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Augmented Reality in Dentistry: Uses and Applications in the Digital Era

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Abstract

Introduction: With all the advancements that technology has reached, Dentistry can't be left behind. In the past few years, researchers have focused on emerging technologies like Virtual and Augmented Reality with clinical practice. **Objectives:** This literature review aims to provide an update on the latest technological applications and development in augmented reality in the dental field. **Methods:** The PubMed database was reviewed, and the studies that fulfilled the inclusion criteria in the last 20 years, from 2000 to 5 May 2020, were included. **Results:** The search results revealed a total of 72 articles, 32 were excluded, while 40 articles were included. It's been observed that augmented reality application is still under testing, as certain drawbacks still tie the spread of this technology in the dental field. Multiple studies have resulted in a system that is suitable for clinical use. Yet no routine clinical application has been reported. **Conclusion:** The research department has already covered more advanced technologies like mixed reality. Therefore, a question arises, whether augmented realty will continue to grow independently or will mixed reality dominate the field.

Keywords: Augmented reality, Dentistry, Dental technology, Clinical application, Technology, Dental practice.

Abbreviations: CAM-Computer Aided Manufacturing, CAD-Computer-Aided Design, RP-Rabid Prototyping, ML-Machine Learning, VR-Virtual Reality, AR-Augmented Reality.

Introduction

With each passing day, technology evolves, improving prospects in multiple fields in life. whether in the applied sciences fields, education, military, sports, entertainment industry, medical field, dental field or others [1,2]. Many digital production management workflows have already been implemented into treatment protocols, particularly in the fast-growing Computer-Aided Design\Computer Aided Manufacturing (CAD\CAM), Rabid Prototyping (RP), automated processing in radiological imagining by the usage of Artificial Intelligence (AI) and Machine Learning (ML), Virtual Reality (VR), and Augmented Reality (AR) [1]. Virtual Reality (VR) technology is a synthetic environment composed of computer-generated images, audio, and videos where the users are emerged inside the artificial environment and can't see the real world [1]. Consequently, Augmented Reality (AR) is the technology that combines computer-generated images, audio, and videos on a screen with real-life scenes [1,3]. Therefore, for AR creation, computerized virtual components or elements are needed. The AR technology allows the users to superimpose virtual content in the real world; thus, it supplements reality with virtual content as a mix, rather than a complete replacement [4]. Due to this distinctive feature, AR is much easier to be realized and understood than VR [5].

For the creation of augmented reality systems, multiple components are required to be present. First and fore most is a camera, a sensor, or a scanning device; that will capture real-life scenes and objects. A second component is a computer unit; which can be described as the processing phase of the captured images and movements, analyzing the position, tilt, acceleration, and adding depth to the captured images; hence generating 3D images. Thirdly, a display system to display virtual and 3D objects in the real world. Lastly, a tracking device is needed to accomplish the registration phase, which is a phase that is needed to continuously track the user during the procedure to allow for real-time visualization [6]. Registration techniques can be categorized into two main groups: marker-free registration, such as laser skin surface scanning, and marker-based registration, such as anatomical landmarks, bone screws, and skin adhesive markers [7,8]. The virtual objects can be viewed from multiple angles and follow the patient and the operator's movements by the usage of tracking systems [6-9].

There are two techniques used for tracking. The first technique uses the Fiducially Markers, which depend on the anatomical landmarks obtained from the X-rays. The second technique uses Surface Matching, which depends on position sensors placed on the instrument used and on the patient. Tracking systems are used to track the patient, the instruments, and the operator's movement. Then, transferring the collected data to the processing unit; allows for almost real-time visualization. This process of registration and re-registration (in case any of the elements being tracked moves) takes time and depends upon the speed of the processing unit [9].

From a dental perspective, the pre-operative X-rays of the patient resemble the previously taken images that will later be used to obtain the 3D x-rays. Such x-rays can be obtained from 3D X-rays, like Computed Tomography (CT), or from multiple 2D images [10,11]. Four main types of 3D imaging systems have been used to capture dental and ore-facial structures; Cone-Beam Computed Tomography Systems (CBCT), Laser scanner, Structured light scanner, and Sterophotogrammetry [12].

After the images were captured and analyzed, they are displayed on the operating field (patient mouth or face) as superimposed objects; to allow navigational support intra-operatively from the previously obtained pre-operative X-rays directly on the patient. This can be based on video-based display, see-through display, and projection-based AR. The video-based display uses endoscopic cameras or Head-Mounted Displays (HMD) to superimpose virtual objects on a (stereo) video stream, thus increasing the viewer's understanding of depth, motion, and stereo parallax. See-through display and projection-based AR uses translucent silver mirrors, see-through devices, and projectors. Those devices are placed between the operator and the patient; to allow the projection of the virtual objects [6,13-16]. Multiple researchers have proved the effectiveness of the AR simulators in assisting dentists by showing and displaying virtual models in the operating field. This directly contributed to the reduction in the difficulty of hand-eye coordination [17].

AR has already been introduced in the dental research, incorporating the dental implant, oral and maxillofacial surgery, orthodontic, endodontic, prosthodontics, paedodontics, operative dentistry, as well as dental education [1,4-6,17-26]. The reason why this study aims to acknowledge the latest technological development related to augmented reality uses and applications in the dental field, also its future, and how can it be improved.

Materials and Methods

Duration: 6 months.
Study Design: Literature Review.
Inclusion Criteria: 2000-5 May 2020, database that was searched: PubMed.
Exclusion Criteria: All the studies that were published in a language other than English were excluded, as well as editorial, letters to the editor, experimental studies on animals, short communications, articles related to Cranial-Maxillofacial Surgery, and articles that do not present an application or use of AR systems in dentistry. Studies focusing on other technological advancements that modify the normal visual environment like mixed reality, hybrid reality, and virtual reality were also excluded.
Data Collection Procedure: the search terms "Augmented reality" and "Dentistry" were used to search the PubMed database from the year 2000-2005 May 2020 for augmented reality uses in dentistry. n=72 articles were found in which n=40 were included and n=32 were excluded. Articles selection occurred in 2 stages, title and abstract evaluation, which resulted in the exclusion of n=19 articles leaving n=53 articles, followed by the full article evaluation, which resulted in the exclusion of n=13 articles leaving n=40 **Figure 1**. The list of included articles present in **Table 1**. The included articles presented in Table 1 are arranged in chronological order and start from 2005 as the previous articles did not meet the inclusion criteria.

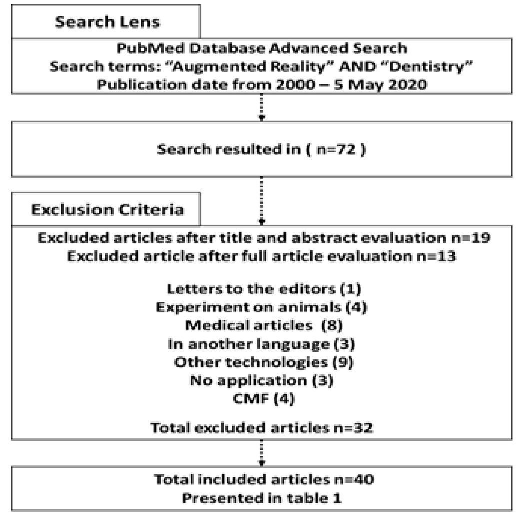

Figure 1: flowchart of the method of data collection.

Ethical Consideration: This literature review was approved by RAK Medical and Health Sciences University ethical committee and institutional review board.

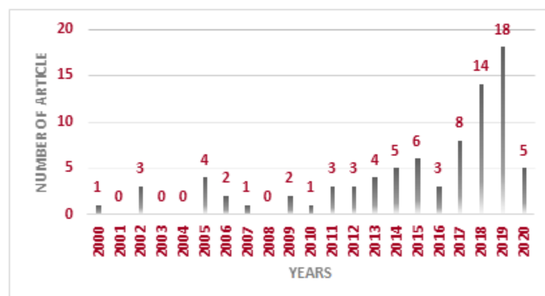

Figure 2: Number of articles published per year under the search term (Augmented reality) AND (Dentistry).

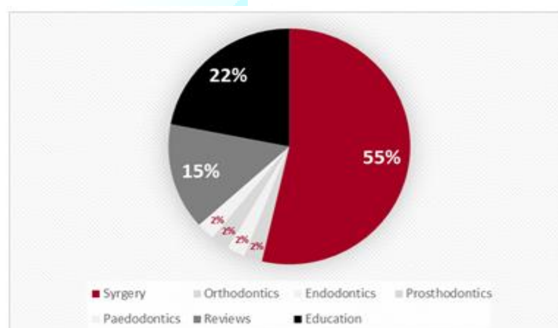

Figure 3: Pie-chart showing the amount of articles covered in this review, according to the speciality.

It's been observed that most articles were published in the last 5 years as n=48 articles from n=72 were published from 2016-5 May 2020 **Figure 2**. 55% of our included articles covered the AR applications, as a navigational system, in surgery, which exceeds the amount covered for other dental specialties **Figure 3**. The applications found were summarized in **Table 2** and were divided according to the dental specialties. A detailed description of the AR systems was covered in **Table 3**.

Author	Year	Study Design	Sample	Human/ Phantom	Field of interest	Hardware (display) and Software (processing)
Nijmeh AD	2005	Review	Review	Review	Surgery	Microscope, HMD
Mischkowski RA	2006	Clinical trail	5	Humans	Surgery	LCD screen with digital camera and X-Scope software.
Tran HH	2011	Experimental study on a phantom and a feasibility study on a volunteer	1 Phantom/ 1 Volunteer	Both	Surgery	Half silvered mirror and GPU based rendering algorithm.
Zhu M	2011	Clinical trail	15	Humans	Surgery	ARToolKit software.
Aichert A	2012	Clinical trail	3	Humans	Orthodontics	Monocular AR system.
Bruellmann DD	2013	Experimental in vitro study	126 Human Teeth	Human teeth in vitro	Endodontics	Intra-oral or microscopic camera and Software implemented using C++, Qt.
Suenaga H	2013	Pilot study	1 Phantom/ 1Volunteer	Both	Surgery	Half silvered mirror and multiple software.
Zinsera MJ	2013	Clinical trail	16	Humans	Surgery	IGVD with VGA camera and I-plan CMF software.
Wang J	2014	Experimental study on a phantom	1	Phantom	Surgery	Half silvered mirror and HALCON Library software with algorithms implemented using C++, Qt.
Badiali G	2014	Experimental study on a phantom	1	Phantom	Surgery	HMD and Autodesk software.
Lin YK	2015	Experimental study on a phantom	40 Osteotomy Sites on 4 Maxilla and 4 Mandible Stereo lithographic Models	Phantom	Surgery	HMD
Espejo-Trung LC	2015	Qusitionnaire-based Clinical trail	77	Resin Teeth	Educational	XCadCam scanner and a camera and HITLabNZ software.
Suenaga H	2015	Pilot study	1 Phantom/ 1Volunteer	Both	Surgery	Half silvered mirror and Multiple software.
Albuha Al-Mussawi R	2016	Review	Review	Review	Review	Review
Zhu M	2017	Experimental study on a phantom	20 Stereo lithographic Models	Phantom	Surgery	Semi-transparent glass and AR Toolkit software.
Won YJ	2017	Clinical trail	1	Human	Educational	Monitor and Multiple software.
Wang J	2017	Experimental study on a phantom and a feasibility study on a volunteer	1 Phantom/ 1Volunteer	Both	Surgery	4K Camera and Self developed string codes.
Llena C	2018	Qusitionnaire-based Study	41 Student Divided into two groups	Models	Educational	Computers and mobiles and Aumentaty Viewer software.
Huang TK	2018	Review	Review	Review	Review	Review
Murugesan YP	2018	Experimental Study	6 Groups	Humans	Surgery	Translucent mirror and New rotation matrix and translation victor (RMaTV) custom made by the author.
Zhu M	2018	Clinical trail	93 patients, divided into three comparison groups.	Humans	Surgery	HMD and AR Toolkit with Autodesk 3ds Max.
Kwon HB	2018	Review	Review	Review	Review	Review
Jiang W	2018	Clinical trail	12 RP Mandibular Models	Models	Surgery	See-through device and custom made by the author.
Basnet BR	2018	Experimental Study	10 Groups	Humans	Surgery	Translucent mirror and Custom made software by the author.
Goodacre CJ	2018	Perspective Study	Not presented	Not presented	Educational	Not presented
Ma L	2019	Experimental study on a phantom and a feasibility study on a volunteer	5 Phantom/ 1 Volunteer	Both	Surgery	Half silvered mirror.
Bosc R	2019	Review	Review	Review	Surgery	Review
Mladenovic R	2019	Prospective Study	41 Student Divided into two groups	Models	Educational	HMD and Dental Simulator mobile app.
Touati R	2019	Questionnaire-based Pilot Study	18 Student	Humans	Prosthodontics	iPad or iPhone and Ivo Smile app.
Wang J	2019	Experimental study on a phantom and a feasibility study on a volunteer	1 Phantom/ 1Volunteer	Both	Surgery	Custom made stereo-Camera and Self developed 3D stereo-matching algorithm.
Joda T	2019	Review	Review	Review	Review	Review

Pietruski P	2019	Experimental study on a phantom.	126 osteotomies were performed on 21 identical mandible models	Phantom	Surgery	HMD and Multiple software modified by the authors.
Farronato M	2019	Review	Review	Review	Review	Review
Pellegrino G	2019	Clinical trail	2	Humans	Surgery	HMD.
Kim-Berman H	2019	Questionnaire-based Experimental Study	93 Student	Not presented	Educational	Mobile and Costume made by the author.
Ayoub A	2019	Review	Review	Review	Surgery	Review
Zhou Y	2019	Pilot Study	Extracted human teeth installed on model	Not presented	Operative	HMD.
Amantini S	2020	Questionnaire-based prospective Study	Not presented	Not presented	Educational	Monitor and Multiple software has been used.
Mladenovic R	2020	Prospective Study	21 Student	Humans	Educational	Mobile and Dental simulator mobile app.
Zafar S	2020	Questionnaire-based Study	88 Student	Humans	Educational	HMD and HoloHuman software.

Table 1: The list of included articles, with study design, sample, field of interest, hardware used for display, and software used for processing.

Dental Specialty	Application of AR
Surgery	- Outlining lesions - Zygotic Reconstruction. - LeFort 1 Osteotomy bi-maxillary orthognathic surgery. - Implant placement. - Mandibular Angle Oblique Split Osteotomy (MASO). - Projecting and Locating of Inferior Alveolar Nerve (IAN). - Projecting and locating both arches with the teeth (crowns and roots). - Projecting and locating the skull in relation to the maxilla. - Projecting and locating the carotid artery.
Orthodontics	Bracket placement guide.
Endodontic	Root Canal Detection.
Prosthodontics	Facial Recognition for smile design.
Operative	Dental Decay Monitoring.
Paedodontics	Game Serious to motivate children for oral hygiene practice.
Educational	- Virtual Teeth identification test for dental anatomy course. - OSCE Simulation. - In anatomy courses. - Administration of Inferior Alveolar Nerve Block (IANB) Anesthesia. - Administration of Anterior Superior Alveolar nerve block (ASA). - Preparation of Class I and Class II Cavities - Preparation of gold only restoration.

Table 2: The application of AR in dentistry.

Components of AR system	
Pre-operative patient data	- CT. - PET scan. - MRI. - Digital Volume Tomography (DVT). - Intra-oral or microscopic camera. - CBCT. - 3D Cephalometric. - Optical Coherence Tomography (OCT), and infrared Scanning Fiber Endoscope (SFE).
Software used	- X-Scope. - GPU based rendering algorithm. - AR Toolkit. - Software implemented using C++, Qt. - 3D Slicer. - I-plan CMF software. - HALCON Library software. - Autodesk. - HITLabNZ software. - Open GL. - Aumentaty Viewer software. - New Rotation Matrix and Translation Victor (RMaTV). - Holloman software.

Display technique	- Microscope. - HMD. - LCD screen with digital camera. - Half silvered mirror. - Projector based display. - Monocular AR system. - Image-guided Visualization Display (IGVD) with video graphics array (VGA) camera. - Semi-transparent glass. - 4 K Cameras. - IPad or iPhone. - Monitor.
Tracking technique	- Occlusal splint with fiducially marker. - Surface matching. - Polaris Spectra optical tracking system. - Virtual planes. - Customized stereo-camera with fiducially marker. - Processing of video frames grabbed by the cameras. - 4 K Cameras. - Optical image tracking technique. - Kinect Xbox 360 sensor (Microsoft Corp.)

Table 3: Detailed description of AR systems in the included literature.

Discussion

In this review, multiple systems and methods have been covered for the implication of AR in clinical practices. The reason behind this is that no standard method for AR technology application in clinical practice has been yet proposed [4,14]. This encouraged the researchers to modify the previously used systems to create new systems that would provide better outcomes [13,15,19,24,27]. The results revealed that the amount of literature covering the uses of AR as a navigational system in surgeries exceeds the amount covered for other dental specialties. This coincides with a review done by Ayoub A. et al. in 2019, which had described it as the primary area of use [12].

Many of the studies in this review have focused on improving certain aspects that could consequently enhance the AR systems. Such aspects would be accuracy, processing time, image registration, depth perception, and occlusion handling [13,15,19,24,28,29]. In comparison with manual procedures, Implant AR-supported navigation systems have shown more accurate results and less deviation. Also, it reduces iatrogenic complications such as sinus perforations, fenestrations, dehiscence’s, or mandibular nerve damage [19,20,30]. Although good results have been proven in multiple studies, Pellegrino G. et al. had a negative result in using the AR system for placement of two implants, as angular deviations for the first and second implants were respectively 3.05° and 2.19°. Thus further testing and researches are needed [31].

2D and 3D Computer-assisted navigational systems have been of great value to surgeons in the preceding years. In particular, the field of OMF surgery, where surgeons are faced with complex anatomy, the narrow spatial relationship of vital structures, and high esthetic demands. One of the major improvements was image-guided navigation that uses the pre-operatively acquired scans to enable intra-operative guidance.

Nevertheless, certain flows and challenges were accompanied by the use of these devices [20,32]. These include a lack of image depth in the virtually displayed images, the need for hand-eye Transformation, indirect recognition of the patient’s anatomy from the two-dimensional images, and inaccurate Registration in indirect visualization of three-dimensional images, as the small surface details may be smoothened out [6,13]. Accordingly, a constant comparison between the surgical field and the displayed image is required, conveying the need to look away from the operating field to see the displaying screen [6,13].

The usage of the augmented reality technology as a navigational tool could decrease the mean positional errors to 0.7 mm [6]. A study in 2018, done by Zhu M. et al., compared the usage of the AR system, Individualized Templates (IT), and free-hand technique in a Mandibular Angle Osteotomy (MAO) [33]. The study sample was divided into three groups; 31 patients were in the AR group, 28 patients in the IT group, and 34 patients in the free-hand group.

The study results showed that AR needed more time than the free-hand technique in the pre-operative phase, but in regards to the procedure time, the AR system proved to be less. The AR system showed an advantage over the IT system as the AR system pre-surgical option can be altered anytime. Furthermore, the surgeons performing the procedure favored the use of the AR system on the IT technique, as it provided more understanding of the operative field and provided better viewing [33]. A study was done in 2019 by Pietruski P. et al [34]. compared the usage of cutting guides created by CAD/CAM and two AR systems, based on simple (SAR) and a Navigated (NAR) Augmented Reality technology, for a mandibular osteotomy procedure, concerning the accuracy of the systems. After performing 21 osteotomies on the identically fabricated mandibles (Seven for each method). The result indicated a more accurate procedure when using surgical guides. CAD/CAM printed guides are gaining a lot of popularity nowadays. Although it has been proven more accurate than AR, this technique is limited by certain drawbacks that permit the widespread use of this technology. A time-consuming process, as the guide needs to be printed, which limits its use for trauma and cancer patients. It is also a costly technique. The main drawback is that the guide needs to be placed directly on a bony landmark, which means that greater irritation and extensive dissection of soft tissue are required. AR technologies have the potential to decrease these limitations in the future [34].

The relevant advances in the AR systems and techniques opened the door for the uses of AR in other dental specialties [33]. According to Dr. Charles J. Good acre, an educator at Loma

Linda University School of Dentistry (Loma Linda, CA), there are four key factors to enhance dental education; spatial ability, interactivity, critical thinking, and clinical correlations with the integration of multiple dental disciplines. He described how 3D software (eHuman (https://ehuman.com/)) could help in enhancing dental education and the advantages it gives to the students [35]. Preclinical classes help dental students in improving fine motor abilities, mastery of new tools, as well as, provide an understanding of therapeutics, biomaterials, and techniques before patient treatment where the convergence of these disciplines takes place [36].

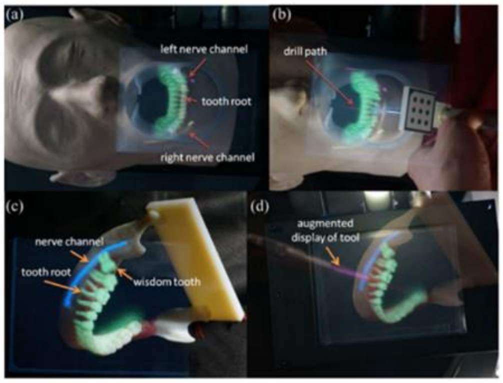

Figure 4: (a) Teeth model overlay with critical structures to visualize the hidden tooth roots. (b) Augmented display of the surgical instrument with the overlaid drill path. (c) Three-dimensional images of molars including a growing wisdom tooth were overlaid on a lower jaw model. (d) Augmented display of the surgical instrument indicating the drill path.

According to the literature, AR has proved to increase those skills needed for this convergence, as it is strongly related to spatial vision, since it increases both the surgeon's visual awareness in high-risk surgeries and increases the surgeon's intuitive grasp of the operating field [4,11,37]. Also, it decreases the iatrogenic complications of the treatment performed like the injuries of the surrounding anatomical structures **Figure 4**, proved effectiveness by assisting the oral surgeons to better visualize the operating fields that are not directly observed, aiding in the reduction of surgical time and morbidity, which may result in a reduced overall treatment coast, and help address the challenges that may confront the surgeon during a procedure [4,11,19,24,31,34]. Furthermore, it helps in decreasing the amount of X–rays the patient is required to have [8].

In contrast to the previously mentioned benefits, AR does have certain drawbacks. In OMF surgeries, the implementation of AR decreased because of the sophistication of such surgeries and the longer time required for the implementation of such devices. Additionally, the technical application and the limited accuracy have been proposing a difficulty [14]. Without forgetting to mention, that the system needs expensive necessary equipment, as the expenses of AR systems are still high [4,15,25]. This is why this technology demands both economic and methodological rationalization [4,33,38]. Those drawbacks not only apply to OMFS, but also the routine dental application of AR. A study by Won Y. in 2017 covered the usage of a simple AR system for assisting in the IAN block administration [14].

The study suggested a simple method of implementation of AR in dental practice without the need for a sophisticated system, as they attempted to create an AR on a screen monitor. It also suggested that the utilization of this technique could prove beneficial in orthodontics or prosthodontics, with certain enhancements made **Figure 5**. Zhou Y. et al [14]. published a study in 2019, also proposed the use of an HMD with a low-cost 2D imaging modality like SFE in the early detection of dental caries [17]. Such simple AR systems could enable the usage of AR in routine dental clinical practice in the future [14,17].

Figure 5: performing of an inferior alveolar nerve block procedure using a simple augmented reality method, in which the superimposed images are used as references to locate the mandibular foramen in an intraoral view during the injection of local anesthetics.

Unfortunately, the use of HMD devices may cause vertigo, nausea, blurred vision, eyestrain, and headaches. That is why a proper examination of the potential occurrence of these elements is important before the first use [26,34]. The reason behind those side effects may be because of the mismatch between the visual and vestibular systems. Conversely, avoiding these side effects may be possible by adjusting the headset, moving the eyes at an adequate speed, circumventing any abrupt bodily movements while using it, and having rest for a while after using the device [26]. These side effects might be the reason why most of the authors are indicating the usage of non-wearable display camera systems [39]. In this review, we also reached to the same conclusion. This was also supported by Zhu M. et al. in 2011 [7]. Yet, according to Espejo-Trung LC et al., using such systems may reduce the augmenting perception of the operator [39].

Moreover, Wang J. et al. proposed a video see-throw AR system to address the methodological and implementation issues that other systems resulted in [40]. The study suggested the usage of a simple video camera that can register and project the virtual objects on the camera itself, which resolves the issue concerning the space occupied by the external tracking and display system. Thus, reducing the need for extra space and the time needed to adjust them. Putting in mind that almost all modern operating rooms already utilize the use of an optical camera that allows for AR technology applications **Figure 6 [28]**. Another limitation is that AR cannot be used for emergency treatments, as it requires proper pre-operative investigations [33]. Certain studies had a prolonged time and delay due to the registration phase and other technical problems [25,32].

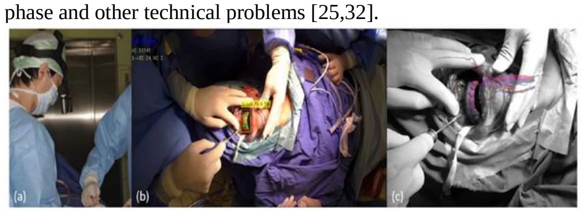

Figure 6: (a) Picture of the surgeon wearing a video camera. (b) Teeth tracking and (c) video see-through augmented reality validated on clinical data. The model of the carotid artery of the patient is overlaid.

Due to the continuous development in the field, new systems became available for use and eased the way to a solution for this obstacle. Suenaga H. et al. published a study in 2015 that introduced a new system. Instead of taking an hour for the registration phase, it takes less than 30 seconds for the completion of it [11]. Wang J. et al. also had similar results [24]. In like manner, Ma L. et al. in 2019 proposed a system that can register the Occlusal splint outside the patient mouth, thus reducing the intra-operative time [30].

For further enhancements of the previous points, Basnet B. R. et al. in 2018 shed the light on further issues in regards to the processing phase, including noise in real-time images, image registration, high processing time, and poor occlusion handling [29]. The study also proposed a solution to handle those limitations by introducing a new system aimed to increase the navigational accuracy by removal of occlusion and noise in real-time navigation. This was accomplished by the use of a weighting-based de-noising filter and depth mapping-based occlusion removal to exclude occluded objects (Blood, surgical tools, and the surgeon's body) [10,29]. In this context, legal regulations must be clearly defined with a clear standard for the directive of patient data [3].

The fastest way for the brain to capture content is through images and visual experience. The concept of human understanding of reality is confined with the three dimensions of space, as the human brain functions on the principles of images and associations, which in return supports the AR concept, thus, yields the promise for further adaptations [41].

Conclusion

This review article covered the AR history, its systems, clinical applications, and the advancements in the AR field from 2000 till 5 May 2020. The publications indicate that AR application is still under testing, as certain drawbacks do tie the spread of this technology in the dental field. Multiple studies have resulted in a system that is suitable for clinical use, yet no routine clinical application has been reported. Improving the speed and accuracy of the processing unit should be the focus of future studies. The results revealed that AR was not used in all dental specialties as the applications found only covered oral surgery, orthodontics, endodontic, prosthodontics, operative, pedodontitics, and dental education As technological advancements resemble a continuous cycle, mixed reality is a new promising technology that combines both VR and AR. The research department has already covered this technology; therefore, a question arises, whether AR will continue to grow independently or will mixed reality dominate the field.

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