UNIVERSIDADE FERNANDO PESSOA

SURGICAL SIMULATION IN DENTISTRY: A SCOPING REVIEW

[Simulação cirúrgica em Medicina Dentária: uma revisão de escopo]

Thesis presented to the Faculty of Health Science of Fernando Pessoa University

As part of the requirements for obtaining the degree in Dentistry

Thierry LE DIVENACH

Orientador(es):

Doutor/Mestre/ Jorge PEREIRA

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Never the first time on a patient

Center for Medical Simulation in Boston, USA

There is no simulation without evaluation

Dr. Gilles CHINIARA

ACKNOWLEDGMENT

Un tout est la somme de petits riens.
Que soient remerciés tous ces petits riens, famille, amis, professeurs, qui ont contribué chacun à sa manière, à la réussite de mon projet.

ABSTRACT

Introduction: Since the origins of surgery, simulation has played an important role in surgical training, especially in the medical field. However, in dentistry, simulation has predominantly focused on conservative care, neglecting aspects of oral surgery despite extractions and other endodontic or periodontal surgeries are part of the daily routine. Given this lack of attention, this study seeks to address this gap by examining the scope of simulation systems dedicated to oral surgery.

Objective: This scoping review aims to explore the literature related to simulation in dentistry for surgical training purposes.

Methods: Following PRISMA guidelines, this scoping review utilized the JBI methodology in a two-step iterative process. Initial searches identified application models (e.g. animal, cadaver, 3D printing, Virtual Reality) using PubMed & Google scholar for their broad coverage and grey literature databases. A second round of research was conducted for each simulation model identified using these databases plus Science Direct and B-On to make it more thorough. Publications were managed using Mendeley Reference Manager, and data are presented in a comprehensive narrative summary.

Results: Among 534 publications initially identified, 148 were included in this review. Topics covered simulation models, associated technologies, surgical procedures, and relevant surgical skills. A trend toward synthetically-based simulators was observed, despite their lower realism, due to greater prospects for technical development.

Conclusion: This review outlines the literature to existing surgical simulation models in dentistry, scoping the different alternatives proposed for both soft and psychomotor skills. The abundance and diversity of simulators, along with the benefits described by most authors, strongly suggest to enhance the use of simulation in the surgical curriculum. Perfused cadavers emerged as the most realistic simulators albeit the most expensive and difficult to implement while animal model remains the standard for many procedures. 3D-printing shows great potential for evolution and pedagogical advantages and virtual solutions require further advancement even if promising avenues for future development.

Keywords: Oral Surgery, Surgical Simulation, Simulation model, Surgical training

RESUMO

Introdução: Desde os primórdios da cirurgia, a simulação tem desempenhado um papel importante na formação cirúrgica, especialmente no campo médico. No entanto, na odontologia, a simulação tem-se focado predominantemente na medicina dentária conservadora, negligenciando aspetos da cirurgia oral, apesar de as extracções e outras cirurgias endodônticas ou periodontais fazerem parte da rotina diária. Dada esta falta de atenção, este estudo procura abordar esta lacuna examinando o âmbito dos sistemas de simulação dedicados à cirurgia oral.

Objetivo: Esta revisão de escopo visa explorar a literatura relacionada com a simulação em medicina dentária para fins de treinamento cirúrgico.

Métodos: Seguindo as diretrizes PRISMA, esta revisão de escopo utilizou a metodologia JBI num processo iterativo de dois passos. Pesquisas iniciais identificaram modelos de simulação (como animais, cadáveres, impressão 3D, Realidade Virtual) utilizando PubMed, Google Scholar pela sua ampla cobertura e bases de dados de literatura cinzenta. Uma segunda rodada de pesquisa foi realizada para cada modelo de simulação identificado utilizando estas bases de dados, bem como a ScienceDirect e a B-On, para a tornar mais exaustiva. As publicações foram geridas utilizando o Mendeley Reference Manager, e os dados são apresentados num resumo narrativo abrangente.

Resultados: Entre as 534 publicações inicialmente identificadas, 148 foram incluídas nesta revisão. Os tópicos abordaram modelos de simulação, tecnologias associadas, procedimentos cirúrgicos e habilidades cirúrgicas relevantes. Foi observada uma tendência para simuladores virtuais, apesar do seu menor realismo, devido às maiores perspectivas de desenvolvimento técnico.

Conclusão: Esta revisão descreve a literatura relacionada com os modelos de simulação cirúrgica existentes em medicina dentária, analisando as diferentes alternativas propostas. A abundância e diversidade de simuladores, juntamente com os benefícios descritos pela maioria dos autores, sugerem fortemente o aumento da utilização da simulação no currículo cirúrgico. Os cadáveres perfundidos surgiram como os simuladores mais realistas, embora sejam os mais caros e difíceis de implementar, enquanto o modelo animal continua a ser o padrão para muitos procedimentos. A impressão 3D mostra um grande potencial de evolução e vantagens pedagógicas e as soluções virtuais requerem mais avanços, ainda que sejam vias promissoras para o desenvolvimento futuro.

Palavras-chave: Cirurgia oral, Simulação cirúrgica, Modelo de simulação, Formação cirúrgica

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ABBREVIATIONS

AR: Augmented Reality

DoF: Degree of Freedom

ER: Extended Reality

HMD: Head-Mounted Display

IANB: Inferior Alveolar Nerve Block injection

IASAN: Infiltrative technique for the Anterior Superior Alveolar Nerve

LA: Local Anesthesia

MNB: Mental Nerve Block

MR: Mixed Reality

OMF: Oral and Maxillofacial Surgery

SG: Serious Game

VP: Virtual Patient

VR: Virtual Reality

GLOSSARY

Augmented reality: Technology that overlays computer-generated virtual images onto the existing reality, enhancing sensory perception and enabling interaction with the augmented environment.

Degree of freedom: refers to the number of independent directions in which movement or force can be applied. A simple joystick offers two degrees of freedom meanwhile complex haptic devices enable translation along three axes (X, Y, Z) and rotation around each of those axes.

Dental surgery: the term, equivalent to dentistry, appeared with the creation of the first dental college (Baltimore College of Dental Surgery) in 1840.

Dentistry: refers to any surgical procedure performed on the teeth, gums, or jawbones by a dentist.

Extended Reality: Umbrella term that includes virtual reality (VR), augmented reality (AR), mixed reality (MR), and other immersive technologies. It reflects the idea of extending or expanding reality perceptions and interactions through various digital experiences.

Haptic: The term appears in the 1970s with the development of technologies that aimed to simulate the sense of touch in human-computer interactions. Since then, it is playing a key role in various applications, including virtual reality, gaming, medical simulations, etc.

Head-Mounted Display: Part of a helmet that has a small display optic in front of each eye. The more advanced HMD setup has a six-axis position degree-of-freedom (DoF) to allow the user to ‘look around’ the virtual world with their head orientation and move around to the respective direction.

Immersive: Experiences that deeply engage the senses and fully absorb individuals in an activity or environment to the extent they feel entirely immersed within it.

Maxillofacial surgery: contraction of "Oral and Maxillofacial Surgery" (OMS) is a recognized international specialty that deals with the diagnosis and treatment of diseases,

injuries and defects involving both the functional and aesthetic aspects of the hard and soft tissues of the oral and maxillofacial regions, requiring a dual qualification in dentistry and medicine.

Minor oral surgery: comprises those surgical operations that can comfortably be completed by a practiced non-specialist dentist in not more than 30 minutes under local anesthesia. (McGowan, 1989). There is no official list, and the procedures used in this study are those covered by the reference books cited in the bibliography, which have given rise to a comprehensive list attached in Appendix A.

Mixed reality: Mixed reality refers to all technologies that combine real and virtual spaces to create a new space in which real and virtual objects interact in real time. (Sasaki et al., 2022)

Oral surgery: is a specialty described by the General Dental Council (GDC) as treatment and ongoing management of irregularities and pathology of the jaw and mouth that require surgical intervention. It includes the specialty previously known as Surgical Dentistry.

PRISMA-ScR: Preferred Reporting Items for Systematic Reviews and Meta-Analyses extension for Scoping Reviews.

Serious Game: Any type of game that is designed for a primary purpose other than entertainment. (Queiros et al. 2023). An older definition was: any form of interactive computer-based game software for one or multiple players to be used on any platform and that has been developed with the intention to be more than entertainment. (Ritterfeld, Cody & Vorderer, 2009)

Simulator: Device or model used to train people by imitating the situations that they will need to deal with. (Valentine, 2016)

Surgical dentistry: mainly used in United Kingdom, was referred by the General Dental Council (GDC) in U.K. as: Those surgical procedures within the mouth, which would normally be accomplished for a cooperative patient under local anesthesia with or without sedation in a tolerably short operating time. The term is falling out of common usage.

Virtual Patient: Contraction of virtual patient simulator (VPs). Interactive computer simulations used in health care education to train students on clinical processes such as making diagnoses and therapeutic decisions.

Virtual reality: Artificial computer-generated simulation of a real life environment that immerses the user by making him feel like experiencing the simulated reality first-hand.

I. INTRODUCTION

Since the origins of surgery, simulation has played an important role in surgical training, especially in the medical field. With this in mind, before tackling the subject of simulation and defining what kind of surgery we are interested in, it is a good idea to first define its respective scope. Words can play tricks on us, and this introduction will set the scene.

Going back to the Middle Ages and the writing of the treatise "Chirurgia Magna" by Guy de Chauliac (c. 1300-1368), often called the father of modern surgery, the word "surgery" comes from the Old French ‘surgerie’, itself derived from the Greek ‘kheirourgia’ in the sense of ‘done by hand’. This gave rise to an opposition over several centuries between the physician who practiced medicine and the barber surgeon who went by ‘manipulating’, doing physical removal, repair, or readjustment of organs and tissues. This definition was confirmed by another pioneer of surgery, Ambroise Paré (c. 1510-1590) in its publications concerning mouth and teeth, as noted by Philippe (2014), marking a milestone in the establishment of dental surgery.

The role of the hand being the distinguishing feature, virtually, all dentistry is surgery, which explains the title DDS, Doctor of Dental Surgery. Nevertheless, ‘Dental surgery’ is not ‘Oral surgery’ nor ‘Surgical dentistry’ and the nuance is particularly relevant when it comes of simulation.

Indeed, conservative dental simulators, when not body-based, have already been the subject of various thesis works (Treanton, 2022; Li, Y. et al. 2021; Collomp, 2019; Perry et al., 2015) but none of these simulators can deal with surgical procedures.

Limiting ourselves exclusively to the surgical side, two studies were identified and used as a starting point as they partially addressed the subject of training in oral surgery using simulators: the complete 2-part study by P. Grall, J. Ferri and R. Nicot (2020) “Surgical training 2.0: A systematic approach reviewing the literature focusing on oral maxillofacial surgery”, which deals with training using new technologies but covering all modes of teaching and not only simulation. And on the other hand, the Brazilian integrative study from Dos Santos et al. (2021) on “The use of simulation models for surgical training” but which is more cursory and based on only 7 articles, the most recent of which from 2018.

However, in dentistry, simulation has predominantly focused on conservative care, neglecting aspects of oral surgery despite extractions and other endodontic or periodontal

surgeries are part of the daily routine. Given this lack of attention, this study seeks to address this gap by examining the scope of simulation systems dedicated to oral surgery.

The aim of this work is therefore to review the full scope of oral surgery simulators used in dentistry and to discuss the features of each model in relation to the different surgical procedures and targeted objectives.

II. CORE CHAPTERS

II. 1. THEORICAL FRAMEWORK

Without going back over the complete history of simulation and its application which has been covered many times, the use of simulation extends beyond training and is a versatile tool for analysis, prediction, design, decision support, and various other purposes across different domains but, in medicine, it is mainly linked to training, at least in surgery.

II. 1. 1. Historical starting point

Simulation, or better-said, Simulation-based Training, has a rich historical background, dating back to ancient times. Bienstock and Heuer (2022) pointed out examples such as stone carvings of human form in Eurasia, from 24,000–22,000 BC, clay livers discovered in Babylonia dating back to 1900–1600 BC, etc. Another example is given by Owen (2016) in the book "Simulation in Healthcare Education: An Extensive History" providing, among other many examples, a comprehensive list of surgical simulators established by Sushruta (see Appendix B), probably the first Plastic Surgeon and pioneer of Ayurveda, in its treatise "Sushruta Samhita" in 600 BC (Saraf & Parihar, 2006).

From the Middle Ages, doctors-to-be were apprentices, acquiring skills under the guidance of older peers (Gourevitch, 1999). This historical practice laid the groundwork for mentoring - a supportive and structured relationship between a more experienced and knowledgeable professional (mentor) and a less experienced trainee (mentee). First with cadavers, mainly to learn anatomy, then directly with the patient.

To make it more real, in the Sixteenth Century, due to the immense surgical needs arising from the numerous wars led by Spain, Andrés Alcazar, a surgeon at the University of Salamanca, had an adult-sized wooden mannequin built in 1570 for the training of bandaging and the reduction of broken and dislocated bones (Appendix C). Initially intended for surgical education, the mannequin fell into disuse by the end of the 18th century, serving thereafter exclusively for anatomical training (Rodríguez Sánchez, 1991). In France, in 1778, Angelique Du Coudray, designed a life-sized women's pelvis covered with fabric and leather to teach the art of childbirth. From nursing, the use of mannequin extended then to resuscitation with the world-famous dummy Resusci-Anne from Dr. Laerdal (1960) and anesthesia and other specialties such as emergency medicine, pediatrics, etc. (Ben Ahmed & Dziri, 2020)

II. 1. 2. Involving animal models

At the same time, for as long as humans have been observing and seeking to understand the living world, animals have been the subject of study and experimentation. Naturally, and especially since Claude Bernard (1813-1878) pioneered the rigorous use of animals to further physiological and medical knowledge, the anatomical proximity of animals to human (Appendix E) has served for research but also to train and educate surgical techniques. The use of animals in scientific research has always been the subject of heated debate for the longest time (Kushali et al., 2020) being rats, mice, guinea pigs, rabbits, beagle dogs, goats, and nonhuman primates the most preferred animals used for medical and dental studies (Guttu & Laskin, 1989; Weinberg, 1999). For oral and maxillofacial surgery training, the most commonly used animals are porcine, goats, sheep and dogs, with predominance for the pig. It is well known that physiology of pigs is similar to that of humans. As early as 1939, H. Round utilized a pig's jaw for experimental bone chiseling, and its effectiveness for oral surgical training. Investigated in 1965 by Moore, Stacy, and Gillbe, Stacy definitively established the pig's head as a realistic model in 1967 providing a wide scope for basic practical instruction: anesthesia, extraction (forceps and surgery), apicoectomy, gingival surgery, soft tissue lesions, techniques for biopsy, removal of submaxillary salivary gland, fractures, impacted teeth, enucleation of tooth germs and closure of oro-antral fistulae. In 1972, Cumming & Glavind focused their investigation on periodontal surgery and stated that pig mandible provided a remarkable representation of the human and ideal model for reverse bevel flap operations, curettage, detail planning and suturing.

II. 1. 3. Models & methods

As models were developed, so were methods. Thus, as a continuity of the mentoring approach, the So-Do-To methodology (See one, Do one, Teach one) gained popularity through the work of American surgeon Pr. William Stewart Halsted (1852–1922) as part of the Halstedian principles, referring to the surgical techniques and principles he developed and promoted, which became a definitive standard in surgery training. Peyton's 4-step technique (demonstration, deconstruction, comprehension and performance) introduced one century later, further improved this method, just to mention one of the noteworthy advancements in this domain (Giacomino et al., 2020).

II. 1. 4. Advent of new technologies

The emergence of new technologies changed the paradigm and introduced new tools and uses. The proximity of mentor and teacher is no longer a necessity, and telemedicine/telesurgery became operational. Training via the exchange of information on social networks or distance learning using open field cameras have all come into their own. Grall, Ferri & Nicot (2020) describe the pedagogical advantages of these new processes: video channels like YouTube®, being very useful for learning surgical procedures, contribution of networks like X® (formerly Twitter), Facebook® or Instagram™ enabling easy peer-to-peer interaction. Or telementoring used for teaching surgery: an expert gives advice to a student from a remote location with or without an Open-Field Camera attached to the surgeon or above the operating table giving to the surgical students the view they would like to have themselves.

Whatever the technology, all are teaching methodologies that encompass both theory and practice. In the specific field of dental education, as in surgery, the training of professionals involves two key areas: the transmission of information (through books, lectures, etc.), which involves the acquisition of clinical reasoning and decision-making abilities, and the development of psychomotor skills (Allaire, 2015). The former aspect is often overlooked when discussing about surgical simulation. Mistakenly, simulation is commonly perceived solely as a means for enhancing manual dexterity, neglecting its potential to enrich knowledge and discernment in formulating accurate diagnoses and treatment plans. Chart 1 details how simulation models can be divided into the theoretical and practical aspects.

Clinical reasoning	Psychomotor skills
Virtual Patients (VPs) - Web-based Simulation - Web-SP - Serious Games	**Physical, benchtop & Virtual** - Animal & cadaver models - Mannequins & 3D-printed models - Haptics devices & XR (VR, MR, AR)

Chart 1: Segmentation of Surgical simulators - Cognitive versus motor skills

II. 1. 5. Improving soft skills

With regards to clinical reasoning and decision-making abilities, Dr. William G. Harless and his team designed in 1971 the Computer-Aided Simulation of the Clinical Encounter (CASE) which is considered as the first Virtual Patient (VP), marking a significant milestone in the history of medical simulation and technology.

According to Cook & Triola (2009), Virtual patients (VPs) or interactive computer-based clinical scenarios are the results of opposing forces: on the one hand, increased training expectations and on the other: reduced training resources. Responding to a real need, virtual patients have become a natural part of the medical education skills continuum as shown figure 1.

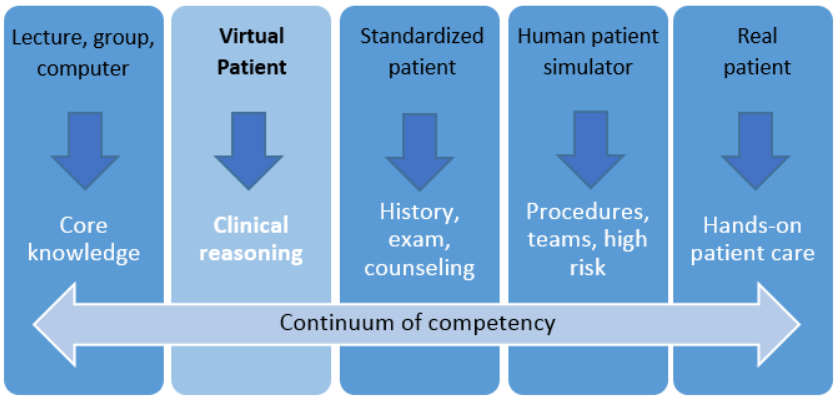


Figure 1: Continuum of competency in medical education (from Cook & Triola, 2009)

Allaire (2015) also mentioned in his study on Virtual Patient Simulation that students did, however, report that the use of virtual patients contributed to building their critical thinking skills and confidence in making good clinical decisions.

In practice, VP technology emerges with the advent of the Internet, initially through Web-based practical courses. Subsequently, under the impetus of the Swedish Karolinska Institutet's R&D group in e-Learning and simulation at the department of LIME, development and implementation of various case simulation systems began in the 1990s and gave birth to the first version of Web-SP (Web-based Simulation of Patients) in 2001-2002 with a user-friendly Web-interface and Patient Cases. The aim of the Web-SP project was to facilitate the use of realistic and interactive virtual patients (VPs) in medicine and healthcare education (Zary et al., 2006) then in dentistry (Zary et al., 2009). Attention must be drawn to the fact that a 'Patient case' is not a 'Clinical case' but much more than that. Definition by the founders is: A patient case is a simulated patient encounter that

provides the student with tools to gather and analyse medical data in order to diagnose and treat a virtual patient. (Zary et al., 2006). Above all, it is interactive.

The Web-SP has seen validation studies and applications across various institutions worldwide. Examples include Stanford University (USA, 2009), Universidad El Bosque (Colombia, 2010), University of New Jersey (USA, 2011), and University of New York (USA, 2020). These studies have contributed to the system's recognition and gradual adoption in diverse contexts globally. Nevertheless, it was gradually replaced by gamification, which offers a wider range of applications and can be coupled with haptic devices.

Kharbech et al. published in 2024 a complete review 'Digital tools and innovative healthcare solutions: Serious games and gamification in surgical training and patient care' which goes beyond the ambition of this work, but describes the full potential of serious games. Some benefits are described in figure 2.

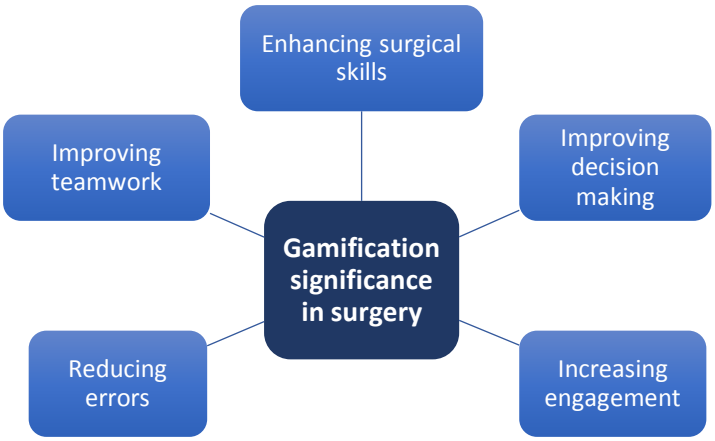


Figure 2: Benefits of gamification in surgical training (from Kharbech et al. 2024)

Serious Games or 'Games used for serious purposes' (Abt, 1970) date back from centuries before the new technologies, mainly for military purposes. In the second half of the 20th century, they were transferred to education and business (Deterding et al., 2011) with the advent of computer science. By itself, Serious Games refer to interactive and educational game-like experiences designed for training and skill development but mainly to enhance skills such as decision-making, and procedural knowledge. Experiencing a somewhat limited scope of application, the introduction of a haptic device enabled the integration of cognitive and manual components, transforming the solution into a truly comprehensive surgical simulator.

II. 1. 6. 3D printing

Linked to the emergence of new technologies, the advent of three-dimensional printing will allow overcoming the limitation posed by the accessibility of human or animal bodies, including factors such as availability, cost, and ethical considerations. This technological breakthrough not only addressed these limitations but also opened up new perspectives as the technology continued to develop. From the simple idea put forward by science fiction writer Murray Leinster in 1945, to the first prototype by Japan's Dr. Hideo Kodama in 1981, we had to wait for the end of patents to witness the arrival of 3D printing in the "Head & Neck" domain in 2008 (Dr. Lantieri, Paris Descartes University). Since then, 3D printing offers a large range of solutions for surgeon training and simulation.

II. 1. 7. Entering into the virtual world

As far as simulation and immersive technologies are concerned, it is imperative to acknowledge the significant advancements in Haptic devices and Virtual Reality (VR) alongside its associated variants such as Augmented reality (AR), Mixed Reality (MR) and Extended Reality (XR). As highlighted by Spiegel et al. in their recent study (2024), there has been an exponential surge in literature pertaining to these topics, as evidenced by the substantial increase in peer-reviewed articles incorporating terms such as "virtual reality", "augmented reality" or "mixed reality" (see Figure 3)

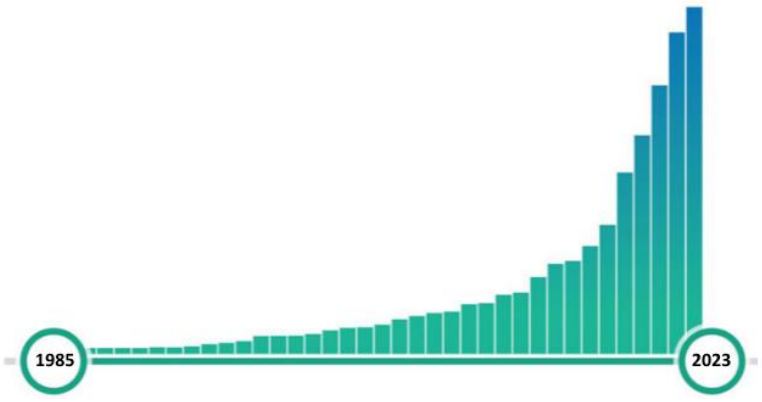


Figure 3: Annual mentions of 'X-reality' terms on PubMed (from Spiegel et al., 2024)

However, there is considerable confusion surrounding the interpretation and potential uses of these emerging technologies. Often, they are depicted with exaggerated promises, leading to misconceptions. The 'X-reality' terminology associated with these technologies can be unclear, warranting a closer examination of their origins and potential applications.

II. 1. 8. Virtual Reality

Concepts such as "Virtual reality" lack a singular 'father' akin to figures like Hippocrates or Pasteur. Discrepancies exist in tracing its history (Figure 4), though many authors point to the American science fiction writer Stanley G. Weinbaum in his short story 'Pygmalion's Spectacles' (1935) as the first immersive fictional model for VR (Zhang et al., 2023). Alternatively, others reference the French avant-garde playwright Antonin Artaud, who described a form of 'Virtual Reality' in his 1938 essay 'Le théâtre et son double' (Lalo, 2019)

Regardless, in 1955, Morton Heilig, a cinematographer, created the Sensorama calling it "The cinema of the Future" he built in 1957 as a large booth. In 1968, Ivan Sutherland (American computer scientist) reduced the size to what is now commonly considered the first head-mounted display (HMD), known as "The Sword of Damocles". Back to concepts, it is also widely accepted that Jaron Lanier (computer scientist & visual artist) coined definitively the expression 'Virtual Reality' in 1985 (Zhang et al., 2023), after which it was adopted by many.

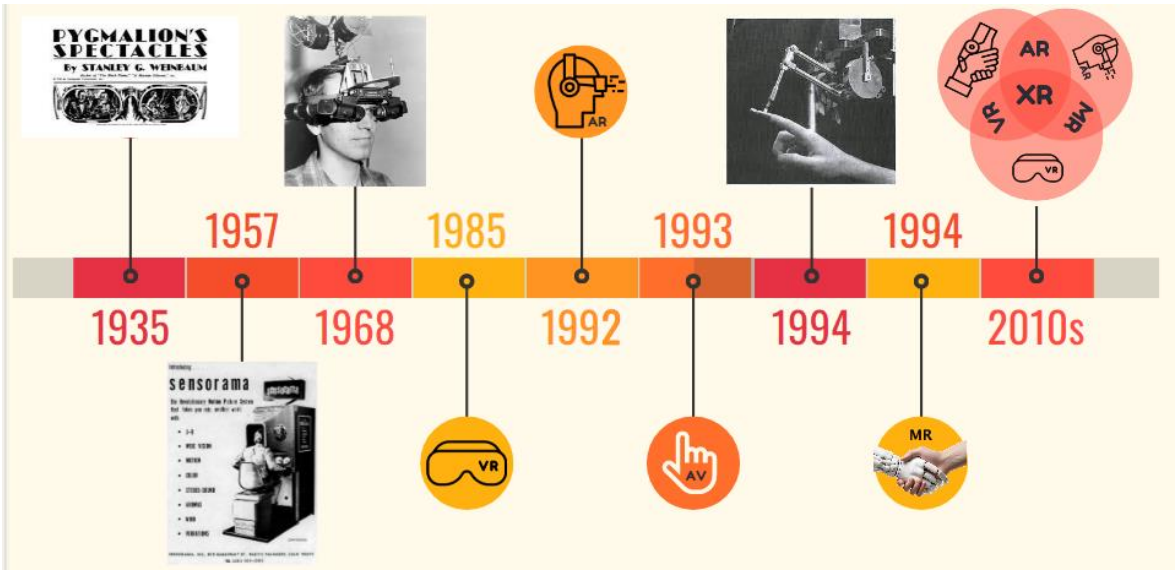


Figure 4: Timeline of Extended Reality

Among many definitions, we could use the one given by McCloy & Stone in 2001 that focuses surgery: VR is a synthetic environment, composed of computer-generated images, audios, and videos were the users are emerged inside the artificial environment and cannot see the real world. Another definition, provided by Joda et al. (2019) and applied to dental medicine, describes VR as an artificial, computer-generated simulation of a real-life

environment or situation that immerses the user, making them feel as though they are experiencing the simulated reality firsthand.

VR initially served to train humans in hostile environments such as undersea, nuclear installations, space, or battlefields. In surgery, the first experiment was the leg simulator (see Appendix D) in 1987 by Scott Delph and Joseph Rosen of Stanford University to practice Achilles' tendon repair. On the impulse of Dr. Richard Satava, leader in the development of laparoscopic and robotic surgical techniques, Dr. Mark Bolas developed in the mid-90s the MIST-VR (Minimally Invasive Surgical Trainer - Virtual Reality) system, first commercialized product for training and assessment of surgical laparoscopic psychomotor skills, "Making surgical simulation real" (D. Meglan, 1996).

Since then, numerous applications have been found in various domains, notably gaming and those relevant to us as training, to the extent that the term has become commonplace. However, following this widespread adoption, a counterpart has emerged: cyber-sickness, visually induced, capable of affecting any healthy individual regardless of age (Arns & Cerney, 2005), but merely a normal physiological reaction to the artificial environment (Bos et al., 2022).

II. 1. 9. Augmented Reality

Augmented Reality emerged as the second milestone in the evolution of virtual experiences. AR technology is a valuable asset in the medical domain, where it has the potential to grant "X-ray vision" to physicians, allowing them to view medical data in situ, in the same physical space as the patient. (Gsaxner et al., 2021). AR complements the real world by adding virtual elements. (Mladenović, 2019)

Virtual Reality (VR)	Augmented Reality (AR)
- Immersive experience - Creates a completely new surrounding - HMD recommended for full immersion - Presents a virtual environment where everything you see is virtual	- Overlays digital information onto the real world - Enhances existing real surroundings - No HMD required (smartphone or AR glasses) - Allows users to observe a real scene and see virtual objects overlaid onto it or through it

Chart 2: Comparison between VR and AR

The term 'augmented reality' is commonly attributed to Caudell and Mizell, who coined it in 1992 while working at The Boeing Company. Assigned with improving aircraft wiring instructions, they proposed a HMD for workers that superimposed cable positions onto workers' field of view, projecting them onto multipurpose, reusable boards. Applied

to medical, as defined by Joda et al. (2019), AR is a technology that overlays computer-generated virtual scenario onto the existing reality, in order to create a sensory perception through the ability to interact with it. In dentistry, oral and maxillofacial surgery is the primary area of use, where dental implant placement and orthognathic surgery are the most frequent applications. (Kwon et al., 2018). Chart 2 details the characteristics of this technology compared with VR.

II. 1. 10. Augmented Virtuality

Augmented Virtuality (AV) as established by Metzger's work in 1993 in 'Adding reality to virtual' serves as the counterpart to AR in which a virtual world, that is generated primarily by computer, is augmented with real-world objects or information, as described by Milgram & Kishino in 1994, who referred to it as the 'converse case'. Very few simulators utilizing AV have been developed in the medical fields, but one particular simulator stands out and deserves mention: 'PalpSim'. Designed to train medical professionals in femoral palpation and needle insertion, it allows the trainees to feel a virtual patient using and seeing their own hands (Cole et al., 2011). An example of the kind of images obtained is depicted in a screenshot provided in Appendix F.

II. 1. 11. Haptics

Haptics, primarily focused on the sense of touch and pressure rather than temperature or pain, traces its origins to aviation training. This technology enables users to perceive tactile feedback or physical sensations when interacting with digital interfaces or virtual environments. In the medical field, haptics made its debut with the PHANToM (Personal HAptic iNTerface Mechanism) developed by Thomas Massie, the founder of SensAble Devices Inc., in 1994 as described by Karl D. Reinig et al. (1995) in the book 'Real-Time Visually and Haptically Accurate Surgical Simulation'. Driven forward by the development of laparoscopy and surgical robots, haptics, or touchsense haptic technology has become a major breakthrough in medical and dental interventions (Kapoor, 2014).

II. 1. 12. Mixed Reality

The concept of Mixed Reality (MR) is often misunderstood as it entails the merging of real and virtual worlds. Indeed, as stated by Sasaki et al. (2022): Mixed reality refers to all technologies that combine real and virtual spaces to create a new space in which real and virtual objects interact in real time.

Both objects are presented together within a single display, that is, anywhere between the extrema of the 'virtuality continuum' introduced by Milgram & Kishino (1994). Their study, which presented "a taxonomy of mixed reality visual displays" became a reference in the field. Virtuality continuum is therefore what connects completely real environments to completely virtual ones and is divided into 6 classes of display (Figure 5).

While AR overlays virtual elements onto the real world, MR integrates these virtual elements into the real world in an interactive and real-time manner. Further clarification on the distinction between the two will be provided in the 'Results' chapter, with examples throwing light on their boundaries The key term to differentiate them is clearly 'interactive', as AR is not.

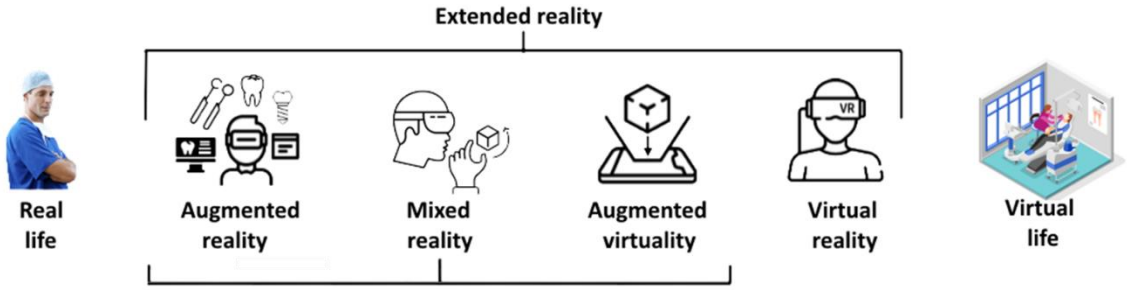


Figure 5: Reality-Virtuality Continuum (Milgram & Kishino, 1994)
Graphic inspired from Zhang et al. (2023)

II. 1. 13. Extended Reality

Finally, Extended Reality (ER) serves as an umbrella term that includes virtual reality (VR), augmented reality (AR), mixed reality (MR), and other immersive technologies. It reflects the idea of extending or expanding reality through various digital experiences, encompassing a wide range of environments, interactions, and applications. ER describes the spectrum from fully immersive, curated digital experiences in VR, to unobtrusive annotations within easy access of the operator in augmented reality (AR) (Silva, J.N.A. et al, 2018).

II. 1. 14. Perfused cadavers

Despite the rapid expansion of these new immersive technologies, in general surgery training, cadavers are still considered the gold standard, given their widely recognized benefits. It is commonplace to affirm that procedures on cadavers enhanced students' confidence on their first patient and reduce potentially in the incidence of complications.

Starting from this idea, Breque, Faure & Richer from the anatomy laboratory at the University of Poitiers (France), introduced in 2013 a procedure for revascularizing and ventilating cadavers, bringing high-fidelity realism back into fashion (Delpech et al., 2017) and fulfilling a long-standing aspiration among surgeons.

Since then, the resulting SimLife® model has been widely adopted across French medical faculties for its educational value in surgery, validated through numerous studies in various surgical specialties. However, the potential applications of pulsatile cadavers in oral surgery remained unexplored, highlighting a gap in the field.

II. 2. MATERIALS AND METHODS

The proposed scoping review adhered to the Joanna Briggs Institute (JBI) methodology for scoping reviews as described by Peters et al. (2020). In this context, the 6-step framework originally proposed by Arksey and O'Malley (2005) has been enhanced to increase both the clarity and rigor of the review process.

A preliminary search of PubMed and Google Scholars has been carried on during the year 2023 and no current or underway integrative, systematic or scoping reviews about oral surgical simulators were identified. The most recent studies about surgical training or simulation in dental field were partial reviews discussing global issues or narrow topics as dental surgery, dental education, surgical training or focusing on a particular technology (e.g. virtual reality) as mentioned in the introduction.

Given the limited number of publications available in the current corpus, and the technological scope of the different systems used in one way or another in the surgical field, a scoping review was the most appropriate step to understand which oral surgery simulator best suits each of the different oral surgery procedures for two main reasons as described by Munn et al. (2018) : (a) to identify the types of available evidence in a given field and (b) to identify and analyse knowledge gaps.

II. 2. 1. Identifying the research questions

The PCC (Population/Concept/Context) framework recommended by JBI was used to identify the main concepts in the research questions and inclusion criteria.

- Population (P): Students trainees in dentistry (undergraduate and graduate), in oral surgery and in maxilofacial surgery (post-graduate)

- Concept (C): Simulation systems and/or technologies used to improve student skills in medical related-issues evidence (education, training, and learning).

- Context (C): Universities, dental schools or any dental or surgical organization providing specialized training programs in surgery.

An Additional (I) for Intervention has been added standing for "What is the intervention or procedure being studied?" to limit the scope to surgical procedures defined by "Minor Oral Surgery" (see Glossary and Appendix A)

No exclusion criteria were established for Population (P) as even if not mentioned clearly in studies, simulation is mostly a short way of saying simulation-based training and can be tailored to students at various skill levels, ranging from absolute beginners to seniors aspiring to specialize in a specific area.

No exclusion criteria concerning the concept (C) were implemented as long as the solution or simulation system described concerned a surgical procedure (regardless of specialty), leaving the hypothesis of its possible implementation in the oral domain to the discussion section.

Published and unpublished documents in English, French, Portuguese, and Spanish were included, as well as German documents when an English translation was provided or a portion thereof. The inclusion criteria were all studies that included the surgical training of students through simulated practice. All types of methodology literature evidence were incorporated, ranging from reviews, case reports, surveys, clinical reports, *in vitro* or *in situ* studies to clinical trials, theses and manufacturers' data sheets in which simulation played a role in learning.

Thus, the research questions were therefore (a) which simulation models were used and whether there were any gaps; (b) what was the rationale for using simulation, and facilitators and barriers to teaching and learning using simulation; (c) which oral surgical procedures have been explored using simulation or simulation-based education; and (d) the strengths and challenges for each procedure/model studied.

II. 2. 2. Identifying relevant studies

The search strategy was conducted during the year 2023 and first semester of 2024. Four electronic databases were searched for relevant articles within the published literature: ScienceDirect, Pubmed, Google scholars, and B-On plus the repositories of French, Spanish, Portuguese and Brazilian universities for unpublished studies as grey literature search and reference checking.

In order to enlarge the search, Perplexity IA, as a search engine with inline citation capabilities, was employed. The Free version utilized is built upon OpenAI's GPT-3.5 model, integrated with the company's standalone Large Language Model.

No restrictions were placed on the date or country of publication. However, in view of the quick evolving nature of new technologies, only the most recent studies has been retained for each study on a similar or previously discussed subject.

Depending on the databases possibilities and using wildcards "*" and Boolean operators every time it was possible, common keywords used for all searches were:

"Simulat*", "Simulation", "Simulator", "Simulated", "Simulation Model", "Simulation-based Training", "Simulation-Based Experiences", "Surgical simulation", "Oral surgery", "Surgical training", "Surgical teaching", "Surgical Education", "Training" "Education" followed by the subject of the search: "Animal model", "3D print*","Virtual reality", "cadaver model", "serious gam*", etc.

To exemplify the search, one of the strategy adopted in PubMed database was as follows: "serious gam*" AND "simulat*" AND "oral surgery" AND ("training" OR "education"). In the searches, the terms included were identified in the titles and abstracts of the studies about the subject.

Explaining our approach

To thoroughly scope all the possibilities already utilized in surgery simulation, the first research has been extended in three directions: Surgical Training, Medical Training and Simulation, giving rise, by means of a Venn diagram, to four different domains (Figure 6), two of which being the subject of our research.

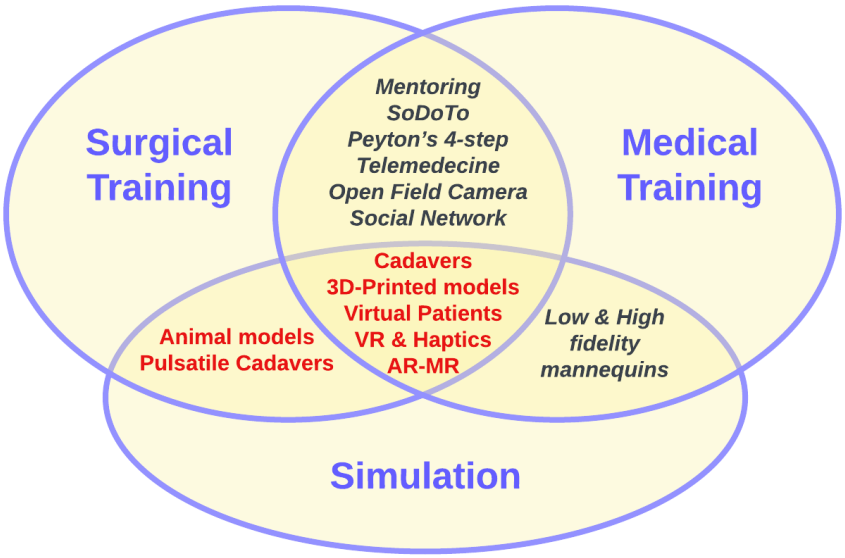


Figure 6: Venn diagram of medical and surgical training tools w/ and w/o simulation

Summing up our research

By restricting our study to only those elements common to simulation and surgical education, a new classification of simulators can be proposed (Chart 3), defining two fields of development: on the one hand, organic or body-based simulators, and on the other, electronic, inorganic and immersive simulators.

Physical, organic or body-based simulators	Electronic & inorganic/ immersive simulators
Animal models Cadavers models Synthetic (3D printed models) Pulsatile cadavers	Virtual patients Haptic Devices XR (VR, MR, AR)

Chart 3: Proposed classification of oral surgical simulators

Once identified the models involved, a further literature review was conducted for each, employing an iterative process to screen all oral surgical procedures used, their backgrounds, benefits and potential future developments. Therefore, this specific approach implied adapting the PRISMA-ScR guidelines to accommodate the inclusion of multiple sub-subjects in the review. Flow diagrams adhering to the PRISMA-ScR guidelines will be provided, with the exception of the pulsatile cadaver solution, as just one publication have been located on this topic and also for mannequins used for surgical training as the discovery of publications was unexpected during the 3D-printing search.

II. 2. 3. Study selection

The search strategy underwent validation by an independent and experienced investigator (teacher) to ensure the integrity of our search results.

As already mentioned, given the nuanced nature of surgical simulation in dentistry, particular attention was paid to the specificity of our focus. Consequently, we excluded from our study all systems or simulators used for restorative dentistry and/or cosmetic surgery.

Furthermore, were also excluded surgical planning methods, although involving simulation, as they were deemed beyond the immediate scope of our investigation. While they contribute to meticulously plan and prepare for surgical procedures, their primary function lies outside the realm of education.

II. 2. 4. Charting the data

In charting the data, surgical procedures were systematically extracted from the selected studies. This process involved identifying the simulator(s) or simulation model(s) used, as well as the study characteristics (e.g., review, training, report case, etc.), simulation techniques utilized, outcomes measured, and any other pertinent findings such as the number and qualifications of the participants. Data extraction was conducted sequencially to ensure consistency and accuracy across all included studies. Furthermore, thematic analysis was employed to classify the publications that did not detail specific procedures. Any discrepancies or uncertainties during the data charting process were resolved through discussion and consensus among the research team.

II. 2. 5. Collating, summarizing and reporting the results

For each encountered simulation system (cadaver models, animal models, mannequins, 3D-printing, Virtual patients, Haptics & VR, AR and MR) the results were compiled and summarized to highlight key findings, such as the number of procedures described and any existing comparisons. Additionally, a graph was constructed to illustrate the temporal distribution of these procedures over time. The final step involved reporting the results of the scoping review in a clear and accessible manner, utilizing various charts to present the findings in tabular format. This approach ensures that the document serves as a comprehensive and easily accessible reference for future consultation.

II. 2. 6. Including expert consultation

Expert consultation played a crucial role in elucidating complex concepts and clarifying nuanced aspects within the scoping review process. Eight experts were identified based on their extensive experience and expertise in perfused cadavers, surgical simulation with cadavers, Mixed Reality procedures, or teaching, etc. These experts were approached via email and invited to provide insights on specific aspects of the review where additional expertise was required.

The following experts generously contributed their time and expertise to the consultation process:

Prof. Cyril BREQUE: Research Doctorate, mechanical engineer. Laboratoire d'Anatomie, Biomécanique et Simulation, UFR Medicine and Pharmacy. Poitiers (France). One of the inventor of the SimLife® (P4P project). Expertise in perfused cadavers.

Prof. Gleyvis CORO-MONTANET: M.D., Ph.D., Director Académica de Odontología Facultad de Medicina y Odontología Universidad Francisco de Vitoria, (Spain). Expertise in Learning and Knowledge technologies.

Dr. Carlo BARAUSSE DDS, PhD Researcher (junior) Department of Biomedical and Neuromotor Sciences Alma Mater Studiorum - University of Bologna (Italy). Expertise in simulation of the sinus lift surgery with the lateral approach with the SimLife®

Prof. Frank HÖLZLE: M.D., D.M.D., Ph.D., FEBOMFS. Department of Oral and Maxillofacial Surgery University Hospital of RWTH Aachen (Germany). Expertise in raising flaps on pulsatile cadavers in the OMFS field.

Prof. Vítor NEVES LOPES: MD, PhD, General Surgeon. Universidade do Porto, Faculty of Medicine, Department of Surgery and Physiology – Porto (Portugal). Expertise in AR for teaching surgery.

Prof. Pedro Alberto PEREIRA: Assistant Professor in the Department of Anatomy at FMUP. Porto (Portugal). Expertise in teaching anatomy & surgery with cadavers.

Prof. Ismet Burcu TÜRKYILMAZ: Associate Professor. Department of Chemistry, Faculty of Engineering, Istanbul University-Cerrahpaşa, Avcilar, Istanbul (Türkiye). Expertise in Mixed Reality advanced dental simulators.

Prof. Rasa MLADENOVIĆ: Professor (Assistant), DDS, PhD, Department of Dentistry. Faculty of Medical Sciences, University of Kragujevac (Serbia). Expertise in Local anesthesia teaching with simulators and virtual patients.

II. 3. RESULTS

II. 3. 1. Cadavers

Throughout the span of 2010 to 2024 (Graph 1), this review investigated the utilization of cadavers in oral surgery education, analyzing 29 pertinent publications (Figure 7). Notably, only one-third (10) of these publications detailed surgical procedures conducted on cadavers (Addenda, table 1). Indeed, oral surgery is often perceived as a subsidiary aspect of general surgery for simulation. For instance, in Japan, its representation within surgical cadaveric programs varies between 5% (Shichinohe, 2022) and 8% (Suzuki, 2022).

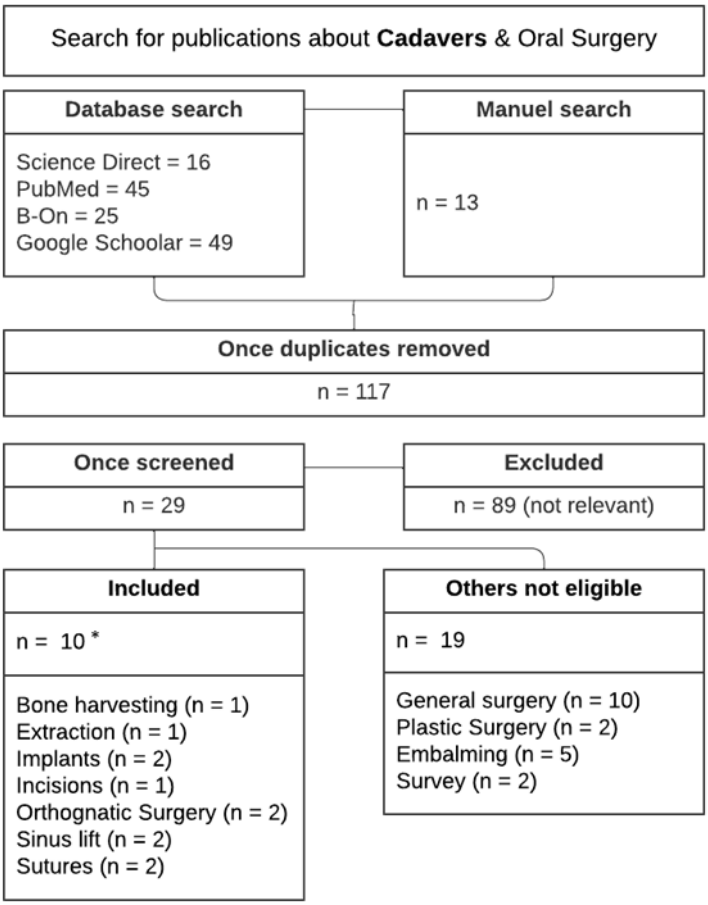


Figure 7: PRISMA flow diagram related to cadavers as surgical simulators

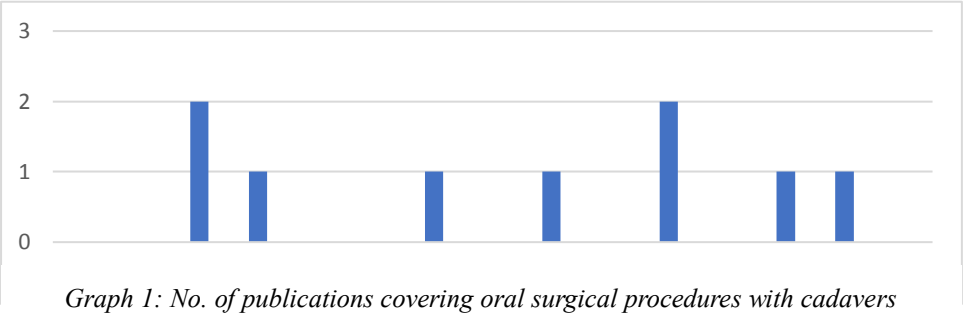
**: The total number of publications may differ from the cumulative number of procedures, as some articles describe several procedures.*

Other articles explored and compared the benefits of various embalming solutions and their effects on surgical simulation we classified as out of scope. Despite the superior tissue quality provided by fresh frozen cadavers, researchers have been compelled to explore alternative techniques due to various drawbacks, notably the high overall cost

(Song & Jo, 2022). The Thiel embalming method emerged as one such alternative with Peuker et al. (2001) evaluating its suitability for educational purposes in oral and maxillo-facial surgery.

The procedures investigated include orthognathic surgeries (2), one of them related to the utility of using cadavers in orthognathic surgery training assessed by Kienle et al. (2012) and the other qualifying it as a promising tool (Walker, 2013). Particularly, the implant-related studies (2) encompassed a comprehensive examination by Hölzle et al. (2012) focusing on sinus floor elevation and various implantological procedures. Kühl et al. (2016) confirmed cadavers as a useful simulator model and used it to compare conventional methods for sinus lift with a piezoelectric device, with equivalent results for both techniques. Additionally, a pilot study conducted by Yu et al. (2020) explored the feedback of drilling forces on fresh mandibles for Virtual Reality (VR) surgical training systems during implant placement. Recently, studies on sutures (2), showed a positive impact on the learning experience (Macluskey, 2022; Zakhary, 2023).

Incisions were assessed with Thiel's embalmed cadavers for educational purposes (Peuker et al., 2001) and Hanson's work (2018) underscored the enhanced realism of cadaveric models compared to mannequin models for extractions. Furthermore, Watanabe et al. (2020) described and approved bone graft harvesting in Saturated Salt Solution Embalmed corpses.



Graph 1: No. of publications covering oral surgical procedures with cadavers

II. 3. 2. Animals

Thirty-eight publications (Figure 8) were reviewed with 28 of them (Addenda, table 2) focusing on research or training involving surgical procedures from 1997 to 2023 (Graph 2). Most of them involved pigs. As reminded by Stelzle & Benner (2010), the use of pig heads is well established in oral surgery procedure training (Stacy, 1967; Bonnette & Hayward, 1969; Cumming & Glavind 1972; Beatty & Vertucci 1984; Stacy 1985).

Sinus elevation emerged as the predominant theme for training, with 7 articles from 1997 until 2013 using animal models such as pigs, lambs, goats, sheep and dogs. Among these, Estaca et al. (2008) compared sheep, goats and pigs for sinus-floor elevation.

Five publications addressed periodontal surgery employing pigs and ovine. Many procedures were described by various authors: gingivectomy, repositioned flap (Widman, apical, coronal), distal wedge, frenectomy, etc. Larsen et al. (2013) concluded that sheep represent a valid option for studying periodontal surgery. Particularly in comparation with pigs. Apart from the papilla preservation flap, which was difficult to perform in both specimen and classified as not suitable in the pig, animal models are considered a valid option as a teaching model (Larsen, 2013; Zangrando, 2014) even for teaching crown lengthening surgical procedures (Zhong, 2022).

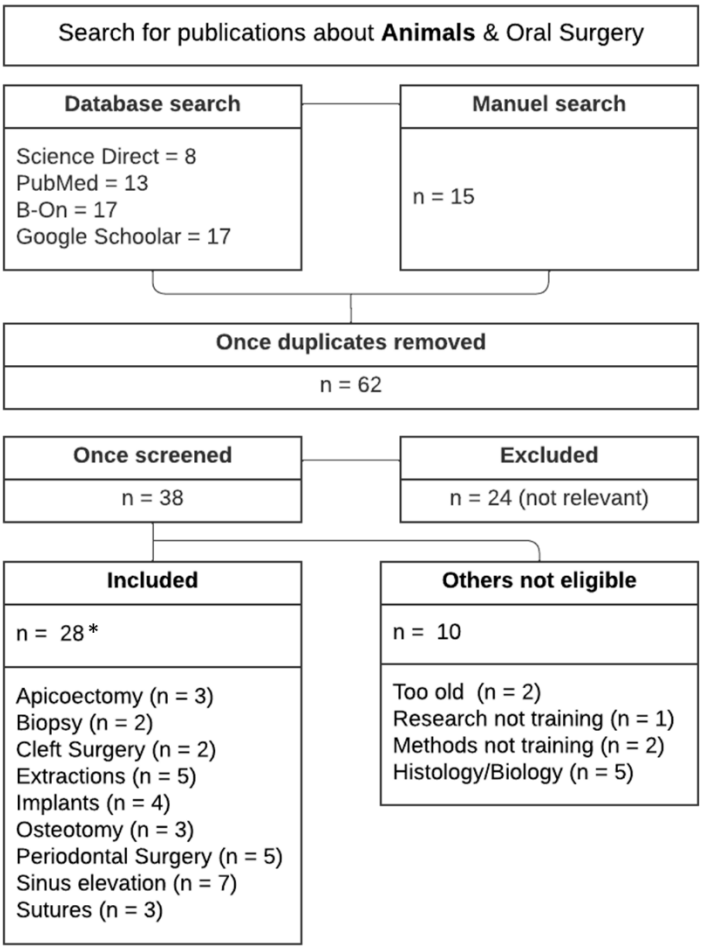


Figure 8: PRISMA flow diagram related to animals as surgical simulators

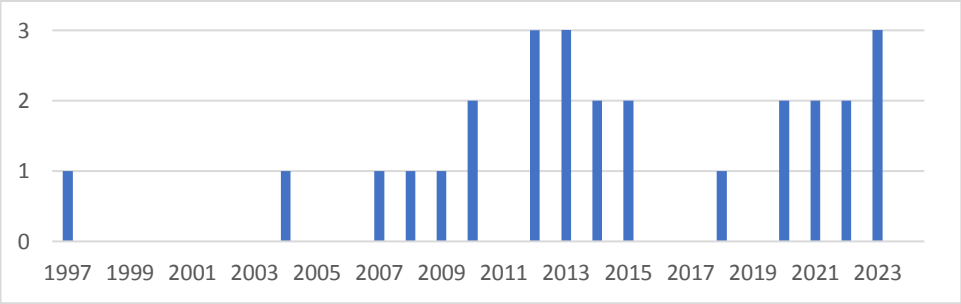
**: The total number of publications may differ from the cumulative number of procedures, as some articles describe several procedures.*

Simple extractions and impacted teeth generated 5 studies. Among them, 3 (Seifert et al., 2020; Feng et al., 2021; Chakravarthy et al., 2022) compared impacted third molars extraction from pig jaws and goat jaws respectively with 3D-printed models. While Feng's study yielded different conclusion, Seifert and Chakravarthy found that students appreciated both the animal models and the 3D-printed models. However, they both noted that there were still room for improvement with the 3D models.

Others procedures studied include implants (4). One of them is particularly noteworthy: Van Erk et al. (2023) have validated skin incision, elevation of the periosteum, drilling of the bone, filling of the defect and application of a membrane for the implant using a perfused mandibular pig. The results should be compared with those obtained using perfused cadavers. It should also be noted that for the evaluation of AR implant surgery (Katić, 2015) or the effectiveness of VR implant platforms (Zhang, 2020), both studies used pigs for their research.

For apicoectomy, the same occured with von Sternberg (2007) or Bosshard (2023), the latter comparing AR with templates. Pig jaw is the reference model. Another comparison for apicoectomy has been done by Seifert (2020) between porcine mandibles versus 3D-printed models, resulting in the pig jaw being deemed a superior model.

Regardless of the specific procedures or studies: whether osteotomy (3), sutures (3), biopsy (2) or cleft surgery (2), animal models offer an effective and well-accepted learning environment for practicing surgical skills. This efficacy has been noted consistently over the years, as already highlighted by Ghiabi & Taylor (2010) in their study on Surgical training in North America, which emphasized the prevalence of animal cadavers as the most common teaching simulator, particularly in periodontics programs, including implants.



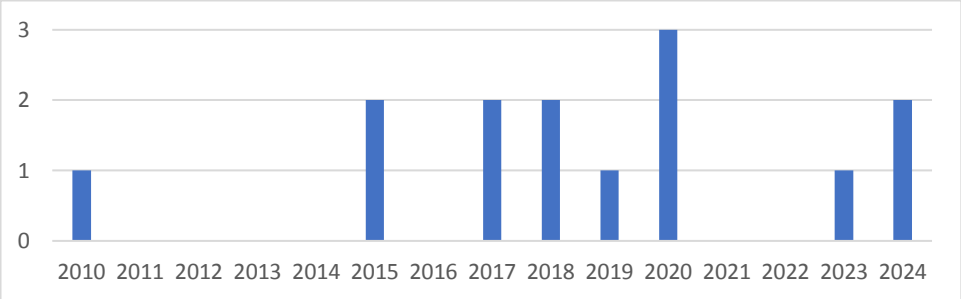
Graph 2: No. of publications covering oral surgical procedures with animal models

Despite the effectiveness of animal models in various surgical procedures, it is worth noting that none of the studies investigated local anesthesia, possibly due to anatomical constraints.

II. 3. 3. Mannequins

While not initially anticipated, the search for 3D-printed models unexpectedly uncovered 14 publications (Addenda, table 3) spanning from 2010 to 2024 (Graph 3) about the use of mannequins in surgical simulation.

Among these, anesthesia emerged with 8 publications. Frasaco (Frasaco GmbH, Germany) and Nissin (Nissin Dental Products Inc., Japan) models were evaluated as viable alternatives to student-to-student injections for local infiltrative injection (Marei et al., 2015), Inferior Alveolar Nerve Block injection (IANB) (Lee et al., 2015; Knipfer et al., 2018), Infiltrative Technique for the Anterior Superior Alveolar Nerve (IASAN) (López-Cabrera et al., 2017) or Mental Nerve Block (MNB) (Reyes-Acuca, 2020; Merino-Parra et al., 2020), all of them contributing to the enhancement of psychomotor skills. Furthermore, similar models from the same manufacturers were utilized for other surgical procedures including extractions (2) or implants placement (2). Additionally, we need to mention handcrafted models for (1) impacted supernumerary canine removal in pediatric surgery (Foley & McDonald, 2018) and (1) suturing techniques (Didhra et al., 2019).



Graph 3: No. of publications covering oral surgical procedures with mannequins

II. 3. 4. 3D printing

Covering the same spanning than for the mannequins (2010 to 2024, Graph 4), this review encountered 44 publications (Figure 9) concerning the use of 3D printing technology in surgical simulation for dentistry. Among these, 16 studies focused specifically on the different technologies of printers and materials involved in 3D printing. Additionally, 5 publications provided reviews or covered topics outside the scope of this study.

The majority of the selected literature (23) (Addenda, Table 4) addressed procedures and surgical techniques with extraction being the most frequently described (7 publications), followed by osteotomy (4), Tumour removal (4) and implants placement (3).

Other procedures such as sinus elevation, periodontal surgery, cleft surgery and apicoectomy were each described by 2 publications.

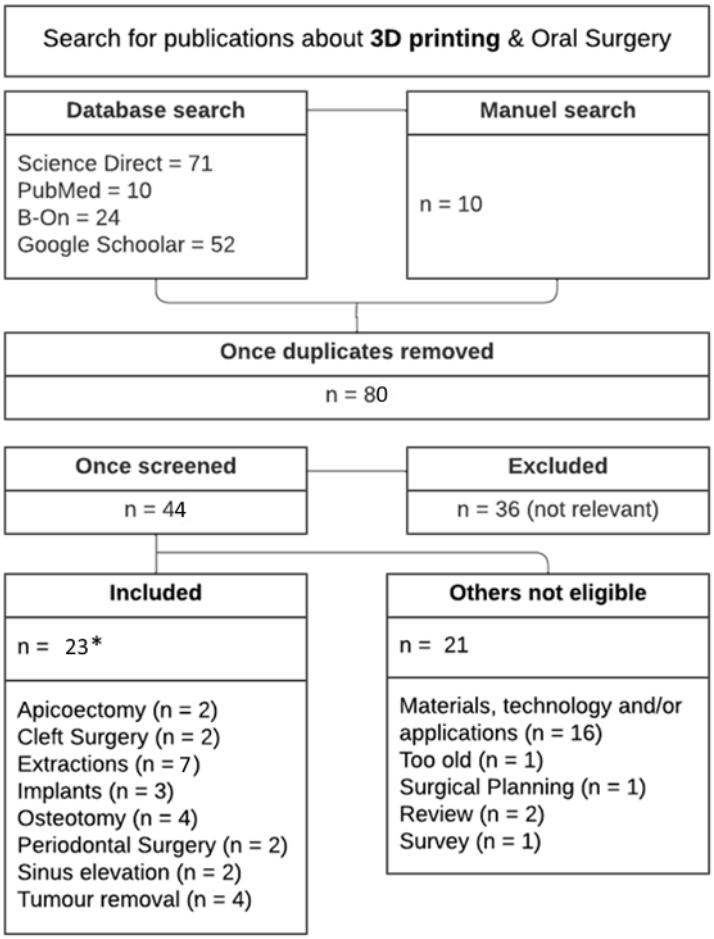


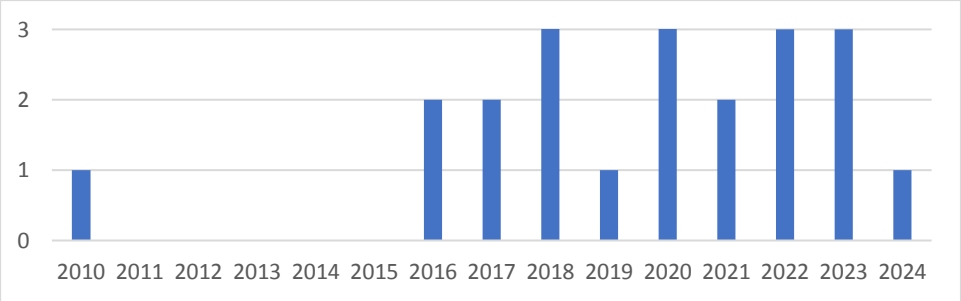
Figure 9: PRISMA flow diagram related to 3D printed models as surgical simulators

**: The total number of publications may differ from the cumulative number of procedures, as some articles describe several procedures.*

As already mentioned, comparative analyses with animal models were also explored in 3 publications. Seifert et al. (2020) compared 3D-printed models with pig models, suggesting both as realistic alternatives, with room for improvement for 3D-printed models. Feng et al. (2021) found that 3D-printed models outperformed pig models in simulating impacted third molar extraction, particularly in terms of anatomical fidelity of bone and teeth, and procedural simulation. However, both models yielded similar results for haptic feedback of the soft tissue. Finally, Chakravarthy et al. (2022) concluded that 3D-printed models offer a realistic alternative to cadaveric models (goats) in the training

of operational skills of dental practitioners with room for improvement for 3D-printed models.

A survey conducted by Poblete et al. (2020) aimed to identify topics, encompassing both knowledge and skills, within dental curricula that would benefit from the integration of 3D learning resources. The survey targeted 4th and 5th year undergraduate students, postgraduate students, dental graduates, and dental academics from three Scottish universities: the Universities of Dundee, Glasgow, and Aberdeen. A total of 128 participants contributed to the study. The results revealed that the most requested procedures for surgical simulation with 3D-printed models were dental anaesthesiology, suturing, and extraction techniques. Remarkably, despite their high demand, these areas have not been the subject of any study or publication.



Graph 4: No. of publications covering oral surgical procedures with 3D printed models

II. 3. 5. Virtual Patients

Virtual patients (VPs) are more commonly utilized in medicine than in surgery, with even less usage noted in oral surgery. However, through manual and automatic searches, 36 publications (Figure 10) on VPs were identified, broadly categorized into two main types: Web-SP and Serious Games, covering 20 years of publication (Graph 5), of which 8 were selected (see Addenda, Table 5). Additionally, a pilot study (Corrêa et al., 2003) was conducted during a period of emerging interest but already focused on surgical procedures such as anaesthesia, incision or suture techniques. Recently McAlpin et al. (2023) compared the learning outcomes of 2 types of whole task patient simulations, role-play and web-based, for local anesthesia and non-surgical extractions. The findings of McAlpin's are striking, with better results for role-playing games than for web-based patient simulation.

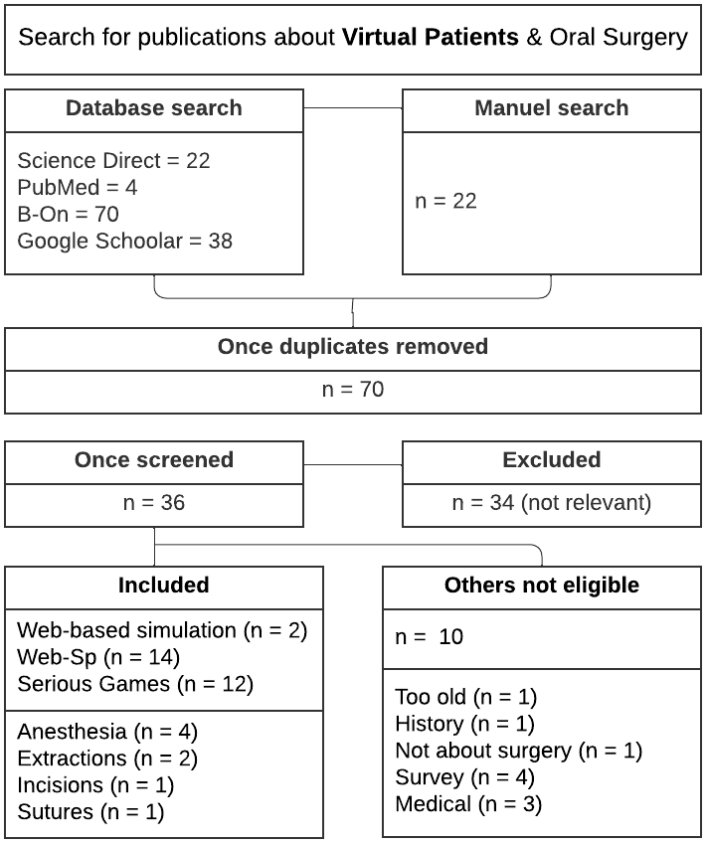
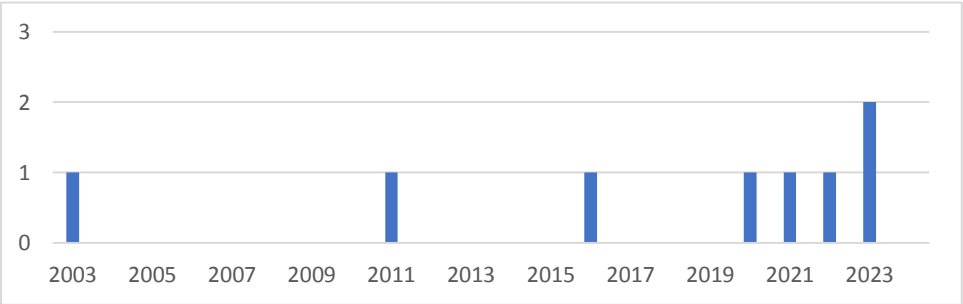


Figure 9: PRISMA flow diagram related to Virtual Patients models as surgical simulators

Nota: Procedures described with Virtual Patients are non-surgical in nature, as they primarily focus on soft skills such as decision making-process and procedural knowledge.

Notably, certain researchers consistently appear in this field, including Prof. Nabil Zary, the developer of Web-SP, Prof. Mihaela Botezatu and Prof. Håkan Hult, from the Karolinska Institutet in Stockholm, Prof. Rasa Mladenović from the University of Kragujevac in Serbia, and Elizabeth McAlpin from New York University. This suggests that the existing literature on VPs is limited and does not receive as much attention as the development of psychomotor skills.



Graph 5: No. of publications covering oral surgical procedures with Virtual Patients

Regarding surgical procedures, only 8 publications covering 2 main topics: local anesthesia (4) and extraction (4) were found. The results are varied, with methods that are

generally well-received by students and shown to improve knowledge and skills (Mladenović et al., 2022).

II. 3. 6. Haptics & Virtual Reality

Through our investigation (2004 to 2024, Graph 6), we observed that two sets of keywords “haptics” and “Virtual reality” yielded remarkably similar outcomes. This indicates the indispensable role of haptic devices in virtual reality experiences. This relationship is logical, as haptic feedback provided by simulators allows students to experience the tactile sensations crucial for developing psychomotor skills in dentistry. Consequently, VR training without haptic feedback may lack the realism and educational value needed for effective skill development in dental procedures. Given this state of affairs, the subsequent searches for these keywords were combined by an OR Boolean operand.

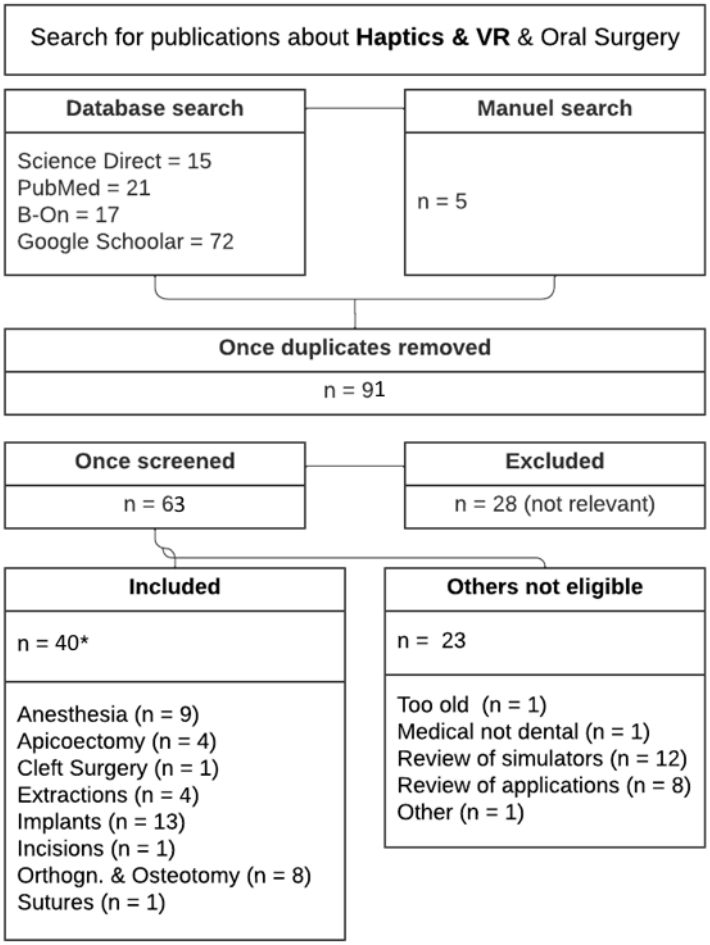


Figure 10: PRISMA flow diagram related to Haptics & VR models as surgical simulators

**: The total number of publications may differ from the cumulative number of procedures, as some articles describe several procedures.*

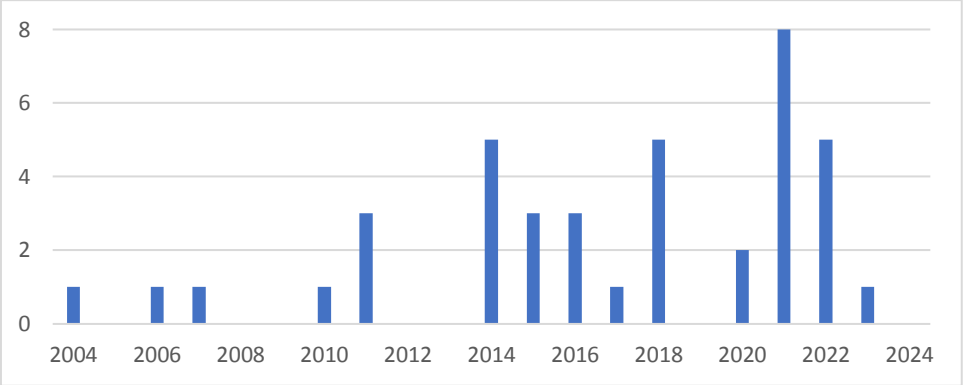
After screening, 63 publications were selected (Figure 11): 40 about surgical procedures (see Addenda, Table 6) and 23 primarily reviewing VR simulators or applications (12 and 8 respectively). Among the 39 articles on surgery, the most extensively studied topic one was implant surgery (13), closely followed by anesthesia techniques (9). From 2006 up to 2023, authors predominantly focused on drilling precision. Several simulators have been specifically designed and developed for this purpose. The Portuguese solution IMMPLANT (Zorzal, 2021) shows great promise for educating on implant placement. Additionally, we observe the evolution of the VirTeasy® haptic simulator from Joseph et al. study (2014) to Vincent's (2022) which incorporates virtual assistance during drilling to enhance drilling ability.

Anesthesia is another area of significant investigation from 2014 up to 2021. It started with the hapTEL solution (Cox et al., 2014) in the UK, the HDIS Simulator (Poyade et al., 2014) and the Vimet Odonto (Corrêa, 2015), all of which presented numerous improvements to be made. Subsequent studies by Pereira (2016) and Corrêa (2017) have shown promise, Vida Odonto (Tori et al., 2018) was approved for pre-clinical use. Finally, since Mladenović et al. (2020), Collaço et al. (2021), and Zafar et al. (2021), the VR simulation systems studied have made it possible to practice LA and IANB under near real conditions.

Other relevant procedures include Orthognatic/Osteotomy (8), which have shown improvement primarily with the advancement of Haptic force feedback devices and the increased number of DoF (Degree-of-freedom) they can handle. Apicoectomy studies amount to (4): Heiland et al. (2004), von Sternberg et al. (2007) and Pohlenz et al. (2010) conducted using the Voxel-Man simulator. A decade later, Buchbender et al. (2021) evaluated the new Kobra® simulator, noting that conventional training methods with plastic models are still favored despite the lack of significant difference.

Only 4 studies focus on extractions. Wang et al. (2015) conducted experiments to simulate the progressive changes of the connection strength between the tooth and its surrounding gingiva, exploring phases of movement of the target tooth but without incorporating the grasping motion of the forceps. Both Buchbender et al. (2021) and Lu et al. (2022) explored the Kobra simulator for the extraction of impacted lower third molars, but only removing the different tissues and without using forceps. Conclusion of Buchbender was resolute: computer-supported surgical simulation with the Kobra simulator cannot replace conventional training on the plastic model or on the patient.

At last, Diaz-Siso et al. (2016) presented two (2) virtual surgery simulators, Yoganathan et al. (2018) explored suturing methods using 360º VR video, while and Cheng et al. (2022) proposed a satisfactory virtual surgical system for training incisions.



Graph 6: No. of publications covering oral surgical procedures with Haptics & VR

II. 3. 7. Extended Reality, Augmented and Mixed Reality

The following researches inquiries were conducted simultaneously, each using the keyword "Extended Reality" (or Mixed Reality, Augmented reality respectively) in conjunction with the other terms defined in the materials and methods chapter such as "oral surgery", "simulation", etc. for the last 10 years (Graph 7) This process resulted in the compilation of the following Chart 4.

	XR	MR	AR
Science Direct	n = 3	n = 8	n = 31
PubMed	n = 1	n = 7	n = 30
B-On	n = 3	n = 24	n = 108
Google Scholar	n = 36	n = 225	n = 619
After screening and selection	**n = 10**	**n = 7**	**n = 30**

Chart 4: Results of XR, MR and AR models as surgical simulators

The search for "Extended Reality" yielded minimal results Out of ten publications retrieved, (9) were reviews, with the remaining one being a taxonomy of XR in the medical field (Spiegel et al., 2024). Thus, no studies specifically addressing surgical procedures were identified in this search.

The search for "Mixed Reality" returned even fewer results, with only 7 articles found. Surprisingly, none of these were reviews (and this was a sign deserving analysis). After excluding the book from Blanchard et al. (2022) that demonstrates how the HMD HoloLens® device can be used in common oral surgery, the remaining 6 described the

use of Mixed Reality in surgical procedures. Specifically, there were 2 studies on Tumor removal, 2 on Anesthesia and 1 on Apical surgery and 1 on Implants.

A total of 30 publications were selected and reviewed for “Augmented Reality”. Among these, one third (10) were reviews on applications, not always focused on dental or OMF surgery. Of the remaining 20 articles, 18 involved procedures with AR, including implant placement (7), anesthesia (5), apicoectomy (3), osteotomy (1), tumor removal (1) and Inferior Alveolar Nerve visualization (1).

After a careful reading of the 24 items (6 allegedly on MR and 18 supposedly on AR), a suspicion has crept into the interpretation of the concepts of AR and MR.

A research inquiry into possible discussions on the misinterpretation of Mixed Reality led to the discovery of the publication "Mixed Reality in Visceral Surgery: Development of a Suitable Workflow and Evaluation of Intraoperative Use-cases" by Igor M. Sauer et al. (2017), along with various articles in response. These articles argued that the technology described in the study by Sauer et al. should be considered AR rather than MR. This argument is based on the perceived lack of true integration and interaction between the real and virtual elements, as defined by the characteristics of mixed (Gheza & Raimondi, 2019; Queisner et al., 2019).

Indeed, superimposing 3D visualizations of anatomical structures onto the real surgical site is more aligned with the definition of AR than MR. Mixed Reality implies, according to the original definition by Milgram & Kishino in 1994, seamless integration and interaction between the real and virtual elements. The use of so-called Mixed Reality HMDs, as the claimed by Microsoft for HoloLens®, does not necessarily imply that the study or procedure corresponds to a true Mixed Reality display. Marketing is not science.

Given the ambiguity at the frontiers between AR and MR, several articles in the selection fell within the overlap between both definitions. Rather than definitively categorizing each item as either an AR or MR solution, a separate study would be necessary to address this issue; therefore, the decision was made to merge the results of both searches into a single category. This decision was particularly influenced by the limited number of publications on MR. Thus, 37 publications have been selected in total for AR/MR (Figure 11), of which 24 were dedicated to surgical procedures (see Addenda, Table 7).

Implant placements emerges as one of the most described procedures using AR/MR with a total of 8 publications dedicated to the subject. This literature ranges from pioneering studies in 2015, such as those by Lin et al. and Katić et al., which introduced methods for incorporating AR to reduce deviation during implant placement, to more recent advancements exemplified by Bochet's 2024 study. Bochet presented a pedagogical solution for novice surgeons, reflecting the evolution of navigation systems in implant dentistry.

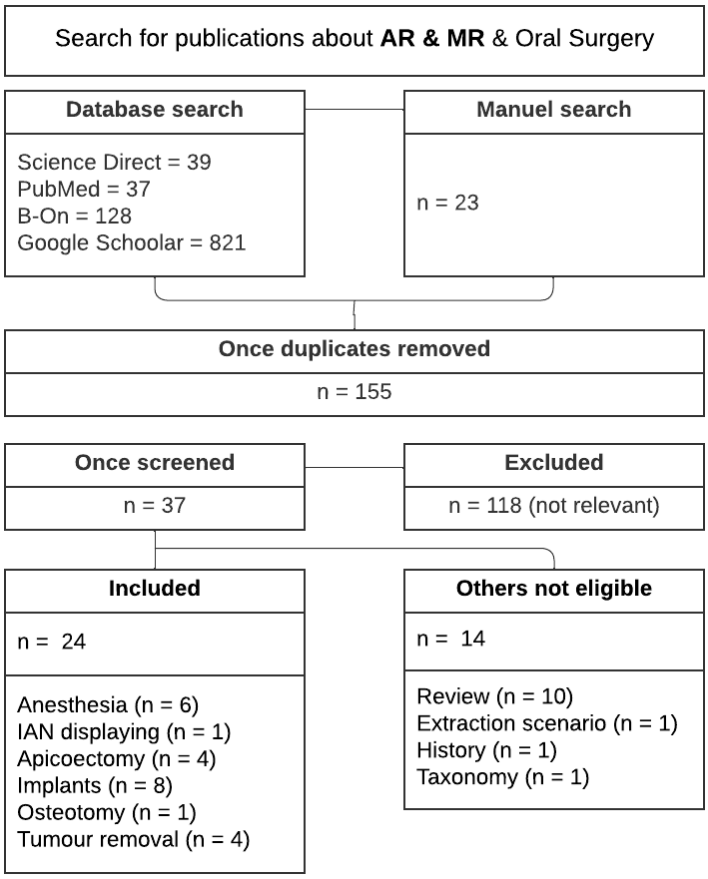
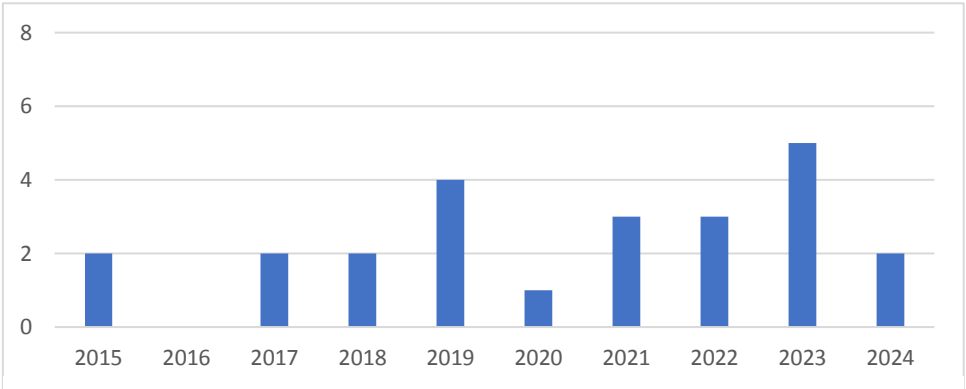


Figure 11: PRISMA flow diagram related to AR & MR models as surgical simulators

The concept of 'Navigation Systems', as primarily described by Fortin et al. in 1995, has experienced significant development and refinement over the years and innovative applications of AR technologies have further enhanced the precision, accuracy, and educational value of implant placement surgeries.

Anesthesia is the next item with several descriptions (6). Won et al. (2017) pioneered the application of AR during an inferior alveolar nerve block (IANB) injection. They generated 3D mandible images from CT scans of a patient's mandible and then overlaid them onto intraoral photographs by matching positions of teeth. In 2019, Mladenović, an author of several publications on teaching local anesthesia with new technologies, took

advantage of a Dental Simulator for iOS and Android to publish each year a new article about this AR simulator, discussing various applications and improvements, including for instance, its pediatric applications (2020).



Graph 7: No. of publications covering oral surgical procedures with AR & MR

Mladenović's perspective offers a remarkable reinterpretation of Augmented Reality, diverging from the conventional approach. Typically, in AR applications for dentistry, a virtual image such as bone structure, impacted tooth, tumor or CBCT image is overlaid onto the real image of the patient's mouth. However, Mladenović presents a contrasting viewpoint where the real image of the syringe, held by the student, is superimposed onto the virtual image of the mouth of a simulated patient. This inversion of the traditional AR model is a noteworthy departure, offering innovative possibilities for dental education and training.

Periapical surgery and apicoectomy have emerged as focal points of new interest in AR applications. Over the past two years, 4 publications have presented contrasting results. Bosshard et al. (2023) suggest that AR has the potential to be introduced into apicoectomy surgery once improvements are made. On the contrary, Remschmidt et al. (2023) observed excellent ratings from experienced surgeons, and Jia et al. (2022) consider the technique to have yield desirable outcomes with minimally invasive therapy. However, Tamayo-Estebaranz et al. (2024) presented a contrasting perspective, indicating that AR did not demonstrate statistically significant accuracy of osteotomies for apical location when compared with the conventional free-hand method.

Not far from periapical surgery is the removal of small tumors with 4 recent publications shedding light. Three of these studies utilized HoloLens® (Microsoft) HMDs, while the fourth employed HiAR G200 AR glasses. Sugahara et al. (2021), Scherl et al. (2021) and Shi et al. (2022) expressed very positive opinions regarding the use of AR technology

during tumor removal procedures. However, Sasaki et al. (2022), who conducted four other oral and maxillofacial (OMF) procedures in addition to the odontogenic tumor removal, concluded that current approach requires too many software components, making the process overly complicated. While not strictly a surgical procedure, the work of Zhu et al. (2017) deserves special mention for having developed an augmented reality (AR) system that displays the inferior alveolar nerve bundles prior to any OMF surgery.

Unlike other simulator models, another criterion needs to be highlighted for AR/MR. Out of the 24 reviewed articles, only 6 were training studies, while the others consisted of case reports (7) or research studies (11). This demonstrates how far AR/MR is still from being a fully developed teaching tool and may require some specific enhancements to fulfill that role.

Furthermore, out of these training studies, 5 focused on local anesthesia, while only 1 addressed implant placement. Three of these studies were led by Prof. Rasa Mladenović and different colleagues, 2 by Prof. Turkyilmaz utilizing the same SimToCare simulator and 1 by Lamira et al. (2023), who developed their own custom simulator 3D-printed from segmented images of an actual cadaver. Their innovative approach likely paves the way for designing the perfect, low cost training model utilizing various technologies to transform it into a reproducible simulator, with all the benefits derived from AR technology.

II. 3. 8. Perfused Cadavers

Of the 20 publications located about surgery on perfused cadavers, only one focused on OMF surgery (see Addenda, Table 8), which was significantly outside the scope.

Nevertheless, in January 2023, the University of Bologna, specifically the Centre of Clinical Surgical Experimental and Molecular Anatomy within the Department of Biomedical and Neuromotor Sciences under the leadership of Prof. Lucia Manzoli, organized a 2-day simulation program. During this event, Dr. Carlo Barausse from Bologna conducted a simulation of the sinus lift surgery with the lateral approach on a perfused cadaver using the SimLife® simulator. While no articles had been published on this program at the time, the following results were graciously provided by Dr. Barausse:

“The aim of our study was to push the re-vascularisation up to its limits testing it on small caliber vessels like the ones of the maxillary sinus. Moreover, we wanted to evaluate the

consistency and hydratation of the Schneiderian membrane, which is still one limit in simulating the technique. Specifically, the hydratation of the membrane with SimLife® technology was better and more realistic than the simple fresh donated body; however on the other hand the vascularisation was better but still far from the reality. In oral surgery, diameter vessels are small, a part in case of complications, so future evaluations could be done in my opinion in the management of complications, or on other surgical techniques like the interpositional block bone technique in the posterior mandible, which is closer to bigger diameter vessels."

II. 3. 9. Summary of results and procedures found

Excluding the results obtained with virtual patients (VPs), which form a separate category and cannot be compared, it is now possible to create a summary table of all procedures carried out with a simulator. The chart 5 allows for the comparison of their number and frequency to identify trends.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Anesthesia				8	9	6
Displaying IAN						1
Incisions	1				1	
Apicoectomy		3	2	1	4	4
Periodontal Surg.		5	2			
Extractions	1	5	6	3	4	
Implants	2	4	3	2	13	8
Sinus lift	2	7	2			
Biopsy		2				
Tumor removal			4			4
Bone harvesting	1					
Osteot./Orthogn. Surg.	2	3	4		8	1
Cleft Surg.		2	2		1	
Sutures	2	3		1	1	

Chart 5: Summary Chart of All Publications by Procedures and Technology

II. 4. DISCUSSION

II. 4. 1. Need of simulation

Worlwide, the oral surgery curriculum starts with a theoretical course and continues with a clinical programme. Students are expected to perform local anesthesia injections, extractions including third molars and apical surgery, minor surgical interventions covering reflection of the mucosal flap and suturing under the supervision of instructor surgeons.

Three studies respectively conducted in United Kingdom from 2006 to 2009, Saudi Arabia (2015) and the last one in Istanbul, Turkey (2019), revealed a positive correlation between the mean number of tooth extracted by the 4th and 5th year students and their clinical confidence. In U.K., a new graduate will have extracted an average of 51 teeth (Macluskey & Durham, 2009) they consider not being a large number over the three clinical years. In Istanbul, students extracted an average of 32,48 teeth (± 28,75) and reported a confidence level of 86% in performing simple extractions (Burdurlu et al., 2020). Similarly, in Saudi Arabia, students extracted an average of 25,3 teeth (range: 9-65) and reported a clinical confidence of 90,6% (Al-Dajani, 2015). The more clinical experience the students had, the more confidence they reported.

Another example is given by Turkyilmaz et al. (2023) stating that the IANB failure rates can be substantial and mostly due to the clinician's lack of technique rather than the anatomical variations seen in some patients.

The problem of potentially providing inadequate training to students is made worse by low number of available patients for surgical procedures like dental extractions or lack of appropriate clinical staff being available (Stacy, 1967; Siddiqui et al., 2021). The incorporation of simulation into dental education provides the opportunity to safely practice and developing procedural skills before performing them on patients (Perry et al., 2015).

II. 4. 2. Advantages and drawbacks

Fidelity

In 2004, Emad Aboud, who pioneered the research for pulsatile revascularized models, stated that a perfect training model is one that can provide the same situation during

surgery, in the same anatomy; the closer to live surgery the model is, the greater the benefit. Ensuring the highest fidelity is essential, and utilizing an authentic corpse with all the physiological characteristics of a living body provides unparalleled advantages.

Just as in the medical field, there are mannequins of low and high fidelity in a quest for a compromise between need, cost, availability, and implementation; it goes without saying that having a perfused cadaver to train incisions and sutures makes no sense.

Versatility

While the historical cadaveric model has been relatively well suited for various procedures, the arrival of new technologies is reshaping this landscape. As highlighted by Gernandt et al. (2023), 3D printing enhances the ability to expose trainees to a wide variety of pathologies and situations with different levels of complexity.

However, other immersive technologies are less versatile and require specific development for each application. For example, conservative dental simulators like Voxel-Man or Simodont, which are designed for caries treatments, are not suitable for oral surgery. Similarly, simulators designed for specific procedures, such as molar extraction, have a limited scope and cannot be used for interventions like endodontics or periodontal treatments.

The human body remains the best model for surgical training due to its adaptability across various procedures, followed by animal models and, to a lesser extent, 3D printing. However, human cadavers are also the most expensive option and have limited availability. Additionally, utilizing human cadavers requires specific infrastructure for handling, such as freezing facilities. Furthermore, once a tooth is extracted for training purposes, it cannot be reused, limiting the repeatability of certain procedures.

Repeatability

Virtual simulators offer a distinctive capability: the ability to replicate uncommon clinical scenarios that surgeons might not encounter otherwise (Agha & Fowler, 2015). This is the strength of virtual systems, which allow students to rehearse a procedure several times until they have mastered it perfectly.

3D printing can also serve as a valuable educational tool for students. The experiment carried out with a multicolored 3D-printed model for the marsupialization of a large

odontogenic keratocyst, demonstrated that interesting cases can be reproduced ad infinitum to teach students about rare cases they probably wouldn't have had the chance to find during their studies (Haribabu et al., 2023). This is also true for typical cases.

Psychological impact

On the negative side, in addition to cost, availability and difficulty of implementation, there can be the psychological impact. Students exposed to corpses have a higher frequency of psychological and mental alterations, according to studies carried out in the United States and Australia. (Gustavson, 1988) (Hancock et al., 1998). Obviously, 3D-printed and virtual solutions do not present this drawback as they also respond favorably to ethical considerations or cultural and religious factors.

Affordability

As mentioned by Dod et al. (2023), affordability of a training model is one of the most essential qualities it should possess. In that way, cadaveric models, human or animal, are not the best suited. Many authors have studied the impact of 3D printing as a low-cost model for education and concluded models of actual patient cases can be produced at a simple and cost-efficient manufacturing process, simulating many kinds of surgical procedures (Werz et al., 2018; Hu et al., 2022; Antunes et al., 2024).

II. 4. 3. About the distinction between Augmented and Mixed Reality

When considering the ongoing confusion surrounding augmented reality (AR) and mixed reality (MR), it is important to describe the features of each technology, especially within the realm of head-mounted displays (HMDs). Devices like Microsoft's Hololens® and 'Magic Leap' indeed offer users the capability to interact with virtual objects while simultaneously perceiving and navigating the real world. Gestures such as tapping, swiping, grabbing, or pinching enable users to manipulate virtual content seamlessly. But does this level of interaction alone justify categorizing the experience as mixed reality?

In addressing the practical application of Mixed Reality in surgical procedures, one might question the necessity of MR when projecting 3D images or holograms can already enhance surgical precision and safety, as highlighted by Sasaki et al. (2022). In procedures like implant placement, while projecting the 3D images resulting from a CBCT, one might question whether there is any benefit for the surgeon to manipulate the virtual images.

While proceeding with the resection of a maxillary tumor, as demonstrated by Sugahara et al. in 2021, if overlaying the holographic images of the tumor undoubtedly enables the safe performance of surgery, as the author himself admitted, what additional interaction could be incorporated? How about automatic, real-time reduction of the virtual image of the tumor as the surgeon resects the real one? That could be one of the future next steps in enhancing surgical precision…

II. 4. 4. Perfused or not perfused?

Cadavers are infrequently used in surgical education because of cost, limited availability and inability to simulate complications such as bleeding (Anastakis et al., 1999; Sarker & Patel, 2007). *Ex-vivo* studies also suffer from the absence of composed tissues and body fluids.

For ethical reasons, *in-vivo* studies are limited to animal experiments and are not valid for training while a pulsatile blood flow effects parameters such as pH, temperature, elasticity and fluid content of surrounding tissues. Moreover, blood flow itself influences the surgical procedure, impacting the application of biomaterial, haemorrhage and means of controlling bleeding.

This study has highlighted a new practice aimed at enhancing realism in both animal and human models:

As previously mentioned, van Erk et al. (2023) conducted a study using a perfused mandibular pig to perform a series of tasks, including an extraoral submandibular skin incision, elevation of the periosteum, drilling a bone defect in the mandible with a dental implant drill, filling the defect with a bone substitute, and applying a barrier membrane over the bone defect. Van Erk's conclusion extends beyond mere use in implant training: The model can be used for a number of purposes in dentistry and maxillofacial surgery, including the assessment of new dental haemostats, oral implants and surgical procedures in presence of challenging circumstances with heparinized full blood.

Similar full-body human cadaveric models were assessed by Faure et al. (2017) as training specimens for various surgical procedures. The realization of the sinus lift by Dr. Barausse of Bologna validated the use of perfused cadavers in oral and maxillofacial surgery, even if the vascularization of small vessels was incomplete.

II. 4. 5. Pre-operatory

Anaesthesia

Local Anesthesia, and more particularly, Inferior Alveolar Nerve Block (IANB) injections, have been the subject of 23 publications.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Anesthesia				8	9	6

Extract of Chart 5 for Anesthesia procedures

Two worlds collide: that of mannequins versus Extended Reality simulators. Whatever the brand, the former (in this case, Frasaco typodont) does not seem to attract much favor as sentenced by Marei et al. (2015): the real patient remains the gold standard in summative assessment of dental students' psychomotor skills. Lee et al. (2015) recommend it (Frasaco) for preclinical education, an opinion shared by López-Cabrera et al. (2017) (with Nissin models) and Knipfer et al. (2018) (also with Frasaco).

The virtual reality (VR) world offer a different vision. Zafar et al. (2021) concluded, VR can be used as an additional means of Local Anesthesia (LA) training. Similarly, Corrêa et al. (2017) saw it as a complementary tool in the IANB teaching procedure. The experimental VIDA Odonto simulator has been the subject of two studies. Tori et al. (2018) validated it to train dental students in the pre-clinical stage, while Collaço et al. (2021) considered the immersive VR simulator allowing the practice of the IANB under near-real conditions.

It seems that Augmented Reality is better suited for teaching Local Anesthesia. Mladenović successfully validated the use of the Mobile Dental Simulator for iOS and Android (2019), then in pediatric use (2020), and even as a tool for distance learning (2021). The current review identified two universities that have implemented the Mobile Simulator described by Mladenović in his studies: the University of Kragujevac (Serbia), as well as the University of Brisbane (Australia) with consistent and exceptionally much appreciated by the students. Turkyilmaz et al. (2023) also validated the use of another simulator, SimtoCare, which has been adapted by over ten universities.

All authors agree that learning local anesthesia, particularly for the IANB, should involve practice with a simulator before student-to-student practice and especially before administrating injections on real patients.

II. 4. 6. Inter-operative procedures

Apicoectomy

Apicoectomy is a compelling subject that has been explored by the different simulator models with the exception of cadavers.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Apicoectomy		3	2	1	4	4

Extract of Chart 3 for Apicoectomy procedures

The three studies using animal models are comparative in nature, allowing us to compare and determine the advantages and drawbacks of the different simulators. Von Sternberg et al. (2007) aimed to assess the VR Voxel-Man simulator, using apicoectomy on pig jaws as a reference. Seifert et al. (2020) compared pig mandibles with 3D-printed models, concluding that despite positive feedback from the students, the 3D-printed individualised patient models left room for improvement in terms of soft tissue simulation. Additionally, Bosshard et al. (2023), in measuring the accuracy of Augmented-Reality-assisted apicoectomy compared with template-guided methods, chose to conduct these experiments on pig mandibles. Animal models appear to serve as the primary reference in these evaluations.

Hanisch et al. (2020) compared a typodont model (manikin) with 3D printing, concluding that individual 3D-printed surgical training models based on real patient data offer a more realistic alternative than industrially manufactured typodont models.

Three different studies were conducted in 2004, 2007 and 2010 with the Voxel-Man Simulator (Heiland et al., van Sternberg et al., Pohlenz et al. respectively). Voxel-Man is a project from the teaching hospital of the University of Hamburg, started in 1984, which exists today in various versions, including Voxel-Man Dental, oriented towards cavity preparation and management of carious lesions. Heiland et al. (2004) concluded that realistic simulation of dental surgical procedures is possible. Van Sternberg et al. (2007) did not describe the qualities and faults of Voxel-Man but concluded it is effective for

virtual surgical training in reducing the rate of surgical complications. Pohlenz et al. (2010) using a modified version of the simulator for middle ear procedures, encouraged further development of the simulator.

In 2021, Buchbender et al. used a more recent oral surgery simulator, 'Kobra', with disappointing results: "Compared to the Kobra simulation, the conventional training method with plastic models was still favored" and qualifying it as "an additional method to conventional surgery training".

Most recent studies using Augmented Reality (AR) have opened new perspectives. Remschmidt et al. (2023) evaluated the Hololens 2® HMD on human cadaver heads and CBCT images. Three experienced surgeons conducted four AR-guided apicoectomies and gave an excellent rating. Another case report by Jia et al. (2022) using a very similar method, but this time with a real patient, successfully accomplished the removal of the inflammatory granulation tissue. Although Tamayo-Estebaranz, et al. (2024) nuanced these results, concluding that the AR technique did not show statistically significant accuracy of osteotomies for apical location when compared with the conventional free-hand method, the path to develop a training simulator based on the cases reported is open. Implementing Augmented Reality on animal models will likely allow future students to practice apicoectomies safely before performing them on real patients.

Periodontal Surgery

It appears that only two simulation models are currently available for training in periodontal surgery, with five studies utilizing animal models and only two employing 3D-printed technology. Can the latter potentially surpass animal models, given that it has been demonstrated that animal models, such as pigs or sheep, are considered valid options as teaching model?

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Periodontal Surg.		5	2			

Extract of Chart 5 for Periodontal surgery

Tomohisa et al. (2022) did not discussed this point but considered that the spread of 3D-imaging and 3D-printing technologies have made such surgical training exercises more practical and cost-effective. Their study aimed to assess the use of low-cost 3D models as valuable tool for achieving periodontal tissue regeneration (with fibroblast growth

factor-2) in teaching inexperienced dentists, such as resident dentists. Their conclusion is that 3D models can benefit all dentists, not just students, and resident dentists.

Antunes et al. (2024) reached similar conclusion in their study but also performed a more in-depth analysis. Reproduction of soft and hard tissues still needs improvement, but silicone technology is approaching reality. However, certain elements such as bleeding on incision, as well as nerves, arteries and veins are still missing. Nevertheless, two significant advantages of 3D-printed models over animal models are the cost (both in terms of model production and management) and the versatility and adaptability they offer in various clinical situations. For instance, the reproducibility of pathological situations that cannot be done with animal models is a notable advantage.

Extractions and impacted teeth

Exodontias training using simulator models is a more discussed procedure as all models have been explored with the exception of AR/MR.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Extractions	1	5	6	3	4	

Extract of Chart 5 for Extractions & Impacted teeth procedures

Animal models is a good reference as it allows to use elevator and forceps exactly the same way as real patients. Five studies explored the realism and benefits of animals, three of them considering it as a reference to assess 3D-Printed models. Pedersen in her thesis (2018) compare sheep and human tooth. Except for the first deciduous premolar, other sheep teeth are not realistic (see also Appendix E): Implementation of sheep as a teaching model could benefit the undergraduates by improving technical skills in periodontal surgery but not for extractions. As already seen, Siefert et al. (2020) compared 3D-printed model with pig jaws on osteotomy of impacted third molars concluding: the pig models achieved slightly better scores in the general evaluation of the reality of the simulation compared to the 3D-printed patient individualised models. In particular, the haptic feedback of the gingiva and mucosa of the pig was evaluated significantly more realistic than the silicone mucosa in the 3D-printed patient individualised models. Feng et al. (2020) who analyzed only extraction of impacted third molars and compared with pig mandibles, assessed the 3D-printed model but for pre-clinical dental students only. Siddiqui et al. (2021) in Australia recommend to practise the skill of tooth extraction on

pigs' heads due to the low number of available patients requiring dental extractions before clinical stage. Finally, Chakravarthy et al. (2022) compared 3-D models with goat jaws, these ones achieving better results in the haptic feedback of the soft tissue. However, the 3D-printed models were regarded significantly more realistic with regard to the anatomical correctness, the degree of freedom of movement and the operative simulation.

Going back in time to 3D-printed models, Lambrecht et al. (2010), at a time when silicone and materials were not yet realistic enough, saw the technology as an alternative method, promising for training due to its cost-effectiveness. Despite advancements in materials, Werz et al. (2018) reached the same conclusion. Participants rated bone simulation as 'good' but soft tissue simulation was still judged as 'moderate'. Yao et al. (2019), focusing solely on the impact of 3D-printed models on surgical skills, concluded that they have the potential to improve dental anatomy spatial representation ability, particularly for pre-clinical students. Lastly, in pediatrics, Chae et al. (2020) demonstrated that 3D-printed models for surgical extraction of supernumerary teeth improve the surgical skills of pre-clinical students who lack experience in this type of extraction.

Hanson et al. (2018) examined the question with Thiel embalmed cadavers comparing with mannequins (Frasaco) over a period of four years in U.K. Results showed extractions on cadavers was generally well received by the students. They had no moral or ethical issues about this model that offers a more realistic feel of extractions for novice students to learn the basic technique of extraction and should better prepare them to undertake their first extraction on a patient without the stress associated with the patient interaction. Similar conclusion is reached by Marei et al. (2015) with 4th year clinical students: the real patient remains the gold standard in summative assessment of dental students' psychomotor skills as they recommend mannequins only for pre-clinical training. Finally, Taysi et al. (2024) confirmed the use of mannequins (Nissin) for undergraduate dental students' (3rd year) felt more confident and ready for various aspects of their first clinical experience in oral surgery.

In reviewing the simulation models for extraction and impacted teeth, four studies analyzed the possibilities offered by haptics devices and Virtual Reality. One of the initial challenges with Virtual Reality is reproducing the realism of elevators and, above all, forceps. Lund et al. (2011) assessed an early version of the surgical VR simulator Kobra®, particularly when used with virtual patients but without forceps. In a research study, Wang et al. (2015) described how to manage force patterns with forceps in VR simulators.

Unfortunately, this functionality has not yet been implemented, as no commercial simulator offers it. As previously mentioned, both Buchbender et al. (2021) and Lu et al. (2022) evaluated the Kobra® simulator. Both studies concluded with nuances. While the simulator could enhance interns' learning experience and self-confidence, further improvement of current functions and more analytical studies of Kobra are necessary.

Implants

Implant surgery, excluding sinus lift procedures, stands as the realm where all simulation models have been explored, with a clear predominance for virtual reality (13) and augmented reality (8) models.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Implants	2	4	3	2	13	8

Extract of Chart 5 for Implant placements

Unquestionably, Hötlzle et al. (2012) endorsed the Thiel embalming method as a unique technique ideally suited for both practicing and teaching oral surgery and implantology on human specimens. Yu et al., a few years later (2020) meticulously measured and analyzed the impact of drilling parameters on drilling force using fresh human cadaver mandibular specimens, aiming to enhance the realism of force feedback to be used by future VR dental implant surgical training systems. Studies involving porcine models also contributed significantly. Katić et al. (2015) pioneered the use of pigs for initial experiments in augmented reality, while Zhang et al. (2020) utilized porcine mandibles to be compared with VR simulators in terms of performance in oral implant teaching. Additionally, van Erk et al. (2023) undertook the task of revascularizing porcine mandibles to heighten realism in oral surgery training scenarios. Once again, the animal model serves as the benchmark against which other systems are to be evaluated.

Implant dentistry is slowly becoming a necessary part of pre-clinical teaching in dental education with more universities including oral implant-related education in their undergraduate courses. (Zhang, 2020). Simulation is the remedy to address the lack of patients and the associated costs. As early as 2010, Güth et al. and in collaboration with the brand Frasaco, developed an 'implantation model' validated by students: The training of essential aspects of implant surgery and prosthetics, coupled with hands-on applications, appears to be an effective educational approach for fostering students'

interest and competence in the field of implant dentistry. In 2016, Stuart et al. produced an 'authoritative' document entitled "The use of 3D printing in Dental Implant Education" affirming the successful integration of 3D printed models in educating and training students at the International Implantology Program at New York University since 2012. Taking the process further, Hu et al. (2022) individualized models for unskilled students, enhancing learning in immediate implant procedures and provisionalization in the maxillary aesthetic zone. Their work demonstrated the feasibility of personalizing models while mass-producing them at a very low-cost for educational purposes.

Without going too deeply into the historical context of virtual reality applied to implants, it is worth mentioning Zhang et al. (2020), who compared the performance of students trained on pig jaws followed by virtual simulator practice with those who began with the simulator before practicing on pigs. The latter group achieved better results. Several simulators have been trialed, including the experimental IMMPLANT simulator (Zorzal et al., 2021), a custom-made simulator (Sukotjo et al., 2021), the VirTeasy Simulator (Vincent et al., 2022), and another custom VR simulator (Yang et al., 2023). All of these studies express enthusiasm and validate the use of simulators for implant surgery, demonstrating benefits for participants through repeated skills practice. A comparative benchmarking would be necessary and interesting to determine the specificities of each simulator, but that exceeds the scope of this work.

AR simulators for implants surgery are all Navigation Systems, as previously noted in the results section. The challenge lies in transforming a case report or research study into a training model. At present, only the SimtoCare simulator claims to be capable of training students for both implant site preparation (osteotomy) and implant placement (Turkyilmaz et al., 2023).

Sinus lift

Models for sinus elevation procedures present the characteristics of being strictly physical: cadavers, animals, and 3D-printed models. No Extended Reality simulator has been designed yet to train for sinus lift procedures. Similar to the challenges with forceps in extraction simulations, the technical difficulties in simulating this procedure are not yet within our reach.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Sinus lift	2	7	2			

Extract of Chart 5 for Sinus Lift procedures

Only two publications relatively old described a sinus augmentation using 3D. Somji et al. (2017) in a case report, explained how anatomical variations of the maxillary sinus make the use of 3D-printed models ideal for surgical preparation (Pre-operative simulation). Werz et al. (2018), in their intent to use 3D-printed models as an educational tool for sinus elevation, demonstrated that 3D printing with inexpensive 3D printers is a promising method to create training models. However, they noted the need to improve the simulation of soft tissue, specifically by increasing the thickness and durability of the silicone layer to better withstand tearing and damage.

Hölzle et al. (2012), in their study about the Thiel embalming method, validated various surgical procedures, even difficult tasks like bone graft harvesting, bone augmentation techniques, loading implants, and sinus floor elevations. Similarly, in their assessment of the piezoelectric technique for transcrestal maxillary sinus augmentation, also utilized cadaver heads.

Seven studies described and validated animal models for sinus augmentation: Goats, sheep or pigs, even dogs (Liu et al., 2013). Definitively, animal models is adequate for sinus floor elevation training (López-Niño, 2012) observing lateral sinus-wall thickness close to that of an edentulous patient, and Schneiderian membrane morphology and thickness identical to the human standard.

Tumor removal

Only two types of simulator models compete for prominence in training for tumor removal: 3D-printed models and Augmented Reality. Although they may seem like opposing solutions, each model has its own applications and could even be complementary.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Tumor removal			4			4

Extract of Chart 5 for Tumor removal procedures

Yusa et al. (2017) detailed, in a case report, the utilization of a full-size 3D-printed model for preoperative planning of surgical procedures, allowing for virtual surgery practice before tumor enucleation was performed on the patient. Following a similar rationale, but leveraging advancements in printers and materials, Haribabu et al. (2023) presented another case report on the marsupialization of a large keratocyst. This time, the procedure was planned using a multicolored 3D-printed model, enhancing visualization of the lesion during surgical planning. This approach also proved to be a valuable teaching tool for educational discussion of this case.

These two examples focus on pre-operative simulations for surgery planning. Augmented Reality (AR) will allow for intraoperative simulation. Sugahara et al. (2021) conducted a case report on the resection of a maxillary tumor using both techniques. They prepared a 3D model detailing the tumor resection domain and utilized Hololens® Head-Mounted display (HMD) to project images at different levels. This combination of a 3D model and HoloLens proved effective not only for intraoperative guidance but also for patient education and counseling. Similarly but without the 3D-printed model, Sasaki et al. (2022) tested the Hololens® HMD device in various oral surgical procedures, including the resection of a mandibular calcifying epithelial odontogenic tumor. They created a 3D image of the mandible, the tumor, and inferior alveolar canal, projecting it onto the surgical field to serve as a reference for determining the resection margin. However, despite these advancements, AR still faces challenges in being well-suited for student training, as it has been already showed with apicoectomies.

Nevertheless, as emphasized by Gernandt et al. (2023), in addition to improving students' learning curve, 3D printing for surgical training enhances the possibility to expose trainees to a wide variety of pathologies and situations of varying levels of complexity.

Other OMF procedures

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Displaying IAN						1
Incisions	1				1	
Biopsy		2				
Bone harvesting	1					
Osteot./Orthogn. Surg.	2	3	4		8	1
Cleft Surg.		2	2		1	

Extract of Chart 5 for other Oral and Maxillofacial procedures

When there are only one or two publications describing the surgical procedure, it is difficult to determine whether this mention is purely anecdotal or if it reflects an obvious practice that ultimately does not warrant specific study on the subject, as is the case for biopsy or bone harvesting.

Moreover, as mentioned in the PCC framework, the aim of this study was primarily to focus on simulators used for minor oral surgery, knowing in advance that the development of simulation systems is probably driven forward by maxillofacial surgeries. It is also worth mentioning that the survey of articles outside minor oral surgery has not been as thorough and exhaustive. These results are therefore only partial. Consequently, results concerning osteotomy, orthognathic or even cleft surgeries are not discussed, leaving readers concerned with OMF to consult the tables detailing publications in the addenda section at the end of this study if wished.

II. 4. 7. Post-operatory procedures

Sutures

Suturing presents limited options for simulation.

	Cadaver models	Animal models	3D-printed Models	Manikins	Haptics & VR	AR & MR
Sutures	2	3		1	1	

Extract of Chart 5 for suturing

In Extended Reality (ER), the study by Yoganathan et al. (2018) emphasizing 'significant merit' in the application of 360-degree VR video technology in surgical training stands out as the sole example. Conversely, the pragmatism demonstrated by Didhra et al. (2019) in developing a simple and cost-effective suturing model that simulates oral tissues and enhances the skills of medical trainees is particularly suitable for pre-clinical students. Ultimately, publications on physical models using cadavers (2) or animals (3) are the most relevant to the final two years of clinical training and validate realism that truly prepares students for suturing on patients (Macluskey et al., 2022; Zakhary et al., 2023).

II. 4. 8. Virtual Patients: after serious games, what's next?

The arrival of Artificial Intelligence (AI), accessible to everyone since 2022 with ChatGPT, is poised to again revolutionize decision-making training. Virtual patients

enhanced with artificial intelligence offer students a controlled, stimulating, and safe environment learning (Suárez et al., 2022). A descriptive cross-sectional study conducted in Madrid (Spain) involved the creation of a virtual patient using artificial intelligence in the form of a chatbot, which was presented to 193 fourth and fifth-year dental students. These students, particularly the fifth year, rated the interaction positively and exhibited higher satisfaction values.

Convergence

This evolution is complemented by the trend towards increasing the realism of Virtual Patients (VPs) with avatars, wherein skin and tissues are replicated by superimposing and merging 3D images. Research in this area continues to advance, with the hope that these developments will soon become integrated into the dental curriculum, serving as a valuable complement to face-to-face interactions with patients (Joda et al., 2018).

III. CONCLUSION

This study underscores that surgical simulation in dentistry extends beyond enhancing psychomotor skills; it also serves as an effective tool for knowledge acquisition and decision-making in diagnosis and treatment planning. Far beyond technical procedures, Doctors of Dental Surgery require comprehensive medical knowledge, diagnostic reasoning, surgical expertise, and a commitment to holistic patient care.

Six simulation models have been identified, and a classification has been proposed distinguishing between organic or body-based simulators (cadavers, animals and 3D printed models), and electronic, inorganic, and immersive simulators (Virtual Patients, Haptic Devices and Extended Reality systems). Furthermore, despite its significant contribution to improving realism and fidelity, body perfusion, for both human and animal models, was a subject that remained unstudied in the field of oral surgery.

The majority of authors consider the use of simulation as crucial to student training, viewing it as a mandatory intermediate step before the clinical phase on patients, in spite of associated costs or potential implementation challenges.

Almost all surgical procedures have been the subject of simulation studies, published using one model or another, particularly in the field of minor oral surgery. This means that there is always a simulation solution available before putting skills into practice on a real patient, and this fully meets the requirement of the Center for Medical Simulation in Boston, USA: "Never the first time on a patient".

Overall, the perfused human cadaver model emerges as the closest to reality, albeit the most expensive and difficult to implement. The animal model remains highly relevant, representing a viable compromise among all existing models. 3D-printed models present a cost-effective solution with significant potential for evolution and pedagogical advantages. Lastly, virtual and immersive models, despite technical progress in haptics and display, require further advancement, at least for the surgical part, to fully meet expectations and truly compete with other models.

Conflict of interest statement

One of the authors, Thierry LE DIVENACH, is a minority shareholder of Simedys SAS, manufacturer of the P4P (SimLife®) simulation device but he has no competing interests with this study. The rest authors declare that they have no competing interests.

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APPENDICES: ADDITIONAL FIGURES

Appendix A

Pre-operative: This phase involves preparing the patient for surgery.

- Anesthesia

Intra-operative: All the procedures that can be performed in Minor Oral surgery

- Extractions
- Exposure of buried teeth
- Impacted teeth
- Pre-Prosthetic Oral Surgery
- Biopsy techniques and excisions of intra-oral lesions
- Surgical Crown Lengthening
- Endodontic Periradicular Microsurgery (surgical endodontics)
- Management of Perioperative Bleeding
- Implantology
- Hard-tissue augmentation
- Soft-tissue surgery
- Removal of intra-oral salivary calculi and cysts
- Management of dental trauma and oral lacerations
- Management of oro-antral communications

Post-operative: begins after the surgery is completed

- Sutures

List of surgical procedures mentioned in the 'Atlas of Minor Oral Surgery Principles and Practice' (David A McGowan, 1989), 'Manual of Minor Oral Surgery for the General Dentist' (Karl R. Koerner, 2006), 'Manual of Minor Oral Surgery for the General Dentist' (Pushkar Mehra, Richard D'Innocenzo, 2016) and 'Minor Oral Surgery in Dental Practice' (John G Meechan & coll., 2006)

Appendix B

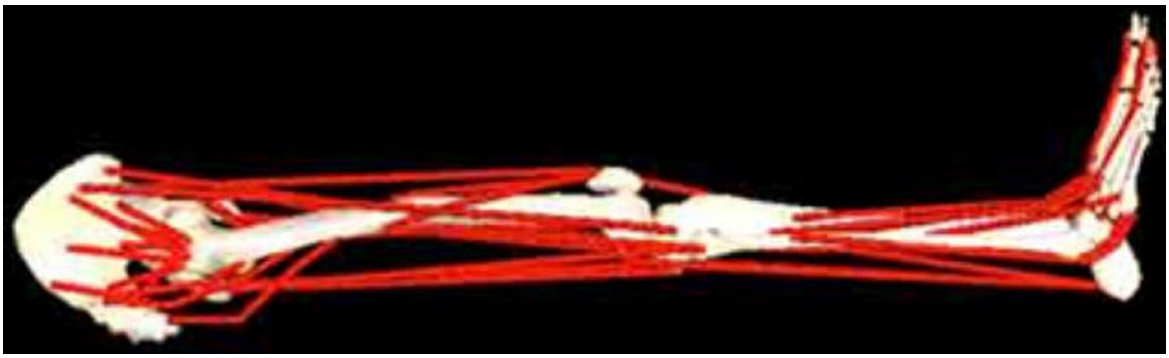
The art (skill)	The simulator for demonstration and practice
Specific forms of incision	Cuts in the body of a Pushpaphla a kind of gourd, Alávu, watermelon, cucumber, or Erváruka
Cuts in the upward or downward direction	As above
Excisions	Openings in the body of a full water bag, or in the bladder of a dead animal, or in the side of a leather pouch full of slime or water
Scraping	A piece of skin on which the hair has been allowed to remain
Venesection (Vedhya)	The vein of a dead animal or with the help of a lotus stem
Probing and stuffing	Worm (Ghuna) eaten wood, or on the reed of a bamboo, or on the mouth of a dried Alávu (gourd)
Extracting	Withdrawing the seeds from the kernel of a Vimbi, Vilva, or Jack fruit as well as by extracting teeth from the jaws of dead animal
Secreting or evacuating	The surface of a Shálmali plank covered over with a coat of bee's wax
Suturing	Pieces of cloth, skin, or hide
Bandaging or ligaturing	Tying bandages round the specific limbs and members of a full-sized doll made of stuffed linen
Tying up a severed ear-lobe (Kama-sandhi)	Soft severed muscle or on flesh, or with the stem of a lotus lily
Cauterizing, or applying alkaline preparations (caustics)	A piece of soft flesh
Inserting syringes and injecting enemas into the region of the bladder or an ulcerated channel	Insert a tube into a lateral fissure of a pitcher full of water or into the mouth of a gourd (Alávu)

Surgical simulators described in the Sushruta Samhita (extracted from Simulation in Healthcare Education: An Extensive History from Harry Owen (2016)

Appendix C

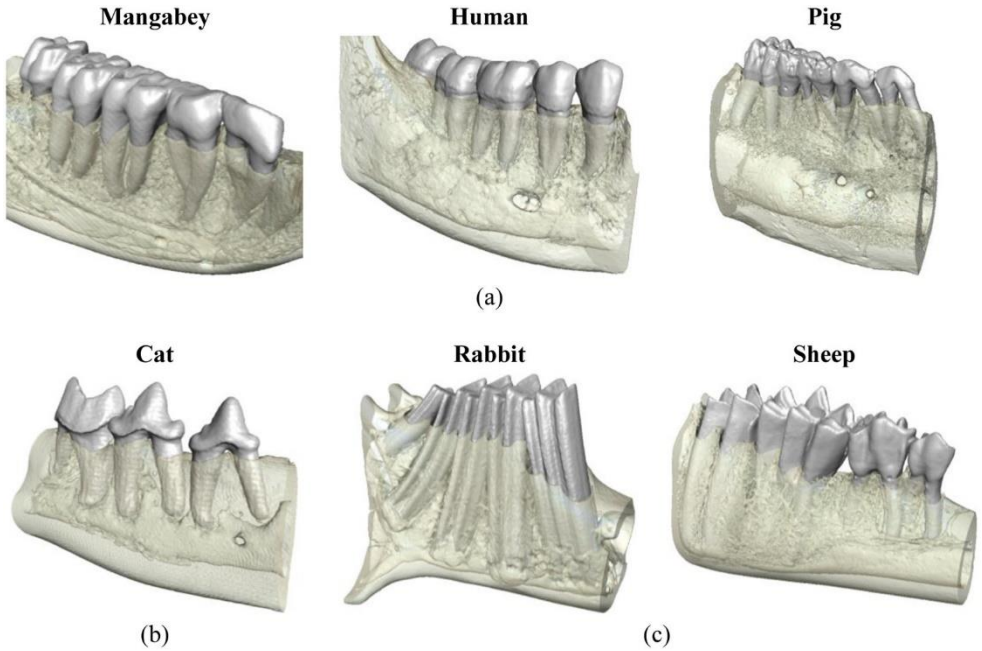
Surgical simulator at the University of Salamanca, Spain. Made in 1570.
Probably the first known mannequin (Credit: University of Salamanca)

Appendix D



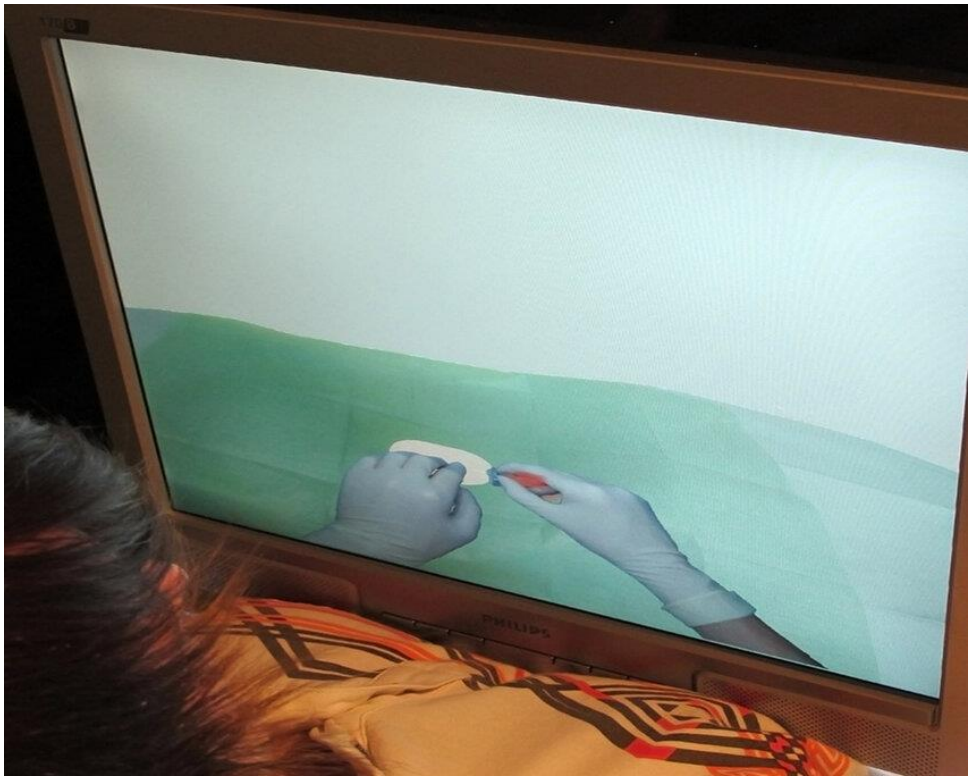
One of the first VR simulator: Leg simulator developed by Scott Delph and Joseph Rosen of Stanford University in 1987 to practice Achilles' tendon repair.

Appendix E



3D visualisations of the post-canine mandibular corpus. The species display diverse molar shapes and functions, namely: (a) molars with flattened or rounded cusps-mangabey, human and pig; (b) blade-shaped molars-cat; (c) flattened molars with ridges-rabbit and sheep.

Appendix F



Training simulator for needle puncture guided by palpation. An example of augmented virtuality where the scene of the virtual patient is augmented with the trainees real hands.
(Picture extracted from "Integrating Haptics with Augmented Reality in a Femoral Palpation and Needle Insertion Training Simulation" by Timothy R. Coles et al. – 2011)

ADDENDA: TABLES

Tables of summary characteristic of included studies of models used in simulation

Table 1: Summary characteristic of included studies of Cadavers used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Peuker, E. et al. (2001)	Surgical procedures in mouth, jaw and facial surgery in Thiel embalmed body donors	Can human cadavers embalmed according to Thiel be used for research and education in oral-maxillo-facial surgery?	Study	Mucosal incision in the the mandible Detachment of the muco-periosteum in the mandibular arterial region	Thiel's embalmed cadavers	(the authors)	Thiel's embalming technique applied to human cadavers provides an optimal basis for research and for basic and postgraduate medical education
2	Hölzle, F. et al. (2012)	Thiel embalming Technique: A valuable method for teaching oral surgery and implantology	Does Thiel embalming method provide suitable conditions for the oral surgery?	Training	Sinus floor elevation and other implantological procedures	30 Thiel's embalmed cadavers	6 courses using 5 cadavers for 10 participants each (dentists, oral surgeons or maxillofacial surgeons)	Cadavers embalmed in the technique described by Thiel have remarkable advantages for running oral surgery and implantological courses.
3	Kienle, M. (2012)	Cadaver Training in the Education of Orthognathic Surgery	Are there better methods than computer simulation to introduce training oral surgery residents to orthognathics?	Training	Various orthognathic surgeries	Cadavers	12 OMFS interns and residents	Cadaver lab training of surgical clinical experience of orthognathic surgery is a promising and effective training medium for oral and maxillofacial surgery residents.
4	Walker, M. et al. (2013)	Orthognathic Surgery Simulation Using Cadavers	To gather data regarding oral surgery residents experience with simulated orthognathic surgery training	Training	Orthognathic surgeries	Cadavers	180 residents	Surgical simulation, specifically in the cadaver lab has the potential to be a promising and effective tool for training oral surgery residents in orthognathic surgery.
5	Kühl, S. et al. (2016)	Transcrestal maxillary sinus augmentation: Summers' versus a piezoelectric technique - An experimental cadaver study	To compare the performance of conventional hand instruments using mallets and osteotomes with that of piezoelectric–hydrodynamic devices	Study	Maxillary sinus floor elevation	17 undamaged cadaver heads	(the authors)	Both techniques generate expedient augmentation volume in the posterior atrophic maxilla. The piezoelectric technique can be recommended as an alternative tool to graft the floor of human maxillary sinuses.

Table 1: continued (Cadaver models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
6	Hanson, C. et al. (2018)	Do dental undergraduates think that Thiel-embalmed cadavers are a more realistic model for teaching exodontia?	To compare Thiel-embalmed cadavers to mannequins.	Training	Exodontia	Thiel's embalmed cadavers versus Frasaco models	174 second year students with the cadaver group and 108 in the mannequin group	The use of Thiel-embalmed cadavers to teach exodontia was well received by dental students, who felt they were a more realistic model for extractions than the mannequin
7	Yu, D. et al. (2020)	Measurement and prediction of drilling force in fresh human cadaver mandibles: A pilot study	Measuring force feed-back for a VR dental implant surgical training system	Study	Drilling in implant surgery	2 fresh human cadaver mandibles	(the authors)	Magnitude of the drilling force decreases with patient/donor age, which indicates that bone density has a significant effect on the drilling force.
8	Watanabe, M. et al. (2020)	The Usefulness of Saturated Salt Solution Embalming Method for Oral Surgical Skills Training: A New Cadaveric Training Model for Bone Harvesting	To assess the usefulness of SSS embalmed cadavers for oral surgical skills training	Training	Bone graft harvesting	8 cadavers	22 participants including oral surgeons, residents, and dentists	The usefulness of the SSS-embalming method was established for oral surgical skills training
9	Macluskey, M. et al. (2022)	An Educational Evaluation of Thiel Cadavers as a Model for Teaching Suturing Skills to Dental Students during the COVID-19 Pandemic	Utility of the Thiel cadaver for teaching suturing skills.	Training	Placing sutures from extra-oral to anterior intra-oral proceeding to posterior intra-oral.	Thiel cadavers	57 fourth year dental students	The students' perception of the cadaver model for teaching suturing skills was positive and the majority felt that this model prepared them for suturing on patients.
10	Zakhary, I. et al. (2023)	Preclinical Suture Laboratory Effectiveness on Dental Student Clinical Experience: a pilot study	To evaluate the students' perception of the effectiveness in preparing them for performing sutures.	Training	Interrupted continuous, continuous locking, horizontal & vertical mattress, and "figure 8" suture.	Skin of cadaver arms	Second year dental students	The data indicated that, within this study population, early clinical exposure appeared to have a positive impact on the learning experience of this sample of pre-doctoral dental students.

Table 2: Summary characteristic of included studies of animal models used in simulation

N°	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Kirker-Head, C. et al. (1997)	A New Animal Model for Maxillary Sinus Floor Augmentation: Evaluation Parameters	To illustrate the utility of the goat model for the maxillary sinus augmentation procedure	Training	Maxillary sinus floor augmentation	6 adult female in-vivo goats	(the authors)	A new animal model was successfully developed to assess the safety and efficacy of rhBMP-2/ACS implants in inducing bone growth in the maxillary sinus floor.
2	Al-Qareer, A. et al. (2004)	A sheep cadaver model for demonstration and training periodontal surgical methods	Suitability of periodontal surgical model for training	Training	Gingivectomy, distal wedge, flap suturing with sling, continuous or interrupted sutures, etc.	Mandibles of 11 ex-vivo freshly slaughtered Australian sheep	(the authors)	The sheep mandible seems to be a feasible training model for the demonstration and exercise of various periodontal surgical techniques for the treatment of periodontitis.
3	Von Sternberg, N et al. (2007)	Learning by doing virtually	To show the value of performing virtual training prior to clinical surgical training	Training	Apicoectomy	Pig jaw versus VR Voxel-Man	41 students	Training with a virtual apicectomy simulator appears to be effective, and the skills are transferable to physical reality.
4	Estaca, E. et al. (2008)	Maxillary sinus-floor elevation: an animal model	To find an animal model for modified Caldwell-Luc procedure training	Training	Maxillary sinus-floor elevation	12 fresh heads: 4 sheep, 4 goats and 4 pigs	(the authors)	The cortical bone thickness and Schneider membrane characteristics in sheep and goat allow a perfect training for the modified Caldwell–Luc procedure
5	Fenner, M. et al. (2009)	Influence of residual alveolar bone height on osseo-integration of implants in the maxilla: A pilot study	Evaluation of minimum bone height of residual bone	Study	Sinus floor elevation and implant placement	In-vivo 8 mini-pigs	(the authors) [46 implants placed]	Simultaneous implant placement yields a sufficient degree of osseointegration
6	Derong, Z. et al. (2010)	Anatomic and histological analysis in a goat model used for maxillary sinus floor augmentation with simultaneous implant placement	To provide accurate and definite anatomic parameters for the design of sinus floor elevation and dental implantation studies in goat model.	Study	Maxillary sinus floor augmentation	10 adult ex-vivo goats	(the authors)	The site and shape of the maxillary sinus of goats are similar to that in humans, and the sinus is close to maxillary teeth roots.

Table 2: continued (Animal models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
7	Stelzle, F & Benner, K. (2010)	An animal model for sinus floor elevation with great elevation heights. Macroscopic, microscopic, radiological and micro-CT analysis: ex vivo	To investigate the suitability of pigs as a model for sinus floor elevation training and research with great elevation heights.	Training	Sinus floor elevation	34 pig heads	(the authors)	The maxillary sinus of adult domestic pigs is a suitable model for sinus floor elevation training and research with greater elevation heights of up to 10 mm.
8	Denadai, R. et al. (2012)	Does bench model fidelity interfere in the acquisition of suture skills by novice medical students?	To compare 3 bench models in the acquisition of suture skills by novice medical students.	Training	Simple interrupted sutures and subdermal interrupted sutures	- Theoretical suture training - Synthetic ethylene-vinyl acetate model - Pig feet skin	36 medical students	The acquisition of suture skills on the low-fidelity bench model was similar to that of the Pig feet skin model, and both were superior to those who received training based on theoretical teaching materials.
9	López-Niño, J. et al. (2012)	Lamb ex vivo model for training in maxillary sinus floor elevation surgery: a comparative study with human standards	To compare the thickness of the lateral wall of the maxillary sinus and the thickness of the Schneiderian membrane between an animal model and the human standard.	Study	Sinus floor elevation	20 fresh lamb heads 30 patient Studies & 5 cadaveric human head	(the authors)	The model based on lambs completely fulfills the criteria for an adequate model for Sinus floor elevation training. Lateral sinus-wall thickness close to that of an edentulous patient, and Schneiderian membrane morphology and thickness identical to the human standard.
10	Seoane, J. et al. (2012)	Simulation for training in sinus floor elevation: New surgical bench model	To describe a bench model for sinus floor elevation training and to assess effectiveness.	Training	Sinus floor elevation	36 fresh sheep heads	36 postgraduate students	Simulation procedures (workshop of abilities) are perceived by the partakers as useful for the surgical practice.
11	Elagib, M. (2013)	The use of animal model heads for demonstration and training of periodontal surgery techniques among undergraduate dental students of KKU	Suitability and feasibility of animal model heads in the training of some periodontal surgery methods	Training (conference paper)	Gingivectomy modified Widman Flap with interrupted & continuous sutures, coronal & apically repositioned flaps with sutures.	Animal model heads (goats and sheep)	Undergraduate dental students.	Freshly slaughtered sheep and goats' heads are good model for training of the undergraduate dental students in the periodontal surgical techniques.

Table 2: continued (Animal models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
12	Seoane, J et al. (2013)	Simulation for training in oral cancer biopsy: a surgical model and feedback from GDPs.	Describe a new bench model for biopsy	Training	Biopsy and simple interrupted suture	Pig tongue	424 general practitioners by pairs	There is a need for including clinical abilities workshops when instructing on oral biopsy techniques.
13	Larsen, P. et al. (2013)	Pig Model Versus Sheep Model in Undergraduate Periodontal Surgical Training	To compare the sheep to pig models for periodontal surgical training	Training (conference paper)	Pocket depth, gingival width, gingivectomy, Simple and sling sutures for access, coronal and apical flaps, wedge procedure	10 sheep and 9 pigs	Fourth-year students	The sheep model is a valid option as a teaching model for undergraduate students, compared to the widely used pig model.
14	Liu, N. et al. (2013)	A comparative study of dog models for osteotome sinus floor elevation and dental implants in posterior maxilla subjacent to the maxillary sinus	To investigate the suitability of beagles and Labrador retrievers as animal models for osteotome sinus floor elevation and dental implants.	Study	Osteotome sinus floor elevation and dental implants.	10 adult female ex-vivo beagles and 8 adult female ex-vivo Labrador retrievers	(the authors)	Labrador retrievers are more suitable as animal models and provide a wider range of choices than beagles through macroscopic, histologic, and CT observation.
15	Shen, P. et al. (2014)	Stability study of total temporomandibular joint replacement on sheep	To evaluate the stability of custom-made prosthesis by establishing the model of sheep TMJ replacement	Study	Condyle, coronoid process and articular disc removed and replaced with prothesis	Sheep heads from 6 in-vivo sheep	(the authors)	The custom-made TMJ prosthesis which was designed and manufactured has good stability after total TMJ replacement.
16	Zangrando, M. et al. (2014)	Pig Mandible as a Valuable Tool to Improve Periodontal Surgery Techniques	To describe the pig model for training periodontal surgical techniques and evaluate the effect on student's progress	Training	6 procedures: Distal wedge, gingivectomy, Frenectomy, Bevel incision, flaps, membranes, graft & sutures	25 pig mandibles	25 graduate students	Pig mandible is a valuable tool to learn periodontal surgery techniques.

Table 2: continued (Animal models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
17	Katić, D. et al. (2015)	A system for context-aware intraoperative augmented reality in dental implant surgery	To develop an AR system for dental implant surgery to reduce information overflow and offer intuitive image guidance.	Study	To place two implants in the mandible	Customed context-aware AR with HMD on a Pig cadaver	(the authors)	The system allowed to fully concentrate on the surgery itself. It offered greater flexibility since the surgeon received all relevant information, but was free to deviate from it. Accuracy to be improved.
18	Ioannou, I. et al. (2015)	Comparison of oral surgery task performance in a virtual reality surgical simulator and an animal model using objective measures.	How does performance in a simulator resemble in the operating theatre	Training	Wisdom tooth extraction surgery	Ovine jaw versus VR simulator	14 fourth year dentistry students	It is difficult to identify clear relationships between automated simulator outcome measures and expert assessments in the physical world.
19	Pedersen and Richardsen (2018)	The sheep head model for educational purposes in periodontal and oral surgery for dental undergraduates	Suitability of the sheep maxilla as a teaching model (Thesis)	Training	Oral surgery: Extractions, impacted tooth, Biopsy, sutures	19	Pedersen and Richardsen (2018)	The sheep head model for educational purposes in periodontal and oral surgery for dental undergraduates
20	Seifert, L. et al. (2020)	3D-printed patient individualised models vs cadaveric models in an undergraduate oral and maxillofacial surgery curriculum: Comparison of student's perceptions	To compare students' perceptions of 4 surgical procedures between animals to 3D-printed models	Training	Dissection of a mucoperiosteal flap. Osteotomy of impacted third molars. Dissection of a free mucosal graft. Resection of a root tip.	Porcine mandibles versus 3D printed models	38 fourth-year students	Both models are realistic alternative with room for improvement for 3D-printed models
21	Zhang, B. et al. (2020)	Virtual versus jaw simulation in Oral implant education: a randomized controlled trial	Investigate the evaluation methods of teaching oral implant clinical courses and estimate the effectiveness of a virtual simulation platform.	Training	Implant placement:	Pig mandible versus virtual simulation system (Zhonghui, UniDental-MS01, China)	80 second- and third-year undergraduates	Virtual simulation education, especially with a jaw simulation model, could improve students' implantology achievements and training.

Table 2: continued (Animal models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
22	Feng, J et al. (2021)	Three-dimensional printed model of impacted third molar for surgical extraction training	Compare 3D-printed models to animals	Training	Extraction of impacted mandibular third molars	Pig mandible versus Rigid photopolymers covered with silicon	205 questionnaires by oral surgeons and students	3D-printed model was better than the animal model in terms of total value, anatomy of the bone and teeth, simulating the surgical procedure, while the 2 models achieved similar results for haptic feedback of the soft tissue.
23	Siddiqui, Z et al. (2021)	Using simulation to learn surgical skills in Oral Surgery: What do students think?	Students' perception of animal tissue to enhance oral surgical skills.	Training	Tooth extraction	Pig heads	48 students	Students perceived that Pig's heads can be effectively used to provide a safe and efficient learning environment to practice surgical skills.
24	Chakravarthy, C et al. (2022)	Comparative Evaluation of Hybrid 3D-Printed Models versus Cadaveric Animal Jaws: A Student's Perspective	Compare 3D-printed mandible to an animal jaw model	Training	Extraction of impacted third molar	Bovine (goat) jaw	41 dental interns and practitioners	The 3D-printed models presented a realistic alternative to cadaveric models in the training of operational skills of dental practitioners.
25	Zhong, J. et al. (2022)	Assessment of a developed pig cadaver model for teaching crown lengthening surgical procedures	To assess the feasibility and efficacy of teaching crown lengthening surgical procedures using a prepared pig cadaver model	Training	Periodontal surgery: crown lengthening procedures	Mandibles of pigs with subgingival crown fracture defects on 2 premolars and 2 molars on each side	20 resident students and 18 instructors/teachers	The pig mandible model can be a feasible, effective, and well-accepted simulation for the teaching and training of crown lengthening surgical procedures.
26	Lutz, R. et al. (2023)	An ex vivo model for education and training of unilateral cleft lip surgery.	Develop an inexpensive, widely available, high-fidelity, ex vivo model	Training	Cleft surgery	Porcine snout disc	16 young medical professionals	The porcine snout disc ex vivo model of unilateral cleft lips is very suitable for teaching and training beginners.
27	Huang, H. et al. (2023)	The pilot study of a blended learning module using porcine tongue for surgical simulation of double-opposing Z-plasty	Develop a blended learning module with low-cost and easy-to-promote DOZ simulation.	Training	Double-opposing Z-plasty surgery	6 porcine tongues	41 Oral surgery residents	The blended learning module incorporating the cleft palate simulator based on porcine tongue can help oral surgery residents practice DOZ palatoplasty.

Table 2: continued (Animal models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
28	Van Erk, M. et al. (2023)	A novel ex vivo perfusion-based mandibular pig model for dental product testing and training	Validate a novel perfusion-based mandibular surgery model.	Training	Oral implants: skin incision, elevation of periosteum, drilling bone, filling defect and application of membrane	Perfused mandibular pig	10 dental professionals and 7 trainees	Validity a novel perfusion-based mandibular pig model for barrier membrane research
29	Bosshard, F et al. (2023)	Accuracy of AR-assisted vs template-guided apicoectomy – an ex vivo comparative study	To compare accuracy of AR to template	Study	Apicoectomy	Pig jaw, Microsoft HoloLens 2 and SMOP software	(the authors) *[40 apicoectomies in 10 pig mandibles]*	The 2 methods were found to be comparable with regard to accuracy

Table 3: Summary characteristic of included studies of mannequins used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Güth, J. et al. (2010)	Description and evaluation of a new approach on pre-clinical implant dentistry education based on an innovative simulation model	To enhance competence level and practical implementation of implant dentistry at an early stage of education	Training	Insertion of 2 standard implants and mounting of a pre-existing full denture for edentulous mandible	30 implant simulation models developed in collaboration with Frasaco	120 second-year pre-clinical students	The introduction of a pre-clinical course of implant dentistry based on this implant-simulation model received excellent evaluations by the participating students.
2	Marei, H. et al. (2015)	Assessment of dental students' psychomotor skills using oral surgery simulation models	To determine the validity of using oral surgery simulation models as a tool to assess the psychomotor skills of dental students.	Training	Local anesthesia. Extractions	Phantom heads, bench-mounted, AG-3, Frasaco and Extraction model of 32 metal teeth in CR Ni-steel, A-EM, Frasaco	23 dental students in the 4th year of a 6 years dental program	The use of oral surgery simulation has been proved to enhance cognitive, psychomotor skills but the real patient remains the gold standard in summative assessment of dental students' psychomotor skills.
3	Lee, J. et al. (2015)	Evaluation of a Local Anesthesia Simulation Model with Dental Students as Novice Clinicians	To evaluate the use of a local anesthesia simulation model before first inferior alveolar nerve block injection.	Training	(IANB) inferior alveolar nerve block injection	Local anesthesia simulation model by Frasaco	60 dental students	The results of this study suggest that the use of a local anesthesia simulation model in a small group setting may be one way to improve the transition for students from preclinical education to clinical education and patient care.
4	Prasad, S. & Bansal, N. (2017)	Predoctoral Dental Students' Perceptions of Dental Implant Training: Effect of Preclinical Simulation and Clinical Experience	To compare perceptions of dental students with didactic training versus those with didactic plus simulation training.	Training	Hands-on training in implant restorative procedures	Implant placement in fake mandible	160 dental students	Students who had simulation training with clinical experience responded better in almost all categories of implant restorations than those without simulation training or clinical experience.

Table 3: continued (mannequins)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
5	López-Cabrera, C. et al. (2017)	Positive influence of a dental anaesthesia simulation model on the perception of learning by Mexican dental students	Influence of three-repetition training with a dental anesthesia simulation model on the perception of learning.	Training	(IASAN) infiltrative anaesthesia technique for the anterior superior alveolar nerve	Typodont conduction anaesthesia model (SUG2005-UL-SP; Nissin) fixed in a phantom head (Nissin) adapted to the back of a Gnatus dental chair	20 second-year students of a 5 years dental program	Students trained with the simulation model showed higher values for perceived confidence in performing an injection and perceived hand control when compared with students without training.
6	Knipfer, C. et al. (2018)	Local anaesthesia training for undergraduate students - How big is the step from model to man ?	To evaluate the relation between training-model and real-life anesthesia performance	Training	(IANB) Inferior alveolar nerve block	Special anesthesia training model (AG 3 IB, Frasaco).	36 third-year students	The anesthesia success rate on mannequin models did not imply an equal performance on the in vivo setting. Local anesthesia training models are just a valuable didactic complement.
7	Foley, J. & McDonald, A. (2018)	A clinical skills teaching-aid for paediatric minor oral surgery	To describe the preparation of a cost-effective teaching model for paediatric minor surgical procedures.	Training	supernumerary-/canine removal	Surgical simulator made with dental plaster with KaVo model teeth and Aquasil Ultra Silicone	(the authors)	Such a surgical simulator can be readily constructed to provide a relatively inexpensive teaching aid for paediatric minor oral surgical procedures.
8	Didhra, G. et al. (2019)	Improved Suturing Model for Surgical Simulation	To develop a simple and cost effective suturing model that simulates the oral tissues and enhance skills.	Training	Sutures: Simple loop, continuous, interrupted sling, etc.	Synthetic sponge of 5-6 mm thickness with a 5 mm thick layer of polyvinyl siloxane impression material and covered with a Macintosh sheet.	(the authors)	Construction of a suturing model that is easy to fabricate and simulates the oral tissues will indeed be beneficial for periodontal surgical training.

Table 3: continued (mannequins)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
9	Reyes-Acuca, M. et al. (2020)	Learning of the mental nerve block technique with dental anaesthesia simulation models builds motor skills and confidence in dental students	To compare 2 distinct dental anesthesia simulation models	Training	(MNB) mental nerve block	Conduction anaesthesia model (MES, Nissin), and the infiltration anaesthesia jaw model (INJ, Nissin)	44 dental students	The learning protocol with two different Dental anesthesia Simulation models had a positive effect on the motor skills and the confidence of dental students performing the mental nerve block.
10	Merino-Parra, J. et al. (2020)	Impact of two distinct dental anesthesia simulation models on the perception of learning by students	To compare the perception of learning with two distinct dental anesthesia simulation models	Training	(MNB) mental nerve block	Conduction anesthesia model (Nissin), and the infiltration anesthesia jaw model (IAM; Nissin)	36 dental students	Dental Anesthesia Simulation training with a conduction or infiltration model increased the perception of knowledge for Mexican dental students. The practice of both models had a similar positive impact on the perception of learning.
11	Hanisch, M. et al. (2020)	3D-printed surgical training model based on real patient situations for dental education	To compare 3D individualized surgical training models for apicoectomy against a typodont model.	Training	Root tip resection (apicoectomy)	3D models/meshes with Mimics (Materialise, Belgium) and Rhinoceros 5 (McNeel, Spain) versus -J OP OK (Frasaco, Germany)	35 students for the typodont model and 33 students for the 3D-printed model.	Individual 3D-printed surgical training models offer a more realistic alternative to industrially manufactured typodont models.
12	Martínez-Melo, K. et al. (2023)	A homemade simulation model improves the impact of e-learning for the practical administration of dental anaesthesia	To compare the impact of two homemade simulation models	Training	Basic injection technique of dental anaesthesia	Lemon versus Styrofoam head	56 dental students	The online learning with a Styrofoam head had a positive effect on the confidence of the dental students and on their attitude towards online learning.

Table 3: continued (mannequins)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
13	Garcia-Blanco, M. et al. (2024)	Student training in administering inferior alveolar nerve block anesthesia with a simple manufactured simulation model	To compare the effectiveness of administering IANB for the first time with or without a previous practical lesson using a simple manufactured simulator.	Training	(IANB) Inferior alveolar nerve block	Simulation model created by 3D printing of the jaws and teeth, assembled by screws and nuts. Soft tissues made with regular addition silicone, and molded manually.	60 dental students	Students who used simple manufactured simulators achieved better outcomes for instrument handling, and possibly for identification of anatomical landmarks, than those who received only theoretical lessons.
14	Taysi, A.E. et al. (2024)	Evaluation of the efficacy of a simulation model used in oral and maxillofacial surgery education	To investigate the efficacy of training on a tooth extraction model and perception.	Training	Extraction	Tooth Extraction Model SUG2004-UL-SP-DM-28 (Nissin)	136 dental students 71 undergraduate in the third year and 65 in the fourth year	It is clear that students who have not started seeing patients, benefit from increased practice with training models, which adequately reflect and represent real-life situations encountered in everyday practice.

Table 4: Summary characteristic of included studies of 3D printed models used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Lambrecht, J. et al. (2010)	Haptic model fabrication for undergraduate and postgraduate teaching	Describe a technique to create haptic models to demonstrate complex anatomic situations, instructing students and planning operations.	Study	Extractions	3D models based on CBCT datasets produced by the PolyJet Matrix method on Objet Connex 500	(the authors)	Generating 3D models based on CBCT datasets may become a useful technique for demonstrating, planning and teaching.
2	Stuart, J. et al. (2016)	The Use of 3D Printing in Dental Implant Education	To discuss the basic principles and applications of three-dimensional printing for educational use in implant dentistry	Training	Immediate implant placement lateral to the IAN, ridge split and sinus augmentation procedures	3D models (Formlab USA) Rapid prototyping, additive technique	12 post-graduate students	Generating 3D models based on CBCT datasets has promising potential for implant education, for understanding, planning and surgical practice.
3	Lioufas, P. et al. (2016)	3D printed models of cleft palate pathology for surgical education	To explore the potential viability and limitations of 3D printed models of children with cleft palate deformity.	Training	Cleft palate	Magnetic resonance imaging data of 2 children (8 and 14 months)	(the authors)	Improvements of imaging combined with printer technology will make feasible 3D-printed replicas potentially suitable for surgical training.
4	Somji, S. (2017)	The use of 3D models to improve sinus augmentation outcomes – A case report	To focus on how a 3D model is useful when undertaking a sinus augmentation procedure with simultaneous implant placement.	Case report	Sinus augmentation	3D printing (Formlabs, USA) for production of a polymer model of the maxilla.	(the authors)	Having an exact 3D model of a patient's sinus anatomy available for a clinician to study and use for simulation of the lateral window sinus augmentation procedure is a great advantage
5	Yusa, K. et al. (2017)	Three-Dimensional Printing Model as a Tool to Assist in Surgery for Large Mandibular Tumour: a Case Report	To present an effective use of the three-dimensional printing model in exploring complex spatial relationship between the tumour and surrounding tissue.	Case report	Enucleation of large tumour	A full sized 3D model printed by a ZPrinter 450 (Z Corporation, USA) with silicone gum for the tumour	(the authors)	Effective application of a novel hybrid three-dimensional printing model composed of hard and soft tissues that can bring significant benefits, especially to the field of oncological surgery.

Table 4: continued (3D-Printed models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
6	Werz, S. et al. (2018)	3D Printed Surgical Simulation Models as educational tool by maxillofacial surgeons.	To evaluate whether inexpensive 3D models can be suitable to train surgical skills to dental students or oral and maxillofacial surgery residents.	Training	Sinus lift and wisdom teeth extraction	Jaw models produced with 3D desktop printers and silicon rubber for soft tissue simulation.	10 blinded, experienced maxillofacial surgeons	3D printing with inexpensive printing filaments is a promising method for training oral and maxillofacial surgery residents or dental students in selected surgical procedures.
7	Chou, P- et al. (2018)	3D-printed models of cleft lip and palate for surgical training and patient education	To describe the methods used to create a suite of modular 3D models of cleft conditions	Study	Cleft lip and palate	Bone printed in ABS plastic (solid) using the Fortus 3D printer (Stratasys, MN).	30 patients	The digital suite of 3D models is modular and made from multiple materials, and can be utilized to demonstrate a large spectrum of clinical issues related to cleft conditions.
8	Reddy, G. et al. (2018)	Training Young Maxillofacial Surgeons or Trainees Using Additive Manufacturing	To explore the benefits of 3D models in maxillofacial surgery	Training	Orthognatic, resection, reconstructive and TMJ surgeries	Additive manufacturing 3D-printed models	Maxillofacial trainees	3D-printed model can allow a young doctor to bypass the limitations of cadaver model
9	Jiang, W. et al. (2018)	Evaluation of the 3D Augmented Reality–Guided Intraoperative Positioning of Dental Implants in Edentulous Mandibular Models	Evaluation of the 3D AR-Guided Intraoperative Positioning of Dental Implants in Edentulous Mandibular Models	Training	Implant placement	12 rapid prototyping mandibular models in 3D printing (Western Time, 3D Systems)	2 experimented surgeons	Dental implants can be placed using this proposed 3D augmented reality–guided system with less than 1.5 mm deviation and less than 5.5º angular deviation
10	Yao, C. et al. (2019)	Measuring the impact of simulation practice on the spatial representation ability of dentists by means of Impacted Mandibular Third Molar (IMTM) Surgery on 3D printed models	Measuring the impact of simulation practice on the spatial representation ability of dentists by means of Impacted Mandibular Third Molar (IMTM) Surgery on 3D printed models	Training	Extraction (removal of impacted mandibular third molar on 3D printed model)	3D models provided by AMMA, Hong Kong with bone-like rigid material and mucosa-like soft tissues.	21 young dentists	Practice on 3D printed, anatomically precise models can benefit dentists on pre-clinical surgical training and has the potential of improving their dental anatomy spatial representation ability.

Table 4: continued (3D-Printed models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
11	Seifert, L. et al. (2020)	3D-printed patient individualised models vs cadaveric models in an undergraduate oral and maxillofacial surgery curriculum: Comparison of student's perceptions	To compare students' perceptions of 4 surgical procedures between animals to 3D-printed models	Training	Dissection of a mucoperiosteal flap. Osteotomy of impacted third molars. Dissection of a free mucosal graft. Resection of a root tip (apicoectomy).	Porcine mandibles versus 3D printed models	38 fourth-year students	Both models are realistic alternative with room for improvement for 3D-printed models
12	Hanisch, M. et al. (2020)	3D-printed surgical training model based on real patient situations for dental education	To compare 3D individualized surgical training models for apicoectomy against a typodont model.	Training	Root tip resection (apicoectomy)	3D models/meshes with Mimics (Materialise, Belgium) and Rhinoceros 5 (McNeel, Spain) versus -J OP OK (Frasaco®, Germany)	35 students for the typodont model and 33 students for the 3D-printed model.	Individual 3D-printed surgical training models offer a more realistic alternative to industrially manufactured typodont models.
13	Bertin, H. et al (2020)	Bilateral sagittal split osteotomy training on mandibular 3-dimensional printed models for maxillofacial surgical residents	To present a 3-dimensional printed mandibular model for BSSO training in a maxillofacial surgical education programme.	Training	Bilateral sagittal split osteotomy (BSSO)	A polymethacrylate mandibular model obtained from CBCT	24 residents	The mandibular model provided a realistic way of handling the trabecular bone after cortical osteotomy, as well as in the splitting phase.
14	Chae, Y. et al. (2020)	Validation of a three-dimensional printed model for training of surgical extraction of supernumerary teeth	To validate a three-dimensional (3D) printed model to provide training for supernumerary teeth (SNTs) extraction.	Training	Supernumerary teeth (SNTs) extraction	3D models printed with DIO PROBO with Light-cured resin material (DIOnavi-Mode)	30 participants (residents, interns and dental students)	A 3D-printed model for surgical extraction of a SNT can improve surgical skill and shorten the beginners' learning curve.

Table 4: continued (3D-Printed models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
15	Feng, J et al. (2021)	Three-dimensional printed model of impacted third molar for surgical extraction training	Compare 3D-printed models to animal models	Training	Extraction of impacted mandibular third molars	Pig mandible versus Rigid photopolymers covered with silicon	205 questionnaires by oral surgeons and students	3D-printed model was better than the animal model for total value, anatomy of bone and teeth, simulating the surgical procedure but offered similar results for haptic feedback of soft tissue.
16	Sugahara, K. et al. (2021)	Mixed reality and three dimensional printed models for resection of maxillary tumor: A case report	To treat a maxillary calcifying odontogenic cyst using MR, 3D-printed and designed application for Microsoft® HoloLens	Case Report	Resection of an odontogenic cyst	Hololens® with 260 Connex, Stratasys 3D printer and UNITY & Visual Studio Community	(the authors)	Incorporation of MR in the preoperative planning and intraoperative visualization of the oral and maxillofacial regions resulted in a precise and safe surgery performance.
17	Chakravarthy, C et al. (2022)	Comparative Evaluation of Hybrid 3D-Printed Models versus Cadaveric Animal Jaws: A Student's Perspective	Compare 3D-printed mandible to an animal jaw model	Training	Extraction of impacted third molar	Bovine (goat) jaw	41 dental interns and practitioners	The 3D-printed models presented a realistic alternative to cadavers in the training with room for improvement for 3D-printed models
18	Tomohisa, O. et al. (2022)	Application of Medical Imaging and 3D Printing Technology in Teaching the Handling of Novel Medicine in Periodontal Surgery	To enhance instruction in the handling of new medicine in addition to teaching conventional procedures in periodontal tissue regeneration.	Training	Treatment of periodontal disease with fibroblast growth factor-2 (FGF-2)	3D printer Value3DMagiX MF-800 (MUTOH) in resin, colored vinyl tape and Silicon (Multisil-Mask Soft)	4 Resident dentists with little clinical experience and 2 instructors	The case-specific 3D models are a cost-effective tool for more efficient teaching by using them as a tool to assist in the acquisition of surgical skills.
19	Yoshida, S. et al. (2022)	Osteotomy training for dental students using three-dimensional simulation software and maxillofacial three-dimensional-printed models	To compare osteotomy performed on 3D models after participating in simulation lecture with osteotomy performed after performing self-simulation with MSS	Training	Le Fort I osteotomy and bilateral sagittal split osteotomy	Maxillofacial simulation software (MSS) Pro Plan CMF (Belgium) versus 3D-printed model (Objet 260 Connex, Stratasys, USA)	24 fifth-year undergraduate dental students	Incorporating MSS and 3D printed models in the curriculum will help accelerate student development.

Table 4: continued (3D-Printed models)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
20	Gernandt, S. et al. (2023)	Contribution of 3D printing for the surgical management of jaws cysts and benign tumors: A systematic review of the literature	To assess the contribution of 3D printing in the management of benign jaw lesions.	Review of 13 articles from 2017 to 2022	Cysts & keratocysts, mesiodens, odontoma and supernumerary teeth	Anatomical models and surgical guides made with 3D printed models	13 studies involving 74 patients	3D printing technologies to manage benign jaw lesions results in less invasive procedures by facilitating precise osteotomies, reducing operating times, and complications.
21	Haribabu, P. et al. (2023)	Model-assisted marsupialization of a large odontogenic keratocyst in the maxillofacial region using a multicolored 3D-printed model: A novel approach in surgical planning and teaching.	To describe the use of a multicolored 3D-printed model as an interactive visual aid for the surgical planning and management of an odontogenic Keratocysts	Case report	odontogenic keratocysts (OKCs) marsupialization and enucleation	3D model printed with an advanced multicolor Stratasys J750 printer	(the authors)	The use of the multicolor 3D-printed model for treatment of OKC improved visualization of the lesion during surgical planning and is a valuable teaching tool for educational discussion of cases.
22	Hu, L. et al. (2023)	Patient-specific 3D printed models for enhanced learning of immediate implant procedures and provisionalization	To describe the fabrication, implementation and evaluation of 3D-printed patient-specific models for unskilled students to enhance learning in immediate implant procedures and provisionalization.	Training	Immediate implant placement and provisionalization (IIPP) in the aesthetic zone	3D models in resin (Dental Series; Rayshape) using a 3D printer (Shape 1 Dental; Rayshape)	30 third-grade postgraduate students	The patient-specific and cost-efficient 3D printed models are helpful for students to improve theoretical knowledge and practical skills.
23	Antunes, D. et al. (2024)	3D-printed model for gingival flap surgery simulation: Development and pilot test	To describe the manufacturing of an in-house pedagogical model for gingival flap surgery simulation	Training	Gingival surgical flaps, incisions and sutures	3 rigid parts printed using the Ultimaker S5 dual-extrusion fused deposition modelling printer (Ultimaker, Utrecht, Netherlands)	37 participants (31 dental students, 5 residents and 1 senior surgeon)	3D printing technology offers new possibilities for training in dental treatments that are currently difficult to replicate.

Table 5: Summary characteristic of included studies of Virtual Patients used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Corrêa, L. et al. (2003)	Teaching oral surgery to undergraduate students: A pilot study using a Web-based practical course	To describe and evaluate a Web-based practical course on oral surgery principles, which was applied to undergraduate students.	Training	Anaesthesia, incision and suture techniques	Web site created for the survey	22-two dental undergraduate students (2nd and 3rd semester)	Training deficiencies were expected, especially in surgical instrument manipulation and inadequate incisions and sutures were observed. Ergonomic is essential, as well as exhaustive tests and simulations
2	Lund, B. et al. (2011)	Student perception of two different simulation techniques in oral and maxillofacial surgery undergraduate training	To investigate students' perception of two different simulation methods for practicing clinical reasoning skills and technical skills.	Training	Mandibular third molar surgery and tooth sectioning in third molar surgery	Forsslundsystem AB Oral Surgery Simulator with haptic device and Web-SP	47 dental students during their final year	The two tested simulation methods were well accepted and the majority of the students agreed that both simulation techniques should be included in the curriculum.
3	Weiner, CK et al. (2016)	Implementation of a web-based patient simulation program to teach dental students in oral surgery	To evaluate a web-based simulation of patients (Web-SP) program on learning skills in clinical reasoning and patient evaluation.	Training	Extraction	Web-SP with 8 Patient Cases	67 third-year students	The results suggest that Web-SP is a valuable tool for oral surgery education.
4	McAlpin, E. (2020)	The Effects of Patient Simulations on Dental Student Learning	To determine the impact of each type of simulation on student learning using various assessments to measure the impact.	Training	Local anesthesia and extractions	Web-SP		
5	McAlpin, E. et al. (2021)	Summative assessments of web-based patient simulations of pre-clinical local anaesthesia and non-surgical extraction	To evaluate the use of Web-SP on learning outcomes regarding cognitive, psychomotor and professional interpersonal skills	Training	Local anaesthesia and non-surgical extractions.	2 Web-SP	365 second-year, dental students	The statistically significant results on the student-recorded role-play patient video project suggest that the Web-SP as a formative assessment type is a useful scaffolding tool to prepare students for this summative assessment.

Table 5: continued (Virtual Patients)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
6	Mladenović, R. et al. (2022)	Effectiveness of technology-enhanced teaching methods of undergraduate dental skills for local anaesthesia administration during COVID-19 era: students' perception	To determine the effectiveness of a serious game as an additional teaching tool to improve dental students' local anaesthesia administration technique and confidence.	Training	Local anesthesia infiltrative and inferior alveolar nerve block	Serious game: Mobile simulator application (Dental Simulator v1.13 for iOS and Android)	19 Fourth-year dental students	Serious games of local anaesthesia procedures as an additional e-learning tool during the COVID-19 era could improve students' knowledge and skills.
7	Huang, Y. et al. (2023)	Dental interns' perceptions of immersive simulated reality scenarios for local anesthesia learning	To explore the effect of dental students' perceptions of immersive simulated reality scenarios for local anesthesia learning.	Training	Local anesthesia: Left inferior alveolar nerve block on a hypertension patient for tooth 38 extraction	HTC Vive immersive virtual reality apparatus combined with Serious game developed for the purpose of teaching	21 dental interns	The immersive simulated reality scenarios could help dental students to memorize the steps in local anesthesia and may empower dental students to fulfill their role and treatment for patients in further clinical settings.
8	McAlpin, E. et al. (2023)	Comparing two whole task patient simulations for two different dental education topics	Which simulation model allows for deeper cognitive engagement that fosters higher learning outcomes for novices practicing complex skills as a professional	Training	Local anaesthesia and non-surgical extractions	Web-SP versus Role-play	115 Second year pre-clinical dental students.	Results suggest that role-play simulations achieved a higher level of learning outcomes than the web-based patient simulation.

Table 6: Summary characteristic of included studies of Haptics & Virtual Reality models used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Heiland, et al. (2004)	Realistic haptic interaction for computer simulation of dental surgery	To portray new algorithms for realistic haptic rendering and sensations.	Training	Apicoectomy	Voxel-Man	40 dental students	Realistic simulation of dental surgical procedures, even in complex anatomical models, is possible.
2	Kusumoto, N. et al (2006)	Application of virtual reality force feedback haptic device for oral implant surgery	To try a novel support system for implant surgery	Training	Oral implant insertion	Haptic device PHANToM used with a 3D CT image	(the authors)	The average misalignment is less than 0.2 mm, and it indicates that the present system is potentially applicable to oral implant surgery.
3	Von Sternberg, N et al. (2007)	Learning by doing virtually	To show the value of performing virtual training prior to clinical surgical training	Training	Apicoectomy	Pig jaw versus VR Voxel-Man	41 students	Training with a virtual apicectomy simulator appears to be effective, and the skills are transferable to physical reality.
4	Pohlenz, P. et al. (2010)	Virtual dental surgery as a new educational tool in dental school	To assess the surgical ear simulator Voxel-Man for intraoral procedures	Training	Apicoectomy	Voxel-Man simulator	53 students	51 of the 53 students recommended the virtual simulation as an additional modality in education validating force feedback and spatial 3D perception.
5	Yu, H. et al. (2011)	Preliminary study of virtual orthognathic surgical simulation and training	To explore the feasibility of tree-structure architectonic model in realizing virtual orthognathic surgical simulation.	Training	Le Fort I osteotomy, ramus osteotomy and genioplasty	CT scanner of 4 patients with skeletal malocclusions and Simplant software	(the authors)	Craniomaxillofacial 3D virtual surgical simulation system can be used in orthognathic surgical planning, simulation, and operation training.
6	Casap, N. et al. (2011)	Evaluation of a Navigation System for Dental Implantation as a Tool to Train Novice Dental Practitioners	To compare the benefits of a VR navigation system for teaching the surgical stage of dental implantation with freehand protocols	Training	Dental implantation	Denex Image Guided Implantology	40 final-year undergraduate dentistry students	Despite the improved performance with the navigation system, the added value of training in dental implantation surgery with virtual reality navigation was minimal.
7	Lund, B. et al. (2011)	Student perception of two different simulation techniques in oral and maxillofacial surgery undergraduate training	To investigate students' perception of two different simulation methods for practicing clinical reasoning skills and technical skills.	Training	Mandibular third molar surgery and tooth sectioning in third molar surgery	Forsslundsystem AB Oral Surgery Simulator with haptic device and Web-SP	47 dental students during their final year	The two tested simulation methods were well accepted and the majority of the students agreed that both simulation techniques should be included in the curriculum.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
8	Joseph, D. et al. (2014)	Relative contribution of haptic technology to assessment and training in implantology	To assess the usefulness of haptic device, a simulator for learning and training to accomplish basic acts in implant surgery.	Training	Drilling procedure for implant placement	VirTeasy simulator	60 people including 40 third-year dental students and 20 practitioners	Haptic simulator brings a real benefit in training for implant surgery.
9	Cox, M. et al. (2014)	An Investigation into the Teaching of Injection Procedures in Dental Education and Other Clinical Skills Programmes Using a Virtual Haptic Simulator	to investigate how advanced haptic technologies might be applied to teaching and learning in clinical settings	Training	Anesthesia	hapTELX-G injections simulator	21 students (dentists and nurses)	Nice experience to be able to practise doing injections using advanced technology with some improvements to be done
10	Wu, F. et al. (2014)	A virtual training system for maxillofacial surgery using advanced haptic feedback and immersive workbench	To develop and demonstrate a virtual training system for maxillofacial surgery	Training	Le-Fort I osteotomy	VR-MFS (virtual training system for maxillofacial surgery)	(the authors)	The VR-MFS provides an effective approach to help novices to become familiar with OMF surgery procedures. The same method can also be applied to other bone simulations.
11	Poyade, M. et al. (2014)	Development of a Haptic Training Simulation for the Administration of Dental Anaesthesia based upon Accurate Anatomical Data	To focus on the development of a haptic training system based upon an accurate anatomical model	Training	Anaesthesia	HDIS Simulator (Haptic Dental Injection Simulation)	(the authors)	The training system fills a gap in the market, but several issues have to be taken into account in further development
12	Dai, J. et al. (2014)	Accurate movement of jaw segment in virtual 3D orthognathic surgery	To offer a new method to obtain a suitable virtual terminal occlusal splint	Training	Orthognathic surgery		(the authors)	The method offers a useful educational method for training junior surgeons and students
13	Ioannou, I. et al. (2015)	Comparison of oral surgery task performance in a virtual reality surgical simulator and an animal model using objective measures.	How does performance in a simulator resemble in the operating theatre	Training	Wisdom tooth extraction surgery	Ovine jaw versus VR simulator Sensable Phantom 1.5 High Force haptic device	14 fourth year dentistry students	It is difficult to identify clear relationships between automated simulator outcome measures and expert assessments in the physical world.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
14	Wang, D. et al. (2015)	Interactive haptic simulation of tooth extraction by a constraint-based haptic rendering approach	To introduce a 6-Degree-of-Freedom haptic rendering approach to simulate the tooth extraction process.	Research study	Extraction	2 haptic devices, a haptic-visual collocation platform, stereoscopic glasses	(the authors)	The approach was able to teach expected force patterns and correct tool posture to the trainee. New haptic devices need to be developed to simulate the grasping motion and grasping force.
15	Corrêa, C. (2015)	Simulacão de inserção de agulha para treinamento de procedimento de anestesia odontológica	To develop a computer system prototype based on VR for simulation of anesthesia procedure.	Training (thesis)	Inferior Alveolar Nerve Block injection [IANB]	Phantom Omni modified for injection (Vimet Odonto)	6 and 20 (students and postgraduate)	In the opinion of the participants, the system is viable and can help with training, but not yet replace traditional methods.
16	Kinoshita, H. et al. (2016)	Development of a drilling simulator for dental implant surgery	To develop and evaluate a dental implant surgery simulator that allows learners to experience the drilling forces	Training	Osteotomy in the posterior mandibular bone	Built force-sensing device	5 dentists	The simulator was found to be useful to train users to recognize the differences in resistance when drilling through the mandibular bone.
17	Pereira, A. (2016)	Development, implementation and evaluation of a virtual reality simulator for local anesthesia for teaching and training inferior alveolar nerve block anesthetic technique	To develop, implement and evaluate a non-haptic VR simulator for local dental anesthesia	Training (Thesis)	Inferior Alveolar Nerve Block injection [IANB]	Customed Dental Anesthesia Simulator	23 students from the fourth semester	The simulator showed to be a promising complementary tool for teaching and training in local dental anesthesia.
18	Diaz-Siso, R. et al. (2016)	Computer Simulation and Digital Resources for Plastic Surgery Psychomotor Education	To present 2 virtual surgical simulators addressing procedural cognition for cleft repair surgery.	Training	Cleft repair and craniofacial surgery.	The Smile Train and myFace virtual surgery simulators	(the authors)	These simulators may serve as case studies for the forging of new partnerships to construct resources that can address different stages of skills acquisition.
19	Corrêa, C. et al. (2017)	Virtual Reality simulator for dental anesthesia training in the inferior alveolar nerve block	To show development and validation of a dental anesthesia · training simulator	Training	Inferior Alveolar Nerve Block (IANB).	Phantom Omni modified for injection	26 participants	Although this research is not finished and many points will be improved in the simulator, volunteers stated that it can be used as a complementary tool in the IANB teaching procedure.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
20	Chen, X. et al. (2018)	A patient-specific haptic drilling simulator based on virtual reality for dental implant surgery	To present a haptic simulator for trainees to study and rehearse the drilling performance of dental implant surgery.	Training	Drilling procedures for implantation	Dental Implant Surgery Simulator (DISS) based on Omega.6	30 novice surgeons	The evaluation of the DISS proves its good performance and it could provide an effective method to improve the skills and experiences of trainees.
21	Tori, R. et al. (2018)	VIDA ODONTO: Virtual Reality Environment for Dental Training	To develop a prototype of VR to realize local anesthesia	Training	Local anesthesia	VIDA Odonto with HMD Oculus Rift DK2	14 participants	The pilot experiment demonstrated the feasibility of using virtual reality technologies to train dental students in the pre-clinical stage.
22	Pulijala, Y. et al. (2018)	Effectiveness of Immersive Virtual Reality in Surgical Training-A Randomized Control Trial	To evaluate the effect of using VR surgery on the self-confidence and knowledge of surgical residents	Training	Le Fort I osteotomy	VR Surgery	95 students from 7 dental schools	The study group participants showed significantly greater perceived self-confidence levels compared with those in the control group
23	Yoganathan, S. et al. (2018)	360° virtual reality video for the acquisition of knot tying skills: A randomised controlled trial	To determine knot tying skills taught with a 360º VR video compared to conventional 2D video.	Training	Sutures (single handed reef knot on a knot-tying jig)	Iphone 7 (Apple) versus Insta360™ Nano	40 foundation year doctors (first year postgraduate)	This study shows there is significant merit in the application of 360-degree VR video technology in surgical training,
24	Pulijala, Y. et al. (2018)	An innovative virtual reality training tool for orthognathic surgery	To test the validity and usefulness of VR surgery for surgical training.	Training	Le Fort I osteotomy	Oculus Rift and Leap Motion devices	7 consultant OMF surgeons	The results confirmed the clinical applicability of VR for delivering training in orthognathic surgery.
25	Zhang, B. et al. (2020)	Virtual versus jaw simulation in Oral implant education: a randomized controlled trial	Investigate the evaluation methods of teaching oral implant and estimate the effectiveness of a virtual simulation platform.	Training	Implant placement:	Pig mandible versus virtual simulation system (Zhonghui, UniDental-MS01, China)	80 second- and third-year undergraduates	Virtual simulation education, especially with a jaw simulation model, could improve students' implantology achievements and training.
26	Mladenović, R. et al. (2020)	The use of mobile-aided learning in education of local anesthesia for the inferior alveolar nerve block	To evaluate effectiveness of Mobile-Aided Learning on practical administering anesthesia	Training	Inferior alveolar nerve block (IANB)	Dental Simulator mobile application (Campinas, Brazil),	34 students	Application of Mobile-Aided Learning showed a significantly higher efficiency in student education for practical implementation of the IANB.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
27	Buchbender, M. et al. (2021)	Kobra surgery simulator: a possibility to improve digital teaching? A case-control study	To investigate how dentists and students perform in the Kobra simulation	Training (done in 2017)	Apicoectomy of an upper lateral incisor and Removal of an impacted lower wisdom tooth	Kobra® Surgery Simulator	49 students and 10 dentists	The Kobra simulation may offer an additional method to conventional surgery training using plastic models, with benefits for students and faculty staff.
28	Collaço, E. et al. (2021)	Immersion and haptic feedback impacts on dental anesthesia technical skills virtual reality training	To assess the impact of immersive technologies on skills training.	Training (done in 2019)	Inferior alveolar nerve block (IANB)	VIDA Odonto with Touch haptic device and HMD	163 clinical dental students	The immersive VR simulator allows the practice of the IANB under near real conditions and with immediate feedback to the dental student with respect to the needle insertion point
29	Zorzal, E. et al. (2021)	An immersive educational tool for dental implant placement: A study on user acceptance	To design and develop IMMPLANT a virtual reality educational tool to assist implant placement learning,	Training	Placing a virtual implant at a specific bone-loss area (lower jaw)	IMMPLANT is a laptop connected to a VR HMD, a hand tracking device and a smartphone	16 medical dentists	IMMPLANT is a promising virtual reality tool to assist student learning and 3D dental visualization for implant placement education.
30	Zhou, Y. et al. (2021)	Application evaluation of virtual reality technology in dental implant training: a new dental implant training system	To evaluate the application of virtual reality technology in a dental implant training system.	Training	3 simulated implant operations on each tooth position in 3 dental arch areas.	HTC vive helmet connected to interactive software Unity 3D 5.5.1	30 physicians and graduate students	The VR surgery system for dental implant training can be used for teaching and training, with good operability and predictability, to achieve a breakthrough in dental implant surgery training.
31	Sukotjo, C. et al. (2021)	Development and student perception of virtual reality for implant surgery	To provide a simple and intuitive interaction for learners in order to lessen the learning curve and reduce adaptation time	Training	Incision, drilling and implant placement	HMD Oculus Quest	7 dental students	The use of VR in teaching and learning implant dentistry offers positive enhancement, especially during challenging times.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
32	Medellin-Castillo, H. et al. (2021)	Haptic-enabled virtual training in orthognathic surgery	To evaluate the use of haptics and virtual reality technologies as an OGS training tool.	Training	Mentoplasty and sagittal osteotomy (among other 2 OGS training)	Omni Phantom (Sensable®) and the Falcon (Novit®) haptic devices	9 OMF surgery postgraduate students	It can be said that haptic-enabled virtual osteotomy training is feasible and has a significant effect on the real osteotomy performance and technical skills of novices.
33	Zhang, J. et al. (2021)	Maxillofacial Surgical Simulation System With Haptic Feedback	To propose a system based haptic feedback device with optimized 3D models for simulating the maxillofacial surgery.	Training	Open reduction, osteotomy, and palate fixation	A 6-DoF force feedback device and SOFA (Simulation Open Frameworks Architecture)	10 stomatology surgeons	The surgical system achieves expectations and receives favorable reviews from surgeons and novices in experiments. However, there are still a lot of technical challenges in the development of virtual surgery.
34	Zafar, S. et al. (2021)	Pedagogical development in local anaesthetic training in paediatric dentistry using virtual reality simulator	To investigate dental student's perception of dental LA VR simulation on a paediatric patient	Training	Local anaesthesia (LA) including IANB	Oculus Quest HMD and Software using Zbrush, Blender, Unity3D and OpenGL	71 students	The use of VR simulation can enhance students engagement and learning experience in paediatric dentistry settings and can be used as an additional means of LA training.
35	Cheng, M. et al. (2022)	Development of a maxillofacial virtual surgical system based on biomechanical parameters of facial soft tissue	To simulate incision-making process on facial soft tissue and to help maxillofacial surgery training.	Training	Incisions	Omega 6 haptic device and software using Visual Studio 2010 and CHAI3D	10 experience surgeons	The proposed virtual surgical system demonstrated excellent performance in simulation and training of incision-making process.
36	Lu, M. et al. (2022)	Interns' perception of haptic virtual reality oral surgery simulator learning for impacted lower third molar extraction.	To evaluate Students' perception of Kobra simulator for impacted lower third molar extraction	Training	Impacted lower third molar #38 extraction	Haptic virtual reality oral surgery simulator Kobra®	16 dental interns	The implementation of Kobra for impacted lower third molar extraction learning could empower interns' learning experience as well as self-confidence and also promote the SDGs in dentistry.

Table 6: continued (Haptics & VR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
37	Vincent, M. et al. (2022)	Virtual aids and students' performance with haptic simulation in implantology	To validate that haptic simulator assistance could improve drilling ability in implantology and that the repetition of training session could highlight a learning curve.	Training	Implantology simulation of an implant drill at the level of a 36 with a 4.5 × 11 mm implant.	VirTeasy® • haptic simulator	88 first-year dental students	By associating virtual assistance and repetition, the student will acquire more quickly the skills allowing to carry out his clinical gestures in real conditions.
38	Rantamaa, H. et al. (2022)	Evaluation of voice commands for mode change in virtual reality implant planning procedure	To evaluate the benefits of the voice commands for mode and tool change.	Training	Three implant planning tasks for two implants	HMD Oculus Quest 2, PlanMeca 3D implant planning and Microsoft MRTK-Unity	6 dento-maxillo-facial radiologists experimented	The voice commands were useful, natural, and accurate for mode change, and they could be expanded to other tasks. Button presses and the voice commands should be both available and used in parallel.
39	Rantamaa, H. et al. (2022)	Evaluation of virtual handles for dental implant manipulation in virtual reality implant planning procedure	To make a preliminary evaluation of how professional users perceive the use of the virtual environment on their field	Training	Three implant planning tasks	HMD Oculus Quest 2, PlanMeca 3D implant planning and Unity 3D software	4 dento-maxillo-facial radiologists experimented	Direct interaction, planning the implant placement without handles, to be better than the indirect condition where the implant model had handles.
40	Yang, X. et al. (2023)	Student perceptions toward virtual reality training in dental implant education	To explore the usability and acceptance of a VR application in the training of dental implant among dental students	Training	Dental implant procedure	Custom software with HMD	119 dental students	This pilot study showed feasibility and usability of VR applications on training dental implant and benefits for the participants by practicing the skills repeatedly.

Table 7: Summary characteristic of included studies of Augmented Reality and Mixed Reality models used in simulation

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Lin, Y. et al. (2015)	A Novel Dental Implant Guided Surgery Based on Integration of Surgical Template and Augmented Reality	To develop an augmented reality-based dental implant placement system and evaluate accuracy	Study	40 implant placements (4 mandibles + 4 maxillary)	HMD (Sony HMZ-T1) with customed software	One experienced periodontist	Deviation of implant placement from planned position was significantly reduced by integrating surgical template and augmented reality technology.
2	Katić, D. et al. (2015)	A system for context-aware intraoperative augmented reality in dental implant surgery	To develop an AR system for dental implant surgery to reduce information overflow and offer intuitive image guidance.	Study	To place two implants in the mandible	Customed context-aware AR with HMD on a Pig cadaver	(the authors)	The system allowed to fully concentrate on the surgery itself. It offered greater flexibility since the surgeon received all relevant information, but was free to deviate from it. Accuracy to be improved.
3	Won, Y. et al. (2017)	Application of augmented reality for inferior alveolar nerve block anesthesia: A technical note	To introduce a simple method for applying AR during an IANB procedure	Case report	Anesthesia, IANB	Simulation custom software	(the authors)	Applying simple AR techniques may lead to the development of clinically applicable AR techniques that can be used widely in dentistry and OMF fields.
4	Zhu, M. et al. (2017)	A novel augmented reality system for displaying inferior alveolar nerve bundles in maxillofacial surgery	To develop a novel registration and tracking technique to establish a navigation system based on AR for OMF surgery	Study	Pre-operatory before OMF surgeries as sysostosis, retrognathism or hypertrophy	AR Custom software applied to 20 patient cases	(the authors)	The AR system that we established for OMF surgery has the advantages of easy manipulation and high accuracy, which can improve surgical outcomes.
5	Jiang, W. et al. (2018)	Evaluation of the 3D Augmented Reality–Guided Intraoperative Positioning of Dental Implants in Edentulous Mandibular Models	Evaluation of the 3D AR-Guided Intraoperative Positioning of Dental Implants in Edentulous Mandibular Models	Study	Implant placement	12 rapid prototyping mandibular models in 3D printing (Western Time, 3D Systems)	2 experimented surgeons	Dental implants can be placed using this proposed 3D augmented reality–guided system with less than 1.5 mm deviation and less than 5.5º angular deviation
6	Matsuo, A. et al. (2018)	Virtual reality head-mounted display for endoscopically-assisted implant surgery	To establish a system of endoscopically-assisted VR for implant surgery using a HMD.	Case report	7 drilling and implant placements on 65-year-old patient	HMD (HMS-3000MT, Sony)	(the authors)	Our HMD device makes it possible to for both surgeon and assistant to see both views without interrupting the flow of the operation.

Table 7: continued (AR & MR)

Nº	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
7	Mladenović, R. et al. (2019)	Effectiveness of Augmented Reality Mobile Simulator in Teaching Local Anesthesia of Inferior Alveolar Nerve Block	To evaluate the effectiveness of a mobile AR simulator for LA training	Training (done in 2016)	Inferior alveolar nerve block (IANB)	Mobile application Dental Simulator (Brazil)	41 fourth- and fifth-year students	Findings suggest that this technology contributed to a better knowledge of reference points and procedure of local anesthesia for IANB.
8	Pellegrino, G. et al. (2019)	Augmented reality for dental implantology: A pilot clinical report of two cases	To evaluate feasibility of using a virtual display for dynamic navigation via AR.	Case report	Implant placements on 2 patients	Hololens HMD, ImplaNav and dedicated software	(the authors)	From the results of this pilot study, it seems that AR can be useful in dental implantology for displaying dynamic navigation systems.
9	Pietruski, P. et al. (2019)	Supporting mandibular resection with intraoperative navigation utilizing augmented reality technology - A proof of concept study	To compare the accuracy of simulated mandibular osteotomies performed with cutting guides and 2 different navigation systems	Study	126 osteotomies were performed on 21 identical mandible models	Custom AR-based intraoperative navigation system	(the authors)	Although AR technology still requires some improvements, it can beused for presentation of digital navigation data, enhancing surgeon's awareness and hand-eye coordination.
10	Ma, L. et al. (2019)	Augmented reality surgical navigation with accurate CBCT-patient registration for dental implant placement	To present an AR surgical navigation with an accurate CBCT-patient registration method to provide clinically desired dental implant accuracy.	Study	Implant placement	Developed AR surgical navigation system	(the authors) + experienced dentist	The developed system provides a real-time, in situ AR navigation scene to eliminate the hand-eye coordination problem.
11	Mladenović, R. et al. (2020)	Effect of augmented reality simulation on administration of local anaesthesia in paediatric patients	To evaluate the impact of AR simulator on the perception of learning and acute stress level in students administering LA to pediatric patients	Training	Infiltrative anaesthesia technique for the anterior superior alveolar nerve (IASAN)	Dental simulator mobile application in AR mode (v1.13 Campinas, Brazil)	21 fourth- and fifth-year students	The AR concept may influence better manipulation and control of the syringe in students administering their first anaesthetic injection to paediatric patients, but may not reduce acute stress.
12	Mladenović, R. et al. (2021)	Augmented reality technology as a method of distance learning for local anesthesia training	To practice through mobile phone/tablet, techniques of local anesthesia in an AR environment	Training	Local anesthesia for inferior alveolar nerve block	Dental Simulator v1.13 for iOS and Android	Final year students	Despite effectiveness, AR is still a tangent of reality and should be seen as educational tools that can improve existing ways and methods of clinical teaching.

Table 7: continued (AR & MR)

N°	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
13	Sugahara, K. et al. (2021)	Mixed reality and three dimensional printed models for resection of maxillary tumor: A case report	To focus on a case to treat a maxillary calcifying odontogenic cyst using HoloLens.	Case report	Resection of maxillary calcifying odontogenic cyst	Hololens 2 with various software and 3D models	(the authors)	Incorporation of HoloLens in the preoperative planning and intraoperative visualization of the OMF regions resulted in a precise and safe surgery performance.
14	Scherl, C. et al. (2021)	Augmented reality with HoloLens in parotid surgery: how to assess and to improve accuracy	To evaluate the feasibility of a 3D augmented reality hologram in live parotic surgery.	Study	Live parotid surgery	Hololens®1 and custom software & specific measuring tool	7 participants	The use of fiducial markers and repeated training reduces the positional error between the hologram and the real structures.
15	Shi, J. et al. (2022)	Augmented reality for oral and maxillofacial surgery: The feasibility of a marker-free registration method	To propose to track the contour of mandible edge instead of markers	Study	Removal of benign tumours	HiAR G200 AR glasses	A third-party organisation (Fujian Metrology Inst.)	The system can accurately enhance the display of the surgical path and provide guidance for the tradition of maxillofacial surgery.
16	Sasaki, T. et al. (2022)	Application of a mixed reality device to oral surgery	To present the use of an MR device in various oral surgical procedures	Case report	5 OMF cases	HoloLens2 and various software: Slicer, Blender, etc.	(the authors)	Many different software needs to be used in each process and the work associated with these processes is complicated.
17	Jia, T. et al. (2022)	Application of Mixed Reality Combined With A Surgical Template for Precise Periapical Surgery	To combine MR technology with a 3D-printed surgical template to achieve visualization in apical surgery.	Case report	Periapical surgery	Hololens	(the authors)	Desirable outcomes using minimally invasive therapy could be achieved with the MR technique.
18	Turkyilmaz, I. et al. (2023)	Local anesthesia training with mixed reality advanced dental simulators	To propose a better way to prepare students for administrating local anesthesia	Training	LA and inferior alveolar nerve block (IANB)	SimToCare	(the authors)	Combination of preclinical course and simulators can better prepare students for intraoral injections and increase confidence
19	Remschmidt, B. et al. (2023)	Augmented Reality-Guided Apicoectomy Based on Maxillofacial CBCT Scans	To evaluate the intraoperative feasibility and usability of HoloLens 2 in the context of apicoectomies.	Case report	Apicoectomy	Hololens 2 used for 4 AR-guided apicoectomies on human cadaver heads	3 experienced surgeons	AR-guided apicoectomies using the HL 2 relying on CBCT scans received an excellent rating for system utilization from 3 experienced surgeons.

Table 7: continued (AR & MR)

N°	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
20	Lamira, J. et al. (2023)	A pilot study of local anesthesia training using a mixed-reality haptic fidelity model	To investigate the impact of a novel IANB simulator, built on a three dimensional (3D)-printed mixed-reality haptic model	Training (done in 2021)	Inferior alveolar nerve block (IANB)	Custom simulator 3D-printed derived from segmented images from an actual cadaver.	39 students	Self-reported confidence in performing an IANB improved and higher anesthetic success was achieved
21	Bosshard, F. et al. (2023)	Accuracy of augmented reality-assisted vs template-guided apicoectomy - an ex vivo comparative study.	To examine the accuracy of augmented reality-assisted apicoectomies (AR-A) versus template-guided apicoectomies (TG-A).	Study	Apicoectomy	40 apicoectomies were performed in 10 cadaver pig mandibles.	One surgeon	Augmented reality (AR) technology has the potential to be introduced into apicoectomy surgery in case further development is implemented.
22	Turkyilmaz, I. et al. (2023)	Taking surgical training to another level with mixed reality advanced dental simulator	To practice the steps of osteotomy and implant placement to gain a further understanding of these procedures	Training	Implant site preparation (osteotomy) and implant placement	SimToCare	(the authors)	This application to implant surgery can better prepare students and residents and allow them to provide better outcomes to their patients.
23	Bochet, Q. et al. (2024)	Augmented reality in implantology: Virtual surgical checklist and augmented implant placement	To create a pedagogical checklist for implant surgical protocol with an AR guided freehand surgery	Study	Implant placement	HoloLens-2 with several software on 3D-printed mandible	(the authors)	The use of AR in education enables real-time implant planning and offers crucial surgical information for novice surgeons
24	Tamayo-Estebaranz, N. et al. (2024)	Is Augmented Reality Technology Effective in Locating the Apex of Teeth Undergoing Apicoectomy Procedures?	To assess the accuracy of apical location using an augmented reality (AR) device with a free-hand method.	Study	Apicoectomy	Hololens2, various software and 60 osteotomy sites prepared	(the authors)	The augmented reality technique did not show a statistically significant accuracy of osteotomies for apical location when compared with the conventional free-hand method.

Table 8: Summary characteristic of included study of Perfused Cadaver models used in simulation

N°	Author, Year	Title	Aim of the study	Domain	Surgical procedures	Simulator(s) used	Participants	Results
1	Manfroni, A.M. et al. (2023)	Anatomical Study of the Application of a Galeo-Pericranial Flap in Oral Cavity Defects Reconstruction	To assess the technical feasibility of flap harvesting through anatomical dissections and surgical procedure simulations.	Study	harvesting a new galeo-pericranial free flap	SimLife®	(the authors)	This anatomical study demonstrated the technical feasibility of the free flap harvesting in surgical procedure simulations on donor cadavers.