically significant better results in a real submandibular gland removal as well. Simulating the prediction of soft-tissue deformation still remains a challenge due to time-consuming computation. (Chen and Hu, 2018)

In order to assess the influence of VR training on the self-confidence of surgeons, Pulijala et al. conducted a study showing a 360° video of a Le Fort I osteotomy to oral and maxillofacial residents. The study group watched the video with VR goggles whereas the control group watched the same video on a normal laptop screen. It could be shown that the study group showed a statistical significant higher level of self-confidence in performing this surgery than the control group. (Pulijala *et al.*, 2018b)

In another study a 360° video of a Le Fort I osteotomy was shown to experienced oral and maxillofacial surgeons. In addition, the users could pause the surgery and interact with 3D models of the patient's anatomy. The possible use of this training tool was evaluated by a questionnaire. The experienced surgeons considered it a good training method for novice surgeons. Further studies with novice surgeons are planned. (Pulijala *et al.*, 2018a)

Besides providing a realistic picture of the scene, haptic feedback is crucial for realistic VR training. Surgeons use their sense of touch during surgeries all the time. Poor haptic feedback is often reported as a major limitation to surgical training in VR. Various studies have thus been conducted to face the problem by measuring the cutting and sawing forces needed to manipulate soft and hard tissue, like, for example, during cutting, stitching, sawing or drilling. With these results it is possible to improve haptic feedback for surgical simulations in VR. (Yua *et al.*, 2012) Although recent studies show positive results for education, they are mostly descriptive and therefore have a low level of evidence. This may be a reason why simulators are still underused in oral and maxillofacial surgery. (Ayoub and Pulijala, 2019)(Maliha *et al.*, 2018)

7.1.2 Planning

For surgical planning an exact overview of the surgical area is required. The surgeon needs to see the clinical situation in order to evaluate the best surgical solution for the patient. This is particularly true in complex anatomical areas and fields with high surgical planning focus as is the case in oral and maxillofacial surgery.

In the last years rapid prototyping (RP) has been very popular in order to produce models by stereolithography (STL). STL uses ultraviolet light to polymerize liquid resin layer by layer in order to build a 3D structure step by step. But as soon as a real model is cut or modified in the planning and simulation process, it cannot be used again.

VR offers the opportunity to simulate as many different surgical solutions as needed. Distances, angles and volumes can be measured easily in a 3D virtual model.

Given that for a STL a 3D virtual model needs to be calculated anyway, creating a virtual model for VR does not incur in any additional costs. (Robiony *et al.*, 2007)

To transfer the virtual surgical planning situation on the patient, an AR device can be used. (Olszewski *et al.*, 2008)

Preoperative planning of an orthognathic surgery, in particular, requires a high degree of precision. Anatomical landmarks can be identified more precisely in VR with a haptic device than with conventional 2D methods. (Medellín-Castillo *et al.*, 2016)

The approach for orthognathic surgery planning was the same in all papers found on this topic (Xia *et al.*, 2000, 2001; Sohmura *et al.*, 2004; Medellín-Castillo *et al.*, 2016). After a 3D model of the skull is generated, the surgeons look at it in VR. The surgeon is then able to perform the surgery in VR with a haptic device. This haptic device gives the surgeon a feeling of drilling or cutting on a solid structure. This haptic feedback gives the surgeon the impression of “touching” the virtual model. The surgery can be performed as often as necessary. (Xia *et al.*, 2001; Sohmura *et al.*, 2004)

The first paper found on the topic of orthognathic surgery planning was by Xia et al. in 2000. They introduced a computer-assisted 3D virtual osteotomy system for

orthognathic surgery (CAVOS). After generating a 3D model of the patient's skull, the surgeons were able to perform the orthognathic surgery on a PC. They used a 3D mouse as "scalpel" and glasses (CrystalEye) to immerse into VR and to carry out the surgical procedure. (Xia *et al.*, 2000) They also concluded that the planning technique of mirroring a healthy side of the face on an affected side was only useful for small defects in simple areas.

Xia et al. also introduced a method for planning orthognathic surgery in VR with a combined prediction of soft-tissue. However, the authors did not evaluate the correctness of their soft-tissue prediction. (Xia *et al.*, 2001) As mentioned above, the precise prediction of soft tissue still remains a major challenge to VR. (Chen and Hu, 2018)

VR is nevertheless a promising tool for preoperative planning. It offers the opportunity of obtaining a better 3D understanding of the operation site than with conventional screens. (Bartella *et al.*, 2019)

This advantage can also be used for planning of tumor resection and reconstructive surgery. (Li *et al.*, 2019)

No studies were found on whether surgeries with a VR planning showed better results or lower risk of complication than surgeries with conventional planning.

7.1.3 Use in preoperative anxiety patients

Apart from its use in teaching and planning, VR is supposed to be helpful in patients with preoperative anxiety. (Joda *et al.*, 2019) Patients suffering from anxiety within a clinical setting were immersed in a peaceful environment, like a beach, wearing VR glasses and an audio headset. Patients were examined before and after the 5 min VR treatment. Stress levels were measured at the physiological, psychological and biological levels. Physiological stress was determined by measurement of the heart coherence (HC). Psychological stress was evaluated by a self-assessment scale of preoperative anxiety based on the Amsterdam Preoperative Anxiety and Information Scale (APAIS). Furthermore, a visual analog scale (VAS) was used. The biological stress was measured by testing the salivary cortisol.

The results showed that the VAS and the salivary cortisol dropped significantly after VR treatment. However, HC did not show significant change. The authors

concluded that VR seems to be an effective complementary technique in dealing with preoperative stress in surgical patients.

In a similar study, natural scenes of seas and rivers were shown to the patients during wisdom tooth extraction. 92% of the patients reported ~~on~~ a decrease of intraoperative anxiety. (Yamashita *et al.*, 2020)

Unlike common ways of anxiety prevention like benzodiazepines and antihistamines, VR has no side effects and is easy to use in office for procedures with local anesthesia. (Ganry *et al.*, 2018)

7.1.4 Intraoperative use

The intraoperative use of VR is limited to its technological nature. As soon as additional information is superimposed, it has to be defined as AR.

Nevertheless, VR can be used in the operating theater to view areas with limited access which cannot be seen directly by the surgeon. Using an endoscopic camera, the operating field can be seen in VR by the surgeons with a HMD. Providing a good realistic overview of the surgical field ensures safety and can also be useful for training novice surgeons. (Matsuo *et al.*, 2018)

7.2 Augmented reality applications in oral and maxillofacial surgery

In order to give a good clinical overview of the use of AR in oral and maxillofacial surgery, the application options are sorted according to their practical use in surgery.

7.2.1 Protection of the inferior alveolar nerve

AR is found to be helpful in understanding the spatial situation in a surgical site. Important anatomical structures can be highlighted. This makes it easier to preserve them in planning and during actual surgery.(Gavaghan *et al.*, 2012) (Wagner *et al.*, 1996)

Such an important structure in oral and maxillofacial surgery is the inferior alveolar nerve. By enabling surgeons to “see” the inferior alveolar nerve through the bone, with an average system accuracy of 0.96 ± 0.51mm, clinical results of oral and maxillofacial surgery can be improved. (Zhu *et al.*, 2017)

Won et al. proposed a simple method to use AR for inferior nerve block anesthesia. Superimposing the 3D reconstruction of the mandible on a photo taken from the surgeon’s perspective made it more efficient to perform a nerve block. (Won and Kang, 2017)

But the decision whether to use AR for a procedure depends on the prospective benefit and on the time and effort to achieve a good result. (Ewers, Schicho, Undt, *et al.*, 2005) It is therefore disputable whether AR is needed for an inferior alveolar nerve block.

7.2.2 Orthognathic surgery

AR offers the possibility to project the exact surgical planning onto the patient. In orthognathic surgery it is especially true for osteotomy lines and the extent of translocation. (Kwon, Park and Han, 2018) (Hassfeld *et al.*, 2003) (Nijmeh *et al.*, 2005)

The first paper found in PubMed on the topic of AR in orthognathic surgery is from 1997 by Wagner et al. from the Department of Oral and Maxillofacial Surgery at the Medical University of Vienna. In this first attempt, the Le Fort I osteotomy line

was superimposed on a patient using a see-through HMD. A 3D tracker was attached to the patient's forehead to track any motion of the head and to define a patient-related 3D coordinate system. With a 3D stylus the surgeon digitized fiducial points on the patient in order to match the virtual planning with the real patient. With the transfer of preoperative planning to intraoperative visualization the authors concluded that AR helps to perform orthognathic surgeries less invasively. But because of the low system accuracy it was not considered suitable for procedures which require an accuracy of less than 1mm. (Wagner *et al.*, 1997)

In 2006 Mischkowski et al. used a X-scope® video see-through display to control a maxillary translocation after performing a Le Fort I osteotomy. The translocation of the maxilla was simulated by a special software and was superimposed on the patient. The patient's head was fixed in a Mayfield clamp and the image to patient referencing was achieved with a navigation pointer. During surgery the patient's maxilla was moved in the position so that it matched exactly the virtual image of the maxilla. The correctness of this final position was double-checked with an intraoperative spint. Cephalometic analysis showed an system accuracy within the range of 1mm to the surgical plan. Because of handling and registration, the operative time took one hour longer than usual. (Mischkowski *et al.*, 2006)

The same delay was reported in a similar paper from 2013. The authors evaluated the system accuracy and the usability of an image-guided visualization system for orthognathic surgery. Surgical planning data was superimposed on the patient by a handhold video see-through display in order to perform a bimaxillary osteotomy on sixteen class III patients. In six patients a Mayfield clamp had been used for image to patient referencing while the remaining ten patients were registered with a head-mounted referencing star. Without using a wafer to determine the position of the maxilla, the maxilla was adjusted by matching the planned virtual one in the augmentation. Cephalometric measurement showed a discrepancy from planning to actual postsurgical position of <0.37mm in anteroposterior direction, <0.2mm in mediolateral direction and <0.67mm in vertical dimension. The authors concluded that further studies are needed to see whether the AR planning and navigation can lead to a waferless alternative to orthognathic surgery. The use of a Mayfield clamp was found to be less useful because, due to the high forces during downfracturing of the maxilla, the head was dislocated in the clamp. A completely new registration was necessary. The authors preferred the head-mounted star for

registration, which has the advantage that the head is not fixed and can be rotated during surgery. (Zinser *et al.*, 2013)

Zhu et al. introduced a new registration method. A tracking marker is attached to an occlusal splint. First, a 3D model of the patient's skull and soft tissues is generated and an occlusal splint is produced. The tracking marker is fixed to the splint, which creates a constant relationship between the mandible and the marker during surgery. A 3D model of the unit of marker and splint was generated by a laser scanner. The virtual model of the mandible and the virtual model of the splint and marker unit were brought together by matching the tips of the teeth in the virtual mandible model with their counterparts in the virtual splint and tracking marker model. This offers the advantage that every time the mandible is moved during surgery the virtual image moves simultaneously.

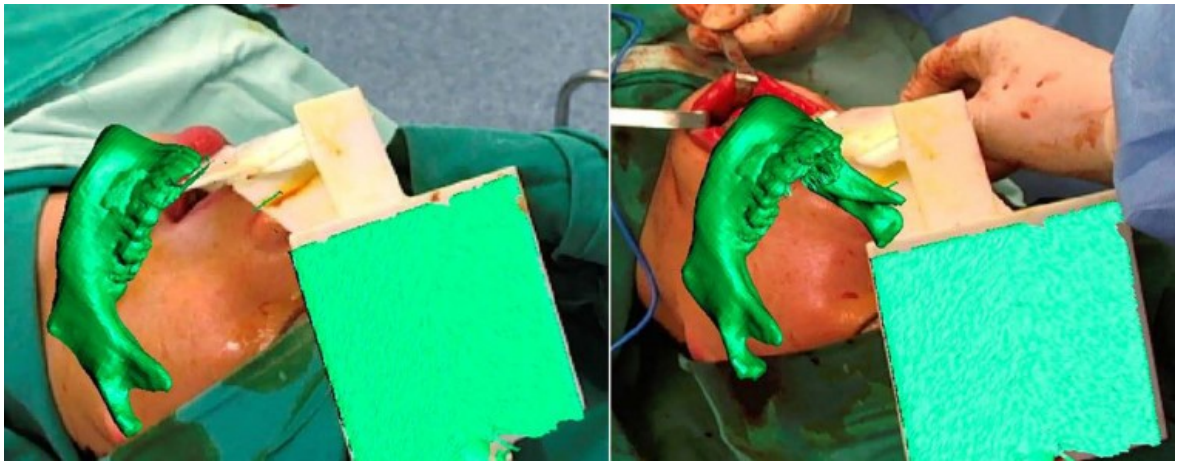

Figure 6 Surgeon's AR view on the patient with superimposed mandible
(Zhu *et al.*, 2017)

When surgery was performed on the patients, the splint with the tracking marker was fixed to the patient's mandible and thereby the virtual image of the mandible could be superimposed. During surgery the surgeons wore optical see-through head mounted devises.

To evaluate the accuracy of the tracking a model of the mandible was printed and after combining it with the splint and tracking marker, the precision of the overlay was evaluated by measuring the distance between the superimposed image and real structures on the model. The error ranged between 0.52 to 2.00mm, 0.96mm in average with a deviation of 0.51mm. The authors considered the error as negligible. (Zhu *et al.*, 2017)

The usability of AR has also been evaluated in temporomandibular joint arthroscopy. A puncture point is needed to perform an arthroscopy. Using only the surface anatomy to evaluate the exact puncture point can mean an 18% chance of failure, mainly due to individual anatomical deviations. Using AR on the basis of CT scans showed promising results in a cadaver study. But the study consisted of only six cases and therefore studies comprising a bigger population are needed to evaluate the advantages of AR in temporomandibular joint arthroscopy properly. (Wang *et al.*, 2019)

Superimposing the preplanned access tunnel in the live video from the arthroscope was found to be useful. The surgeon was directly led to the region of interest by passing through a preplanned superimposed tunnel. (Wagner *et al.*, 2001)

7.2.3 Tumor resection

Performing and confirming an R0-resection of a tumor in the head neck region presents great challenges due to the complex anatomy that involves both soft and hard tissues.

In order to find a balance between aggressive surgical therapy and obtaining a relevant quality of life it is essential that resection of the tumor is as precise as possible. To achieve that goal it is essential that the surgeon knows the exact spatial extent of the tumor. (Essig *et al.*, 2011)

The first attempt of using AR for a tumor surgery was reported by Wagner et al. in 1995. In the CT, they marked with green squares a bony lesion they wanted to resect. With a head-mounted video camera and display the virtual squares in the CT-space were integrated in the 3D space recorded by the head-mounted video camera. (Wagner *et al.*, 1995)

Due to intraoperative swelling, attempts to scan the surface of the patient's face were not accurate enough to be useful in tumor surgery. Therefore additional markers had to be fixed to sharp anatomical landmarks to guarantee an exact overlay of the augmented images with a deviation from of less than 1mm. (Marmulla, Hoppe, Mühling and Eggers, 2005; Marmulla, Hoppe, Mühling and Hassfeld, 2005) AR was limited to tumors of bony structures. (Nijmeh *et al.*, 2005)

Nowadays with better segmentation and scanning techniques high-resolution pictures of the tumor are available for AR. Scolozzi et al. reported on a successful

removal of a pleomorphic adenoma of the lacrimal gland using a microscope-based AR system. The authors stated four main advantages of performing tumor surgery with AR.

1. The extension of the tumor could be defined, especially in terms of depth.
2. The microscope was used as a virtual probe that correlated the surgical fields and the navigation's images.
3. The microscope itself was tracked and the virtual images were projected according to its position.
4. The surgeon had a stereoscopic view of the surgical scene.

(Scolozzi and Bijlenga, 2017)

In tumor therapy an effective and precise communication between surgeons, pathologists, radiologists and oncologists is essential. Exact naming of specimens or resection margins in relation to their 3D orientation during a surgery is often difficult. The written word is a source of misunderstandings and the pathologist is often not able to rule out a residual tumor.
The same problem appears if an adjuvant radiation therapy is necessary because of a residual tumor. Therefore, it is necessary to 3-dimensionally map histopathological findings digitally and in a language-independent way.
AR data can be a serviceable tool in this issue. When using AR during resection and reconstruction, the surgeon can mark the locations of biopsies and surgical margins directly in the augmented picture. This 3D data can be stored in a DICOM-format and transferred to the pathologist and radiotherapist. (Essig *et al.*, 2011)
For detection of sentinel lymph nodes, AR can be used by superimposing a SPECT image in the surgeon's sight. (Profeta, Schilling and McGurk, 2016)
Using AR in tumor resection surgery requires a high level of accuracy. Gsaxner et al. presented a library of PET/CT-scans of malignant head and neck tumors with stereolithography (STL) files. It allows researchers to 3D print a model of the patient. The corresponding PET/CT scans can be used to investigate new and more accurate algorithms of image to patient registration for AR systems in tumor patients. (Gsaxner *et al.*, 2019)

7.2.4 Reconstruction

Especially hard tissue reconstructions of bone deformities due to trauma or within congenital and secondary surgical treatments are another important subfield of oral and maxillofacial surgery. In this subfield expanded operation times and complex operative procedures can be expected to achieve functional and aesthetic standards.

AR was found to be helpful in performing reconstructive surgery during of zygomatic arch reconstructions. The intended position of the zygomatic arch was determined by mirroring the healthy side to the deformed side of the face. A virtual line that presented the outer surface of the zygomatic arch was superimposed on the patient during surgery. When the surface of the zygomatic arch and the virtual line met the position was assumed to be correct. The aesthetic results were then evaluated. (Watzinger *et al.*, 1997)

Schreurs et al. proposed the use of AR for positioning of an orbital implant in orbital reconstruction. In their work, the implant was attached to an instrument which could be tracked by reflecting balls on the instrument itself. Due to the rigid connection between the implant and the instrument, the exact position of the implant could be measured. This made it possible to evaluate the correct position during insertion. In their approach, the virtual picture and the virtual picture of the implant were shown on a normal display. The authors suggested that the combination of their technique with AR could lead to easier placing of the implant. (Schreurs *et al.*, 2018)

AR was recently introduced to support free fibula flap harvesting for reconstructive surgery. Instead of using a CAD/CAM osteotomy guide, the authors superimposed the surgical plan directly on the patient. Given that no guides had to be fabricated and delivered, the surgeons were able to perform reconstructive surgery a few hours after the initial CT scan. Furthermore, the surgical plan could be adapted intraoperatively if necessary. Compared to CAD/CAM osteotomy guides, the authors concluded there were several advantages in using AR.

- Lower costs
- No specialized CAD/CAM company/industrial partner needed
- No delay due to delivery time
- For this reason, useful for urgent indications (tumor resection and trauma acquired defects)
- Can be adapted easily to intraoperative situation if necessary

But the use of AR is still limited to structures that remain spatially stable. If the structures drift intraoperatively, the surgical plan, based on the CT of these structures, is no longer accurate. Some surgeons also complained of nausea, headache and vertigo when wearing the 3D glasses over a certain period of time. (Pietruski *et al.*, 2019)

Battaglia et al. proposed a combination of AR and CAD/CAM technology by superimposing a virtual cutting guide based on CAD/CAM data on the fibula. During their case series with 3 patients the authors additionally used a printed cutting guide which they placed exactly on the fibular according to the surgical plan superimposed with AR.
(Battaglia *et al.*, 2019)

In order to use AR intraoperatively the technology has to meet special standards. The most important requirement is the hands-free interaction with complex virtual 3D data. Since it meets this important requirement, Microsoft HoloLens is seen as the first system with high clinical potential. It offers the ability to interact with the data by voice commands and/or using hand movements in space. This makes it perfect for use in a sterile environment. (Tepper *et al.*, 2017)

7.2.5 Dental implants

The use of AR for oral implantology was recognized right from the beginning. The preoperative spatial planning of implant positions can be superimposed on the jaw. By visualization of the inferior alveolar nerve, iatrogenic trauma can be avoided. (Wagner *et al.*, 1996)

Nowadays AR can be used for teleplanning and surgical navigation for dental implantation. (Kwon, Park and Han, 2018) (Ewers, Schicho, Wagner, *et al.*, 2005)

Evers et al. empirically assessed the medical benefit of AR in dental implantology as “excellent”. 72 patients underwent dental implantation over a period of 8 years. The authors saw an improvement in quality and intraoperative safety especially in difficult implant situations. However, cases in which technical problems occurred were not included in this study because the surgery was completed in a conventional way. This occurred in 5% of the procedures. Furthermore, using specialized software for AR was found to be cost-effective and reduced time for planning and performing an implantation. (Ewers, Schicho, Undt, *et al.*, 2005)

Static guided surgery is currently the most commonly used method for achieving an exact positioning of the implant is the use of a surgical template. This has the disadvantage of not being able to change the implant position intraoperatively. Dynamic navigation is able to overcome this problem of static guided surgery. Pellegrino et al. superimposed the dynamic navigation plan on the operating field using Microsoft Hololens. The authors suggested that AR may be useful to integrate dynamic navigation in the surgical environment. But further studies have to be done to validate its use. (Pellegrino *et al.*, 2019)

7.2.6 System accuracy

As mentioned above, AR superimposes virtual images in the real world. An oral and maxillofacial operating room offers different options of bringing the virtual information and the real patient together. HMDs, projections on a semi-translucent screen or projection in the optics of a surgical microscope can be used. (Nijmeh *et al.*, 2005)

Regardless of which of these devices is used to augment virtual information to the scene, the level of system accuracy is essential. Augmented images must match perfectly with the real object. Evaluations of system accuracy have been given by many authors who first introduced a new registration method in their studies. An overview of the described accuracy and the used registration method is given in Table 5.

Authors	Described system accuracy	Registration method
(Mischkowski *et al.*, 2006)	<1mm	Infrared marker
(Essig *et al.*, 2011)	1.3±0.6mm	Screws
(Suenaga *et al.*, 2013)	<1mm	Splint + tracking marker
(Zinser *et al.*, 2013)	<0.67mm	Scull mounted referencing star
(Wang *et al.*, 2015)	~1mm	Real time registration
(Suenaga *et al.*, 2015)	<1mm	Markerless registration
(Wang *et al.*, 2017)	0.67-1.05mm	Markerless registration
(Zhu *et al.*, 2017)	0.96±0.51mm	Splint + marker
(Schreurs *et al.*, 2018)	1.12-1.15mm	Marker fixed to orbital implant
(Murugesan *et al.*, 2018)	0.3-0.4mm	Rotational matrix + translation vector algorithm
(Wang, Shen and Yang, 2019)	<0,5mm	Markerless tracking (CT+ 3D intraoral scan)
(Yao *et al.*, 2020)	1.52 ± 0.58mm	Splint + marker
(Ahn *et al.*, 2019)	0.0596mm	Marker + stereo camera

Table 5 Achieved system accuracy reported by the authors

To improve system accuracy and processing time, different AR techniques and algorithms (software package) are used. System accuracy of about 1 mm is achievable. Murugesan et al. proposed a modified ICP algorithm that checks for overlaying errors before the superimposition of the 3D image. With this new algorithm an accuracy error of 0.3-0.4mm is attainable. (Murugesan *et al.*, 2018)
New markerless tracking methods use the patient's teeth as a characteristic landmark to track the scene. Suenaga et al. introduced a markerless tracking method that uses the high contrast of the teeth and the oral cavity. The incisal margins were tracked by a stereo camera. The spatial position of the incisal margins could be determined by using both images from the stereo camera (parallax images). By "knowing" the spatial positions of the incisal margins the 3D CT model could be superimposed the right way. By using an integral videography the AR images could be observed correctly from any direction without the use of special glasses. (Suenaga *et al.*, 2015)

A source of difficulty is that soft gingival structures are not depicted in a teeth model generated from a CT scan. Therefore, the CT model differs from the actual region of interest by the fact that parts of the teeth are covered by gingiva. Metal artifacts can also affect the dental image in the 3D CT model. This discrepancy on the characteristic landmark for matching can cause the matching process to be unstable and inaccurate.

For this reason, an intraoral 3D scan can be performed. The 3D model obtained is matched with the corresponding CT model by ICP. The CT model is enhanced with the exact shape of teeth and gingiva and the discrepancy between the CT model and the actual site in the mouth is reduced.

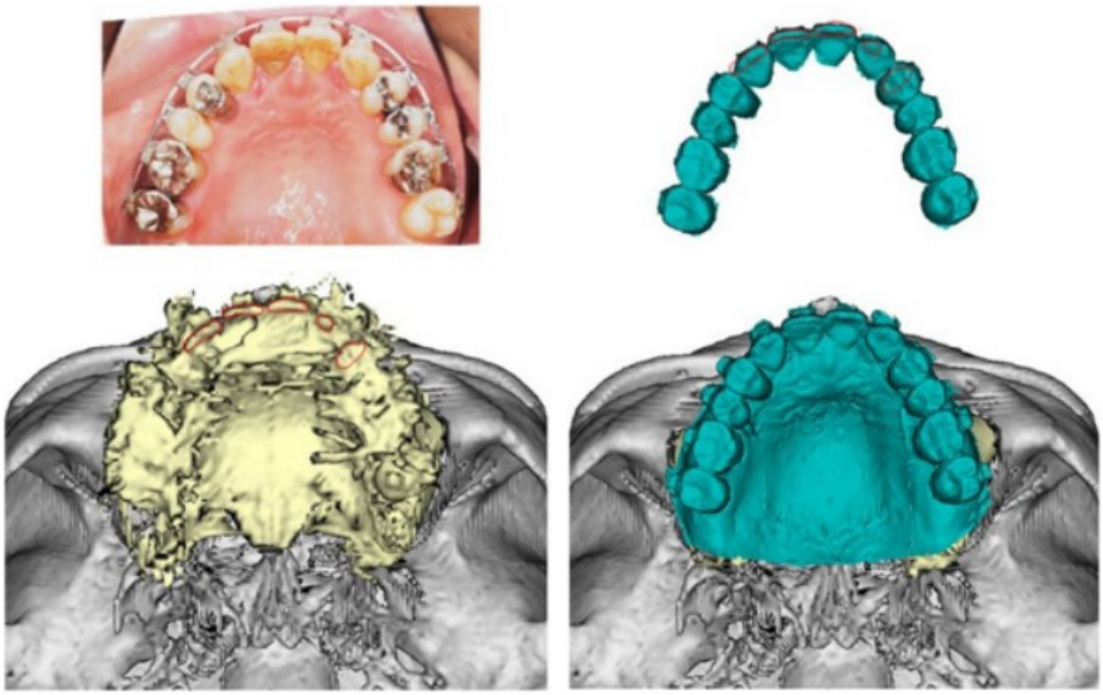

Figure 7 Combining intraoral 3D scan with the CT model
(Fushima and Kobayashi, 2016)

The authors described an achievable system accuracy of less than 0.5mm. (Wang, Shen and Yang, 2019) (Fushima and Kobayashi, 2016)

8 Conclusion

In this thesis a review of literature was conducted to evaluate the clinical potential of augmented and VR in the clinical field of oral and maxillofacial surgery.

Although augmented and VR technologies have been subjects of research in oral and maxillofacial surgery for approximately 25 years, still no functional stable technology has yet been established for the clinical practice. Both technologies have been evaluated intensively in several reports, however, more in small experiments and theoretical pilot projects than in representative clinical settings. (Farronato *et al.*, 2019) Furthermore, AR is often confused with VR and viceversa. The terms are often misleadingly used for virtual planning on a computer screen on a model without any immersive or interactive experience which is actually known to be typically characteristic of these technologies. Due to this unprecise use of the terms, reviewing the literature has to be done very carefully. AR and VR represent different shades in the virtuality continuum. Therefore, their areas of applications are different.

VR is mainly used for planning and simulation of surgical procedures.

Today VR is increasingly becoming a tool of interest for education, especially for very basic surgical training concerning hard tissues like apicectomies and orthognathic surgery. According to the literature, it seems that training supported by VR has a positive effect on spatial understanding of a surgical site and makes trainees feel more prepared for the actual task. This might result from an improved ability to visualize 3D and a more direct information record created through a VR environment. But proper simulation of haptic feedback of soft tissue surgery needs further development. In addition, most studies found within this review did not evaluate if VR trained surgeons perform better than others.

The immersive and interactive features of VR were found by all authors to be highly beneficial for surgical planning. Surgery can be performed in a virtual environment and on virtual models as often as needed. The surgical plan can also be superimposed on the surgical site with AR. Especially in orthognathic surgery. VR was used to display the planning of various cutting lines and the 3D movement of bones. All authors concluded that VR planning is an important and helpful tool for clinical practice in order to spatially understand and plan a surgical procedure

more precisely. However, to date, comparative clinical trials are missing to provide evidence for these opinions.

Placing the patient in a peaceful environment showed promising effects on patients with preoperative anxiety. VR was clearly found to be an alternative tool as exposure therapy for treatment of patients with dental phobia. (Joda *et al.*, 2019)

Only one study was found that used actual VR during surgery. (Matsuo *et al.*, 2018) VR images recorded from a laparoscopic camera were brought to the surgeons with an HMD. This was found to be clinically helpful when the surgical site could not be seen directly.

VR can be used in many different ways in the clinical field of oral and maxillofacial surgery. This is especially true for planning and educational purposes. Due to the rapid progression in the technical field of VR, its use seems to be clear. However, large comparative trials are missing and need to be conducted as a next step towards establishing VR as standard practice and demonstrating its usefulness in the clinical oral and maxillofacial surgery routine.

AR was found to be mainly used in oral and maxillofacial surgery to bring additional information to the surgeon during a procedure.

In particular, superimposing important anatomical structures such as the inferior alveolar nerve or surgical plans such as bone cutting lines are of great interest. In orthognathic surgery, AR is mainly used for transferring the preoperative plan directly to the surgical site in three dimensions in order to perform surgery as precisely as planned. Many different intraoperative setups for AR in orthognathic surgery have been reported. All seemed to be adequate for their specific task, but all the systems described vary from each other and are not standardized yet. Moreover, comparative clinical studies are missing so far.

AR was also described as a useful clinical tool in tumor surgery. An exact spatial orientation of tumor margins was found to be helpful by the authors pre- and intraoperatively. Moreover, in interdisciplinary cases the communication between different medical specialties was found to be easier when supported by visualized AR data.

Only two studies (Watzinger *et al.*, 1997; Schreurs *et al.*, 2018) were found concerning the use of augmented reality for reconstructive surgery. But they were

also based on the principle of transferring the presurgical plan onto the patient as well as controlling the exact position of the transferred tissues used for reconstruction.
The same approach is used for dental implants. AR seems to be a promising technology for accurate placement of dental implants especially in difficult areas where important anatomical structures are present. AR has also been stated to be a cost-effective tool to reduce implant planning time and surgery duration. No studies were found on whether placement of dental implants was more precise by using AR devices compared to conventional templates.

In summary, AR and VR both represent emerging technologies with high potential in many clinical fields since they offer completely new approaches to various kinds of 3D visualizations, training set ups or medical diagnostic and treatment support such as the enabling of projecting anatomical conditions directly onto the surgical site. In oral and maxillofacial surgery this can be especially helpful for diagnostic visualizations in orthognathic or tumor surgery and for surgical planning devices. Furthermore, AR offers the possibility to transfer the acquired virtual knowledge of the 3D situation directly to the exact position on the real patient, pre- or intraoperatively (markerless navigation system). However, published works providing high grades of evidence are still needed on both technologies.
The literature reviewed in this work describes AR and VR as beneficial and outlines the several advantages of using these technologies in clinical oral and maxillofacial surgery. Therefore, according to the literature, a potential clinical use of these technologies seems to be obvious so that further technical developments would create great value for the future.
Yet, in order to achieve that, many more clinical comparative studies need to be conducted to increase the level of evidence regarding these technologies and to prove that AR and VR devices can indeed contribute, in a statistically significant way, to maximizing the success of surgical results and minimizing surgical risks in a clinical set up.

9 Acknowledgement

This work was approved by the Ethics Committee of the Medical University of Graz, Austria – EK No.: EK 31-416 ex 18/19.

The work received funding from the Austrian Scientific Fund (FWF-KLIF): Grant No.: KLI-678-B31.

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