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Programvezető: Dr. Varga Gábor, egyetemi tanár

Témavezetők: Dr. Hermann Péter, egyetemi tanár

Dr. Végh Dániel, egyetemi adjunktus

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PhD thesis

TAMÁS HEGEDÜS

Semmelweis University Doctoral College

Dental Research Division

Supervisors: Péter Hermann, DMD, Ph.D, D.Sc.
Dániel Csaba Végh, DMD, Ph.D

Official reviewers: Tamás Huszár, MD, Ph.D.
Szabolcs Bozsányi, MD, Ph.D.

Head of the Complex Examination Committee:
Gábor Gerber, DMD, Ph.D., D.Sc.

Members of the Complex Examination Committee:
Árpád Joób-Fancsaly, DMD, Ph.D., D.Sc.
Ákos Károly Nagy, DMD, Ph.D.

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LIST OF ABBREVIATIONS

Abbreviation	Definition
3D	3-dimensional
AI	artificial intelligence
AM	additive manufacturing
CAD	computer-aided design
CAD/CAM	computer-aided design and computer-aided manufacturing
CAM	computer-aided manufacturing
CBCT	cone-beam computed tomography
CEREC	Chairside Economical Restoration of Esthetic Ceramic
DL	deep learning
DLP	digital light processing
FDM	fused deposition modelling
IDD	Institute of Digital Dentistry
IOS	intraoral scanner
LLM	large language model
N	number
PMMA	polymethyl methacrylate
SD	standard deviation
SLA	stereolithography
SLS	selective laser sintering
SM	subtractive manufacturing

I. INTRODUCTION

I/1 DIGITAL TRANSFORMATION IN DENTISTRY

In dentistry, recent decades have seen a digital transformation in everyday workflows. With the help of digital tools, nowadays dental specialists, including dentists, dental technicians, and dental assistants, have experienced a rapid development in the digitalization of various treatments.

The introduction of computer-aided design and computer-aided manufacturing (CAD/CAM) technology initiated a rapid progress in various industries. Since the 1970s, research and development of dental CAD/CAM systems has been actively investigated worldwide since the 1980s (1). Beginning in 1971, Dr. Duret pioneered dental CAD/CAM by developing systems that used intraoral optical impressions, functionally guided crown design, and numerically controlled milling to fabricate crowns (2). The clinical history of CAD/CAM technology and chairside dentistry began in 1985, when Mörmann and Brandestini introduced the first commercially available system, the Chairside Economical Restoration of Esthetic Ceramic (CEREC) (3). This chairside system allowed clinicians in private practices to independently design and mill ceramic dental restorations within hours, enabling reconstruction in a single visit (4) (Figure 1).



Figure 1: Evolution of CEREC hardware: (A) CEREC 1 prototype, 1985; (B) modified CEREC 1, 1991; (C) CEREC 2 with an upgraded 3D camera, 1994; and (D) CEREC 3 with separate design and milling units, 2000. (4)

These days CAD/CAM commonly used in both dental laboratories and dental offices, can be applied in the fabrication of prosthodontic appliances such as crowns, veneers, inlays, onlays, fixed partial dentures, implant abutments, and even full-mouth reconstructions. (5).

These systems generally consisted of three main components: a data acquisition unit, design software, and a manufacturing unit. The data acquisition unit captured information from the prepared tooth, adjacent teeth, and opposing structures, either directly using an intraoral scanner or indirectly with a laboratory scanner from a gypsum model made from a conventional impression (6). The software was used to design the virtual restoration on a digital working cast and calculate the manufacturing parameters, while the final restoration was produced either by computerized milling from a solid block of restorative material or by additive manufacturing (7).

As already written, computer-aided manufacturing can generally be divided into two main approaches: subtractive manufacturing (SM) and additive manufacturing (AM) (8). In subtractive manufacturing, restorations are milled from solid material blocks using rotary diamond instruments. In contrast, additive manufacturing, commonly referred to as three-dimensional printing, produces objects by depositing and joining material in successive layers (9, 10).

Alongside the development of digital design and manufacturing workflows, artificial intelligence (AI) has emerged as another important component of modern dentistry. Recent advances in AI have supported improvements in diagnosis, disease risk prediction, prognostic assessment, clinical decision-making, treatment planning and delivery across multiple dental specialties (11, 12). These capabilities support more comprehensive diagnostic assessment and earlier intervention, potentially improving patient outcomes (13). Furthermore, real-time clinical decision support helps dentists make evidence-informed choices, estimate treatment success, and deliver more precise, patient-centred care (14). AI is also transforming dental education by enabling personalized learning, supporting radiographic interpretation, and assisting students in assessing their knowledge through deep learning (DL) models (15, 16). Large language models (LLMs) can also help specialists and students to understand and implement better digital dental technologies.

I/2 INTRAORAL SCANNERS: TECHNOLOGICAL AND CLINICAL ROLE

In clinical practice, the intraoral scanner (IOS) represents a central component of the digital workflow by capturing high-resolution three-dimensional images of the teeth and surrounding oral structures (17). Similar to other three-dimensional (3D) scanners, intraoral scanners project a light source, such as a laser or more recently structured light, onto the object being scanned (18). The images of the dentogingival tissues captured by the imaging sensors are processed by the scanning software to generate point clouds, which are then triangulated by the same software to create a three-dimensional surface model, known as a mesh (19, 20). The three-dimensional surface models of the dentogingival tissues represent the outcome of the optical impression and serve as a virtual substitute for conventional gypsum models (21).

The first intraoral scanner connected to a dental laboratory was developed by the Massachusetts Institute of Technology in 2007 (22). Nowadays, the most widely used IOS brands include 3Shape, Medit, Shining 3D, and Dentsply Sirona (Figure 2).



Figure 2: 3Shape Trios 5 intraoral scanner (own photo)

Following its introduction, a wide range of IOS systems became available on the dental market, which encouraged increasing scientific interest in assessing their characteristics and performance (18, 22, 23).

Currently, intraoral scanners are widely used and highly popular across nearly all fields of dentistry, including restorative dentistry, endodontics, prosthodontics, orthodontics, implantology, and oral surgery (3, 24-28).

Several studies have evaluated conventional and digital impression techniques from both patient and dentist perspectives, reporting that digital impressions require less overall treatment time and shorter impression-taking time than conventional methods (29, 30). However, the time required for intraoral scanning depends largely on the user's experience and position on the learning curve. It is important because sufficient operator experience is required to obtain accurate and efficient digital impressions (31). The benefits of intraoral scanning include reduced gag reflex and working time, elimination of impression material and gypsum-related distortions, improved communication with the dental laboratory, and easy repeatability (32, 33).

Digital impression-taking also has certain limitations, as conventional impressions may still be preferable in complex prosthodontic cases, such as long-span restorations on multiple implants, while deep margin detection and bite registration can remain challenging; additional drawbacks include scanning fees in closed systems and the relatively high cost of IOS devices (20, 34, 35).

The accuracy of digital impressions, defined by trueness and precision, is a key factor influencing the long-term success of final restorations, as it reflects the degree of agreement between the obtained result and an accepted reference value (36, 37). According to the literature, intraoral scanners generally provide higher accuracy than conventional impressions for short-span restorations up to a quadrant, although digital impression-taking still has certain limitations (38-40). However, several factors may compromise the accuracy of digital impressions, including reflections from metal surfaces, excessive saliva, limited intraoral access, and the scanning sequence, particularly in full-arch scans (41-45). In addition, edentulous ridges can reduce scanning accuracy because they provide fewer distinct anatomical landmarks for reliable optical image capture (46). As newer generations of IOSs have been introduced, differences in

accuracy have emerged between devices, with some scanners demonstrating greater suitability for complete-arch optical impressions than others (47).

Together with imaging modalities such as cone-beam computed tomography (CBCT) and three-dimensional facial scanning, advances in IOS technology have expanded its use beyond impression taking to diagnostics, treatment planning, and monitoring, suggesting an increasingly important role in dentistry and oral and maxillofacial surgery (48) (Figure 3).



Figure 3: Intraoral optical impression of a mandibular arch with prepared teeth and an implant holding a scan body (48)

In addition, recent developments in IOS software have incorporated AI-based functions that improve digital impression quality by automatically correcting scanning defects, filling missing areas, and smoothing mesh irregularities, reducing manual adjustments and increasing workflow efficiency (49).

I/3 ADDITIVE MANUFACTURING AND 3D PRINTING IN DENTISTRY

Three-dimensional printing, also known as additive manufacturing, is an advanced manufacturing technology (50). The technology uses computer-aided design (CAD) models to fabricate customized three-dimensional objects from standardized materials through automated manufacturing processes (51).

Industrial-scale additive manufacturing, commonly known as 3D printing, emerged in the early 1980s, with pioneers including Charles W. Hull, S. Scott Crump, Hans J. Langer, and Hans Steinbichler, and following Hull's patent of the first 3D printer in 1986, the technology was initially used primarily for rapid prototyping (52). The rapid advancement of three-dimensional printing technologies has attracted considerable attention because of their high precision, efficient material utilization, design flexibility, and capacity for individualized production. The main stages of the 3D printing workflow, including digital modelling and image processing, are illustrated in Figure 4 (53).

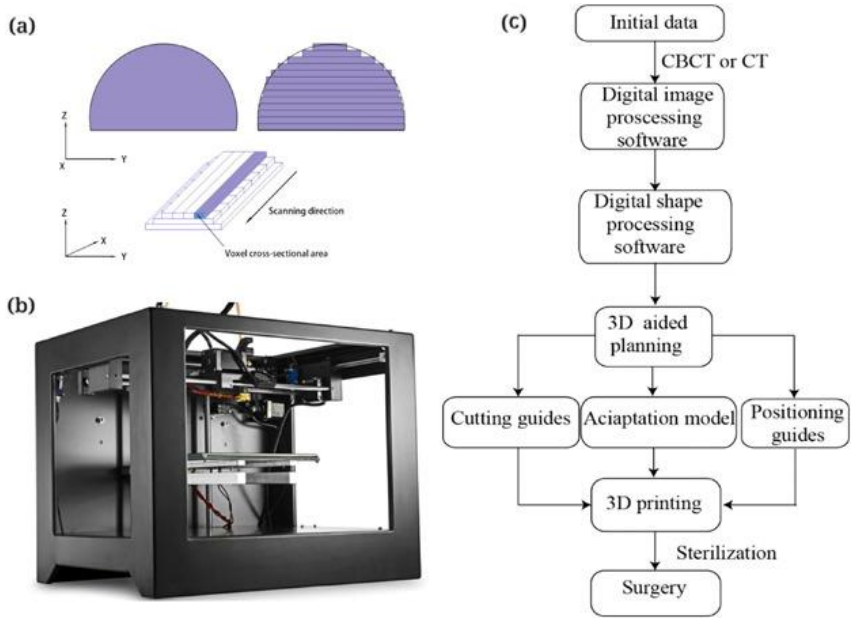


Figure 4: The sequence from image acquisition and digital planning to fabrication and surgical application. (a) Slicing of the three-dimensional model; (b) the 3D printing device; and (c) a simplified workflow (53)

Although medical applications represented only about 1.6% of all industrial 3D printing uses in 2010, their share was projected to rise to approximately 21%, with the medical 3D printing market valued at USD 3.7 billion and expected to reach USD 6.07 billion by 2027 (54).

The oldest and one of the most widely used 3D printing methods in dentistry is stereolithography (SLA). It produces objects layer by layer by using a laser to polymerize and solidify a UV-sensitive liquid resin, with systems differing according to platform and laser movement (55) (Figure 5).



Figure 5: Formlabs Form4B SLA printer (56)

A closely related projection-based technique, digital light processing (DLP), instead uses a digital micromirror device whose individually controlled mirrors project the light source as pixels to polymerize each resin layer simultaneously (57). Other commonly used methods include photopolymer and material jetting, which deposit liquid photopolymer or wax through inkjet-like nozzles to form successive layers that are then solidified by

UV light or cooling (58). In contrast, selective laser sintering (SLS) use a high-power laser to fuse successive layers of preheated powder, primarily metallic materials in dentistry, while the surrounding unfused powder supports the object during fabrication (59). Fused deposition modelling (FDM), which is more widely used than SLS, builds objects by depositing and fusing heated thermoplastic material layer by layer and is commonly applied with polymers in scaffold fabrication, tissue engineering, and pharmaceutical production (60, 61).

The predominant technique for fabricating 3D printed dental prostheses is vat polymerization, in which liquid resin, sometimes containing ceramic particles, is initially cured during printing and subsequently post-cured in a separate unit (62, 63). Resins used for AM must possess appropriate flow properties and allow sufficient light penetration for effective fabrication (64).

Beyond conventional resin-based materials, 3D printable ceramic-filled materials have also gained recognition. In 2023, the American Dental Association broadened its definition of dental ceramics by removing the requirement for materials to be pressed, fired, polished, or milled, allowing printed crowns with more than 50% inorganic filler to be classified and reimbursed as definitive ceramic restorations (65).

Among the earliest medical uses of three-dimensional printing was the fabrication of physical anatomical models for educational, diagnostic, and preoperative planning purposes. (66, 67). Nowadays, with the rapid spread of 3D printing technology has applications across all major fields of dentistry, including orthodontics, maxillofacial surgery, prosthodontics and implantology (68-73).

Despite the broad range of available 3D printing techniques and their expanding applications, their environmental impact remains an important consideration, particularly because failed prints, support structures, and manufacturing byproducts generate substantial waste, while many polymers used in SLA, SLS, and material jetting have limited recyclability (74, 75). Certain 3D printing processes may pose occupational health risks through the emission of toxic fumes, volatile organic compounds, and ultrafine particles during polymer processing; however, these risks can be reduced by using fully enclosed systems and high-efficiency particulate air filters (76).

I/4. USER EXPERIENCE AND QUESTIONNAIRE STUDY DESIGN

The evaluation of digital dental technologies frequently focuses on measurable technical characteristics, including accuracy, processing speed, manufacturing capacity and the properties of the digital or physical output. These parameters are essential when determining whether a technology is suitable for a particular clinical indication. However, technical performance alone does not fully describe how easily a system can be introduced and used in everyday practice. The interaction between the user and the technology is also important, particularly in relation to usability, training and the requirements of the working environment (77).

This is particularly relevant in digital dentistry, where several components of the workflow are directly influenced by the operator. Intraoral scanning, for example, is affected by the experience of the user, and repeated use can reduce the time required to obtain a digital impression. The learning curve may also differ between individual scanner systems (31). In addition to accuracy, factors such as handling, software operation, training, technical support and costs may therefore contribute to the overall experience of an IOS user.

Similar considerations apply to additive manufacturing. The use of a 3D printer involves more than the printing process itself and includes digital design, material selection, preparation of the manufacturing file, washing, post-curing and finishing. Previous questionnaire-based research has identified considerable variation in the use of dental 3D printing, as well as practical concerns related to accessibility, costs, post-processing and sustainability (78). These factors are difficult to evaluate through laboratory investigations alone.

Questionnaire-based studies provide an opportunity to collect information directly from professionals who use digital technologies in their everyday working environment. Surveys can assess professional experience, frequency of use, purchasing decisions, perceived advantages and disadvantages, satisfaction and barriers to implementation (79, 80).

Questionnaire research has previously been used to examine the adoption of CAD/CAM systems among dentists and has shown that the introduction of digital technologies may be influenced by factors other than their technical capabilities (81). Similar findings have

been reported regarding the adoption of CAD/CAM technologies and attitudes towards 3D printing in restorative dentistry (82).

The reliability of questionnaire-based research depends considerably on the way the survey is planned and conducted. Appropriate sampling, clear question formulation, suitable data collection methods and transparent reporting are important elements of survey research (83). In studies involving healthcare professionals, careful questionnaire development and testing are particularly important to ensure that the collected information reflects the intended research questions (84). A systematic approach to questionnaire construction can also reduce ambiguity and improve the quality of the responses obtained from participants (85).

Online questionnaires are especially useful when the aim is to reach a geographically diverse professional population. Digital distribution allows responses to be collected from several countries and professional groups within a relatively short period. At the same time, web-based surveys have limitations, including self-selection and the possibility that individuals with a greater interest in the investigated topic are more likely to participate. Transparent reporting of recruitment, participation, completion and the management of online responses is therefore important when interpreting the results of internet-based surveys (86).

User-reported information should also be distinguished from objective technical measurements. For example, the opinion that an intraoral scanner or 3D printer is accurate reflects the user's perception of the technology and cannot be considered equivalent to an objective assessment of trueness or precision. These perceptions remain relevant because they may influence purchasing decisions, frequency of use and the willingness to introduce digital technologies into additional clinical workflows. User experience can therefore provide information that complements laboratory and clinical investigations. While technical studies describe what a system is capable of under defined conditions, questionnaire-based research can provide insight into how the same technology is used, accepted and perceived in everyday dental practice.

II. OBJECTIVES

The objective of my thesis was to investigate the user experience of two digital technologies that have become increasingly important in dentistry: intraoral scanners and 3D printing systems. During the last decade, both technologies have been widely promoted as accurate, efficient and cost-effective solutions for modern dental workflows. However, much of the available information on their performance, costs, speed and accuracy comes from manufacturers or from controlled experimental settings. These sources are useful, but they do not always show how these devices perform in everyday clinical practice.

For this reason, I wanted to put the focus on the experience of the actual users. In everyday dental work, the value of a digital device depends not only on its technical specifications, but also on how easy it is to use, how well it fits into the workflow, how much maintenance it requires, how reliable it feels, and whether the user considers it worth the investment. These aspects are difficult to judge only from manufacturer data or laboratory studies.

Another important aim was to collect feedback from several countries and regions, rather than from one local professional group only. By investigating international questionnaire data, the thesis aimed to provide a more realistic picture of how intraoral scanners and 3D printers are currently used in dentistry, what users consider their main advantages, and what barriers still limit their broader implementation.

My hypotheses are the following:

Hypothesis 1:

Intraoral scanners and 3D printing systems are increasingly integrated into dental practice; however, their adoption is influenced by accessibility, cost, training and maintenance-related factors.

Hypothesis 2:

Dental professionals who use these technologies report clinical benefits, but also identify technical, financial and workflow-related limitations.

Hypothesis 3:

User experience is influenced not only by the technical capabilities of the devices, but also by ease of use, reliability, software integration, support and perceived clinical usefulness.

III. METHODS

III/1 STUDY DESIGN

The present dissertation is based on two international, cross-sectional questionnaire-based studies evaluating the user experience of digital technologies in dentistry (87, 88). The first study investigated the clinical use and perceived performance of intraoral scanners, whereas the second focused on the adoption, practical application, and user perception of 3D printing technologies in dental practice and dental laboratory workflows.

Both studies applied a survey-based observational design and aimed to collect real-world information from dental professionals and individuals involved in digital dental workflows. The rationale behind this methodological approach was that manufacturer-provided information regarding cost, accuracy, usability, maintenance, and workflow efficiency may not fully reflect the everyday clinical or laboratory experience of end-users. Therefore, both investigations were designed to obtain independent, practice-based feedback from a broad international cohort.

The methodology of the intraoral scanner study was informed by previous research conducted by the authors on user experience with 3D printing in dentistry (78). Based on the limitations identified in the earlier investigation, the survey design was refined in order to improve data quality, respondent accessibility, and the clinical relevance of the questions. Furthermore, the development of the questionnaire considered the methodological value of focus group–based feedback, as this approach may help identify practical user concerns and technology-related aspects that are not always captured by standard survey design.

The 3D printing study was similarly designed as an international questionnaire survey and built upon previous investigations related to the digital transformation of dentistry, including the clinical adoption of intraoral scanners and additive manufacturing. The questionnaire was developed to assess both general professional experience with digital dentistry and specific user perceptions regarding selected 3D printing systems.

III/2. STUDY POPULATION AND RECRUITMENT

The study population consisted of dental professionals, dental students, dental technicians, laboratory personnel, industry representatives, and other members of the dental team with professional or educational involvement in dentistry.

In the intraoral scanner study, respondents were recruited from an international population representing 109 countries. The eligible study population included dentists, dental specialists, dental students, dental assistants, dental hygienists, dental technicians, laboratory workers, dental industry members, and dental office staff. The publication reports an international survey of 1072 respondents from 109 countries, focusing on intraoral scanner use, accessibility, maintenance fees, software use, and satisfaction with scanner systems.

For the intraoral scanner study, predefined exclusion criteria were applied. Incomplete questionnaires, duplicate submissions identified by email address, and responses from individuals without a professional or educational background in dentistry were excluded from the final analysis. Administrative staff, industry experts, and dental office staff who were not considered members of the clinical dental community were also excluded.

In the 3D printing study, participants were recruited from 80 countries by means of nonprobability and snowball sampling. Eligible respondents included dental professionals and individuals involved in dental education, clinical practice, dental technology, laboratory procedures, or the dental industry. In total, 499 completed questionnaires were included in the final analysis. The study specifically targeted users with experience or interest in digital dental technologies, particularly additive manufacturing.

For the 3D printing study, predefined exclusion criteria were also applied. Incomplete submissions, duplicate entries identified by email address, and responses submitted by individuals without a professional or educational background in dentistry were excluded from the final dataset.

III/3. SURVEY DEVELOPMENT AND STRUCTURE

Both questionnaires were developed in English and were designed for electronic completion using a desktop computer, tablet, or mobile phone. Although the use of English enabled standardised international data collection and analysis, it may also have limited participation among potential respondents with insufficient English language proficiency.

The intraoral scanner questionnaire consisted of two principal sections. The first section collected demographic and professional information, including the respondents' background, country of residence, professional role, and previous experience with intraoral scanning. The second section focused on the specific intraoral scanner selected by the participant for evaluation. This part assessed user experience, scanner-related satisfaction, accessibility, maintenance-related aspects, and the use of associated digital software (Table 1).

Table 1: The questionnaire used in the IOS study (88)

Section	Item	Question
Part 1	1	What is your name?
	2	In what country do you live?
	3	What is your email address?
	4	What describes your profession best?
	5	Have you ever used an intraoral scanner for dental work?
	6	How long have you used intraoral scanners?
	7	How many IOS do you have in your office/clinic?
	8	How would you describe your experience level with IOS and digital dentistry?
	9	Have you ever tried using your intraoral scanner to make a digital impression for a fixed prosthetic appliance?
	10	Do you think digital technology is more accurate than traditional casting?
	11	Do you think digital technology may be more accurate in the future?
	12	Do you carry out any CAD (design) in-house?
	13	Were you involved in the purchase of the design software?
	14	How much did this design software cost to buy in USD?
	15	Can you upgrade the software free of charge?

	16	Do you carry out any CAM (manufacturing) in-house?
	17	Which milling machine(s) do you use?
	18	Which 3D printer(s) do you use?
Part 2	1	Add your intraoral scanner.
	2	Were you involved in the purchase of the scanner?
	3	Did you participate in any education or course before you bought the scanner?
	4	What was the main reason you chose this intraoral scanner?
	5	How easy was the process of buying this scanner?
	6	In what price range did you purchase your intraoral scanner in USD?
	7	How satisfied are you with the price of the scanner?
	8	How long did it take for the intraoral scanner to be shipped after the purchase?
	9	Did the manufacturer or dealer provide an in-person educational session or course with the purchase of your scanner?
	10	How satisfied are you with the training course for the scanner?
	11	How often do you use this intraoral scanner?
	12	How satisfied are you overall with this intraoral scanner?
	13	How satisfied are you with the speed of the scanner?
	14	How satisfied are you with the support service for the scanner?
	15	What is the annual cost of the intraoral scanner service and support in USD ($/year)?
	16	What is the main disadvantage of this system/intraoral scanner?

The 3D printing questionnaire was also divided into two major sections. The first section contained 38 items addressing demographic characteristics and general experience with 3D printing, including professional role, country of residence, type and number of devices used, duration of use, and areas of clinical or laboratory application. The second section consisted of 28 questions related to the specific 3D printer selected by the respondent. These items evaluated printer performance, ease of use, maintenance requirements, integration into the digital workflow, post-processing, perceived limitations, and overall satisfaction (Table 2).

Both questionnaires included multiple-choice questions, Likert-scale items, and open-ended fields. This structure allowed quantitative assessment of predefined variables while also enabling respondents to provide additional qualitative feedback where appropriate.

Table 2: The questionnaire used in the 3D printing study (87)

Section	Item	Question
Part 1	1	What is your full name?
	2	What is your preferred email address?
	3	In which country do you currently reside?
	4	What is your year of birth?
	5	In which year did you begin working in dentistry?
	6	Which professional category best describes you?
	7	Which role best describes your position in the workplace?
	8	Which dental specialisation or specialisations apply to you?
	9	Do you consider 3D printing to be more accurate than traditional manufacturing methods?
	10	Which digital manufacturing technologies, if any, do you use in-house?
	11	How many 3D printers are available at your workplace?
	12	How many milling machines are available at your workplace?
	13	What percentage of your work is currently outsourced to a dental laboratory?
	14	What are the three main reasons why you have not yet adopted in-house digital manufacturing?
	15	Do you plan to invest in digital manufacturing equipment in the future?
	16	What are your main reasons for not considering an investment in 3D-printing or milling equipment?
	17	Within what timeframe do you plan to invest in 3D-printing equipment?
	18	Would the availability of validated workflows increase your likelihood of investing in a 3D-printing system?*
	19	What are the five main applications for which you are considering investing in 3D printing?
	20	Within what timeframe do you plan to invest in milling equipment?
	21	What type of milling machine are you planning to acquire?
	22	What are the three main materials you intend to use with your new milling machine?
	23	For how many years have you been using dental 3D printers?
	24	How important is access to a wide range of resins for your 3D-printing applications?
	25	How important is the availability of validated workflows for your 3D-printing processes?
	26	Which post-processing equipment do you use for your 3D-printed products?
	27	Do you use equipment from the same manufacturer for both washing and curing?
	28	Do you follow the manufacturer’s recommended post-processing instructions?

	29	Do you use separate post-processing equipment for biocompatible and non-biocompatible resins?
	30	How much time do you typically spend post-processing each 3D-printed product?
	31	Do you recycle the isopropyl alcohol used during post-processing?
	32	How do you recycle the isopropyl alcohol used during post-processing?
	33	Do you have any concerns regarding the use of 3D printing in dentistry?
	34	Do you perform computer-aided design procedures in-house?
	35	Which software applications do you use to design the final product?
	36	Were you involved in the purchasing decision for the design software?
	37	What was the purchase price of the design software in US dollars?
	38	Can the design software be upgraded free of charge?
Part 2	1	What is the brand of your 3D printer?
	2	What is the model of your 3D printer?
	3	Which dental products do you manufacture using this 3D printer?
	4	How did you first become aware of this 3D printer?
	5	Were you involved in the purchasing decision for this 3D printer?
	6	What were the three main factors that influenced your decision to select this 3D printer?
	7	Do you recall the purchase price of the 3D printer?
	8	How much did you pay for the 3D printer?
	9	How would you rate the ease of purchasing this 3D printer?
	10	Did you participate in any educational programme or training course before purchasing the 3D printer?
	11	How did the educational programme or training course influence your purchasing decision?
	12	What education or training was included with the purchase of the 3D printer?
	13	What additional items or services were included in the purchase package?
	14	How long did it take for the 3D printer to be delivered?
	15	What were the three main methods through which you learned to operate the 3D printer?
	16	What are the three main disadvantages of this 3D printer?
	17	How frequently do you use this 3D printer?
	18	Have you ever used a resin that was not recommended by the manufacturer of your 3D printer?
	19	What differences did you observe when using a non-recommended resin?
	20	What quantity of resin do you use, expressed in litres?
	21	Approximately how much do you spend on resin?
	22	Approximately how much have you spent on support and maintenance services?
	23	If you were to invest in 3D-printing equipment again, what would you do differently?

	24	How likely are you to recommend this 3D printer to another dental professional?
	25	How satisfied are you with the following aspects of this 3D printer?
	26	What is the main challenge or limitation you have experienced while using this 3D printer?
	27	If you could change one aspect of this 3D printer, what would it be?
	28	Do you have any additional comments or feedback regarding your experience with 3D printing?

III/4. DATA COLLECTION PROCEDURE

In the intraoral scanner study, the online questionnaire was distributed through the communication channels of the Institute of Digital Dentistry, Wellington, New Zealand. The survey link was disseminated via the Institute's newsletter and through professional social media platforms, including Instagram, Facebook, and LinkedIn. Data collection was performed during a one-month period between October and November 2022.

In the 3D printing study, the survey was conducted jointly by the Institute of Digital Dentistry, Wellington, New Zealand, and the Department of Prosthodontics, Semmelweis University, Budapest, Hungary. The digital survey link was distributed through organisational newsletters and professional social media platforms across 80 countries. Data were collected between August and October 2024.

Prior to data collection in the 3D printing study, a sample size calculation was performed using a 95% confidence level and a 7% margin of error. The calculation indicated that a minimum of 197 completed responses was required to achieve adequate representativeness. The final number of completed questionnaires exceeded this requirement.

III/5. DATA MANAGEMENT AND STATISTICAL ANALYSIS

In the intraoral scanner study, the collected data were stored and organised using Microsoft Excel. Statistical analysis was performed using Prism version 8.4.2 (GraphPad Software Inc., San Diego, CA, USA). Descriptive statistics were used to characterise the respondents and to summarise scanner ownership and use, accessibility, maintenance-related factors, software use, and satisfaction with the evaluated intraoral scanner systems. Depending on the type of variable, data were reported as means, standard

deviations, ranges, or absolute numbers with percentages. A designated member of the research team performed data collation and quality control.

In the 3D printing study, the collected data were initially organised and processed using Microsoft Excel, while statistical analyses were performed using StataNow version 18.5 (StataCorp LLC, College Station, TX, USA). Descriptive statistics were used to characterise the study population and summarise the distribution of responses. Depending on the type of variable, data were reported as means, standard deviations, ranges, or absolute numbers with percentages. Associations between categorical variables were assessed using Chi-square tests. The level of statistical significance was set at $p < 0.05$, and confidence intervals were reported at the 95% level. Data collation and quality control were performed by a designated member of the research team.

III/6. ETHICAL CONSIDERATIONS

Participation in both studies was voluntary. Respondents were informed about the purpose of the research, the anonymous nature of data collection, and the voluntary character of participation before completing the questionnaire. Consent was implied by the completion and submission of the online survey.

No financial or material incentives were offered to participants. The studies were conducted in accordance with the principles of the Declaration of Helsinki and Good Clinical Practice guidelines. As both investigations were anonymous questionnaire-based studies and did not involve clinical intervention, patient treatment, or identifiable patient-related data, formal ethical approval was not applicable.

During the preparation of the dissertation, AI was used to assist with English-language editing, including grammar, wording, and sentence structure. The scientific content, interpretation of the results, and conclusions were prepared by the author. All AI-assisted language modifications were reviewed and approved by the author.

IV. RESULTS

IV/1. STUDY POPULATIONS AND RESPONDENT CHARACTERISTICS

The intraoral scanner survey received a total of 1751 responses. Of these, 38.8% (n = 679) were excluded from the final analysis. Excluded responses included administrative staff, 5.5% (n = 96); industry experts, 4.6% (n = 80); office staff, 0.9% (n = 16); and partially completed questionnaires, 33.3% (n = 583). Following exclusion, 61.2% of the submitted responses (n = 1072) were retained for analysis. The final study population represented respondents from 109 countries (Figure 6).

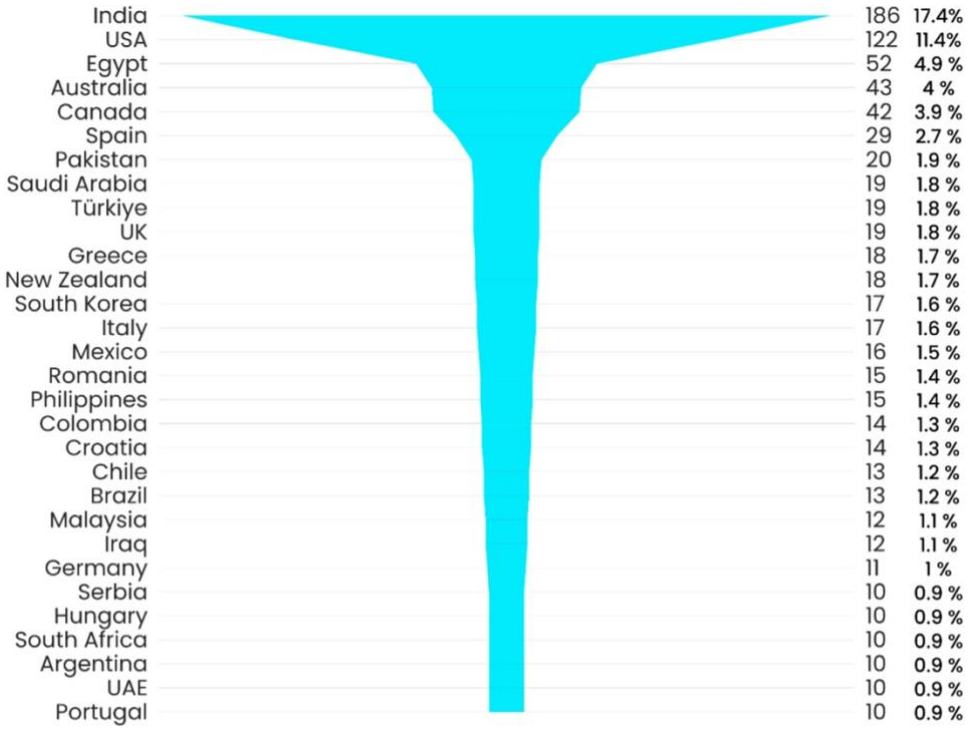


Figure 6: Geographical distribution of respondents in the intraoral scanner study (88)

The highest number of responses in the intraoral scanner study was received from India, with 17.4% (n = 186) of the final sample. This was followed by the United States, 11.4% (n = 122); Egypt, 4.9% (n = 52); Australia, 4.0% (n = 43); and Canada, 3.9% (n = 42). With regard to professional background, the majority of respondents were general dentists, representing 75.8% (n = 813) of the sample. Dental specialists accounted for

16.2% (n = 174), dental technicians for 4.7% (n = 50), dental students for 2.3% (n = 25), dental assistants for 0.7% (n = 7), and dental hygienists for 0.3% (n = 3).

The 3D printing survey received 924 responses. After removal of partially completed entries, 44.9% (n = 415), and duplicate submissions, 1.1% (n = 10), 499 valid completed questionnaires were included in the final analysis. The respondents represented 80 countries. The largest proportion of responses originated from the United States, 20.2% (n = 101), followed by Australia, 8.6% (n = 43); India, 8.0% (n = 40); Canada, 5.4% (n = 27); and New Zealand, 3.8% (n = 19) (Figure 7).

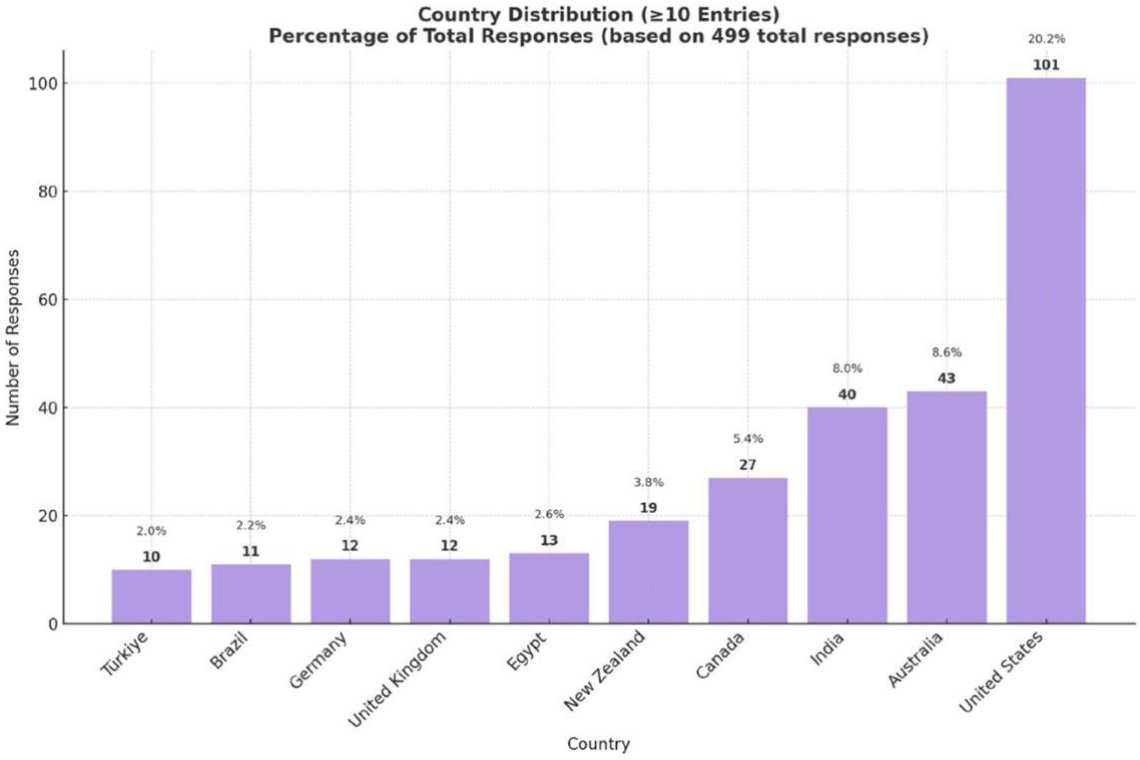


Figure 7: The top ten countries with the largest number of respondents of the 3D printing study (countries with fewer than 10 responders excluded) (87)

The mean age of participants in the 3D printing study was 45 ± 11.8 years. General dentists represented the largest professional group, 57.9% (n = 289), followed by dental specialists, 20.8% (n = 104); dental technicians, 7.4% (n = 37); and dental prosthetists, 4.2% (n = 21). Among dental specialists, prosthodontics was the most frequently

represented discipline, 38.9% (n = 58), followed by orthodontics, 15.4% (n = 23), and oral surgery, 15.4% (n = 23). Other specialties accounted for 30.3% (n = 45).

Most respondents in the 3D printing study were dental practice owners, 61.6% (n = 271). Associates accounted for 20.5% (n = 90), part-owners for 8.4% (n = 37), and managers for 5.0% (n = 22). The mean professional experience among dentists, dental specialists, and dental technicians was 20 ± 11.8 years.

IV/2. USE, EXPERIENCE, AND PERCEIVED ACCURACY OF DIGITAL DENTAL TECHNOLOGIES

Most respondents in the intraoral scanner study considered IOS technology to be more accurate than conventional casting or impression-related workflows. In total, 81.9% (n = 878) reported that, with the current level of technology, intraoral scanners are more accurate than traditional methods, whereas 18.1% (n = 194) considered traditional methods to be more accurate. Only 0.9% (n = 10) stated that digital technology would not become more accurate in the future.

A total of 78.8% (n = 845) of respondents reported using intraoral scanners in their daily work, whereas 21.2% (n = 227) had no daily experience with IOS. Among IOS users, 17.9% (n = 151) had more than five years of experience, 12.9% (n = 109) had three to five years of experience, 34.3% (n = 290) had one to three years of experience, 25.3% (n = 214) had less than one year of experience, and 9.6% (n = 81) had less than one month of experience.

The mean number of intraoral scanners owned by respondents was 1.5 ± 0.9. With regard to self-reported competence, 24.7% (n = 209) considered themselves expert users, 45.7% (n = 386) intermediate users, and 29.6% (n = 250) beginners. The most frequently reported indication for intraoral scanning was the fabrication of fixed prosthetic restorations, which was reported by 85.6% (n = 723) of respondents.

Respondents reported the use of 36 different intraoral scanner systems. Regarding frequency of IOS use, 49.5% (n = 554) used their scanner daily, 27.1% (n = 303) used it two to three times per week, 9.7% (n = 108) used it once a week, 4.6% (n = 51) used it two to three times per month, 3.6% (n = 40) used it once a month, and 5.6% (n = 63) used it less than once per month.

In the 3D printing study, most respondents considered 3D printing more accurate than traditional workflows. This opinion was reported by 75.6% (n = 377), whereas 9.8% (n = 49) disagreed and 14.6% were uncertain. The difference between response categories was statistically significant ($p < 0.001$). Ownership data showed that 35.7% (n = 178) of respondents owned 3D printers only, 5.6% (n = 28) owned only milling machines, 34.9% (n = 174) owned both 3D printers and milling machines, and 23.8% (n = 119) owned neither technology. On average, respondents owned 2.9 ± 7.7 different 3D printers and 2.4 ± 5.2 milling machines.

The mean duration of 3D printing experience was 3.5 ± 2.9 years, and most respondents had used 3D printers for at least one year.

The most frequently reported applications of 3D printing were night guards, 13.9% (n = 241), and surgical guides, 13.7% (n = 238).

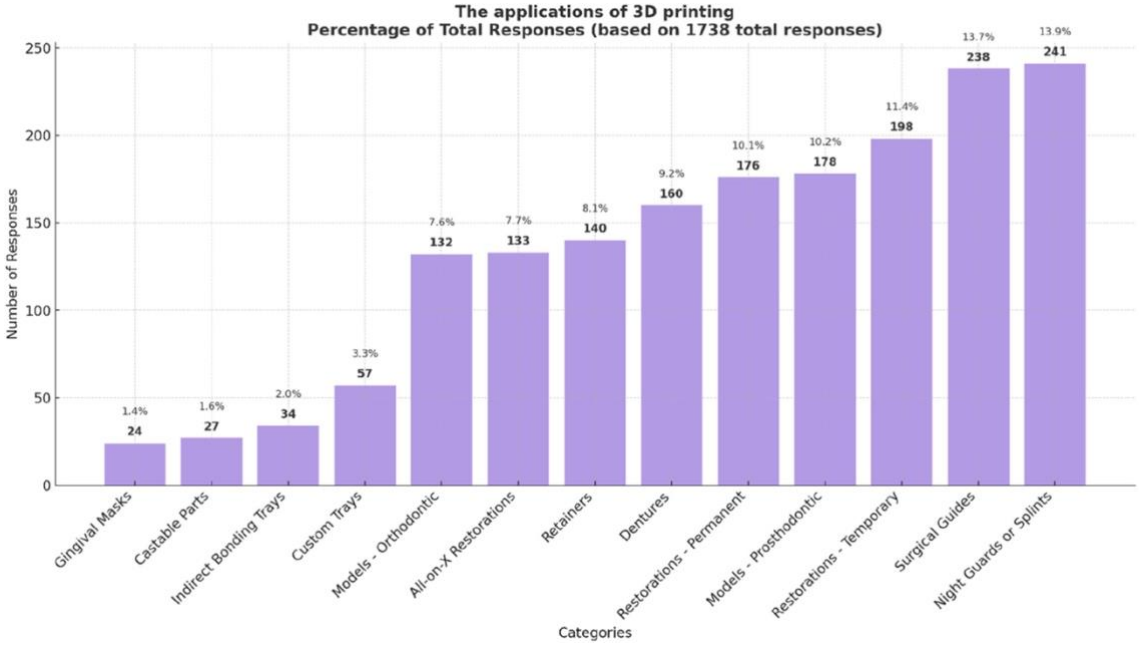


Figure 8: Applications of 3D printing, according to the multiple-choice questions (87)

These were followed by temporary restorations, 11.4% (n = 198); prosthodontic models, 10.2% (n = 178); permanent restorations, 10.1% (n = 176); complete dentures, 9.2% (n = 160); all-on-X restorations, 7.7% (n = 133); and orthodontic models, 7.6% (n = 132). Less

frequently reported applications included custom trays, castable parts, gingival masks, and bonding trays (Figure 8).

IV/3. DIGITAL WORKFLOW INTEGRATION, PURCHASING FACTORS, INVESTMENT INTENTIONS, AND COSTS

A total of 38.62% (n = 414) of respondents in the intraoral scanner study reported performing CAD procedures using in-house software. Among CAD software users, 56.3% (n = 233) had purchased software for in-house use. Reported software costs ranged from free software provided by some distributors to software packages costing more than USD 20,000. Among CAD users, 40.3% (n = 94) reported having access to free software upgrades.

In-house manufacturing equipment was also reported by a proportion of respondents in the intraoral scanner study. Overall, 31.5% (n = 338) had CAM tools available in-house. Among them, 11.8% (n = 126) reported having both a milling machine and a 3D printer, 9.8% (n = 105) had only a milling machine, and 10.0% (n = 107) had only a 3D printer.

More than two-thirds of respondents, 68.6% (n = 768), were actively involved in the purchase of their intraoral scanner. In addition, 40.1% (n = 457) had participated in education or training before purchasing the system. The most commonly reported reason for purchasing the selected scanner was recommendation by colleagues, 26.2% (n = 201). This was followed by the presumed accuracy of the system, 19.4% (n = 149); brand reputation, 16.0% (n = 123); price, 15.8% (n = 121); software design, 14.5% (n = 111); and miscellaneous reasons, 8.2% (n = 63).

In the 3D printing study, approximately two-fifths of respondents reported outsourcing at least part of their work to external laboratories. Among respondents who had not invested in in-house manufacturing, the most frequently reported barrier was equipment cost, 27.9% (n = 77). Other reported barriers included lack of skilled personnel, 16.7% (n = 46); insufficient training, 14.5% (n = 40); unreliable support, 11.2% (n = 31); and adequate satisfaction with external laboratories, 9.4% (n = 26).

Future investment intentions indicated greater interest in 3D printing than in milling alone. A total of 35.9% (n = 179) planned to invest only in 3D printers, 3.4% (n = 17) planned to invest only in milling equipment, and 37.9% (n = 189) intended to invest in

both 3D printing and milling. A smaller group, 6.8% (n = 34), did not plan to invest in either technology.

Among respondents willing to invest, 17.7% (n = 65) planned investment within three months, 13.3% (n = 49) within six months, and 33.2% (n = 122) within twelve months. A further 11.1% (n = 41) preferred to invest after one year, whereas 24.7% (n = 91) were uncertain about the timing. Among respondents who did not plan to invest, the most frequently reported reasons were high costs, 23.5% (n = 8); concerns regarding return on investment, 23.5% (n = 8); and inadequate third-party services, 17.6% (n = 6).

Validated workflows were associated with investment intention. A total of 46.5% (n = 232) of respondents reported that they would be confident to invest in 3D printing if validated workflows were available, while 40.3% (n = 201) indicated that they would be likely to invest under such conditions.

Investment in milling technology was reported less frequently than investment in 3D printing. Among the 206 respondents who were willing to invest in milling equipment, 36.4% (n = 75) were unsure about the timeframe, 22.8% (n = 47) planned to invest within twelve months, and 26.2% (n = 54) planned to invest after twelve months. Among those intending to purchase milling equipment, the majority planned to buy systems capable of both wet and dry milling, 76.2% (n = 157), while the remaining respondents were divided between wet-only and dry-only milling systems.

Most respondents using 3D printers or milling machines performed digital design in-house, 88.3% (n = 316). Zirconia was the most frequently reported milling material, 28.0% (n = 168), followed by glass ceramic, 16.0% (n = 96), and PMMA, 14.6% (n = 88) (Figure 9).

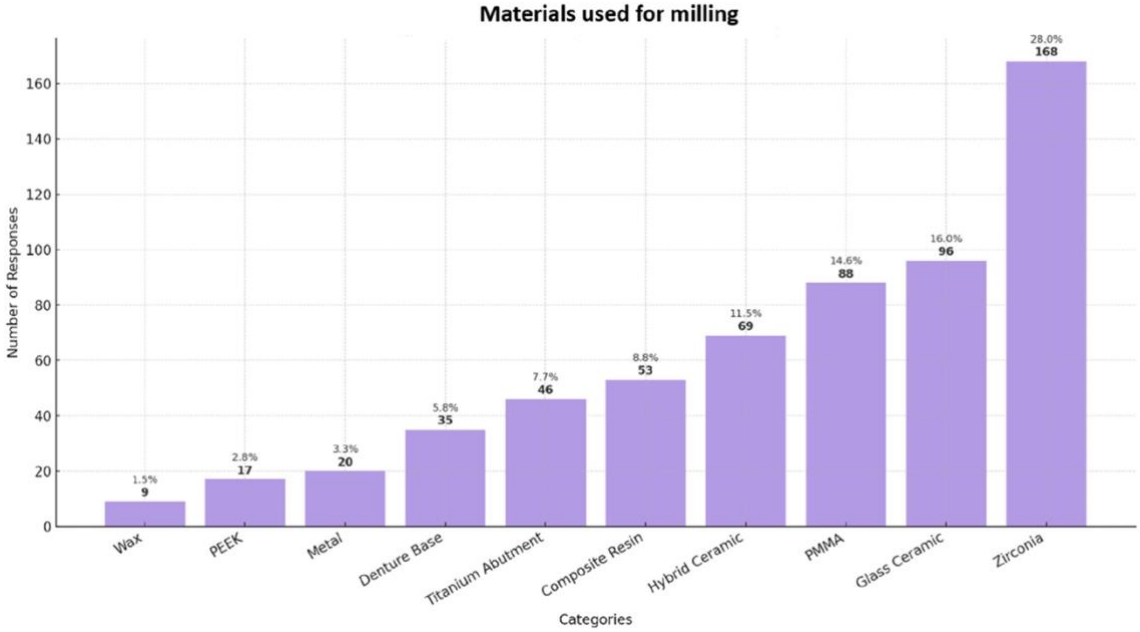


Figure 9: Materials used for milling, according to the multiple-choice question (87)

Among respondents with 3D printing experience (n = 477), the availability of a wide range of milling materials was considered very important by 53.2% (n = 254) and important by 27.7% (n = 132). Fewer respondents considered it moderately important, 11.5% (n = 55), or somewhat important, 6.5% (n = 31).

The most frequently reported CAD software programs in the 3D printing study were Exocad, 21.0% (n = 165); Medit Design, 15.1% (n = 119); and Meshmixer, 14.9% (n = 117). Reported software costs varied widely, with a mean value of USD 4440 ± 6560 and a maximum reported cost of USD 30,000 (Figure 10).

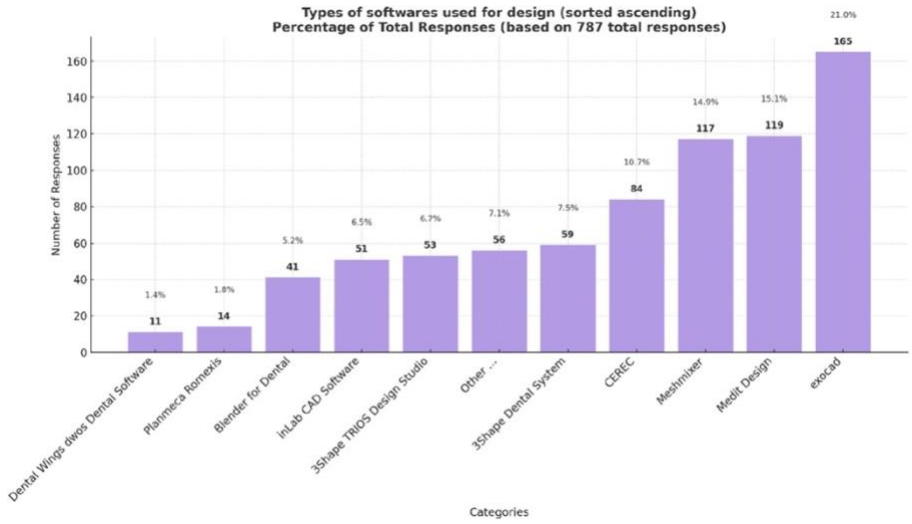


Figure 10: CAD software used and their popularity among respondents (87)

IV/4. DEVICE-SPECIFIC SATISFACTION, POST-PROCESSING, MAINTENANCE, AND REPORTED LIMITATIONS

Respondents in the intraoral scanner study evaluated their selected scanner on a scale from 1 to 5 in relation to speed, support system, accessibility, price, and overall quality. Devices assessed by fewer than 10 respondents were excluded from the ranking analysis. The highest overall satisfaction scores were reported for Medit i700 Wireless, 4.77; Medit i700, 4.50; and Dentsply Sirona Primescan, 4.49 (Table 3).

Table 3: The quality of the different intraoral scanners (IOS) as evaluated by the responders (88)

Type of intraoral scanner	n=	Overall	Speed	Support	Accessibility	Price
Medit i700	179	4.50	4.47	4.30	4.27	4.14
3Shape TRIOS 3	162	4.19	4.22	3.70	4.02	3.26
Dentsply Sirona Primescan	121	4.49	4.52	3.88	4.23	3.51
CEREC Omnicam	106	3.68	3.46	3.50	3.89	3.10
Medit i500	106	4.24	3.86	4.02	4.37	3.95
3Shape TRIOS 4	60	4.35	4.38	3.72	4.09	3.55
iTero Element 2	42	3.76	3.62	3.95	3.86	3.24
Medit i600	39	4.41	4.31	4.31	4.22	4.22
Shining 3D Aoralscan 3	39	4.15	4.44	4.05	4.35	4.12
Medit i700 Wireless	31	4.77	4.77	4.61	4.45	4.55
iTero Element 5D Plus	28	4.25	4.29	4.04	4.32	3.36
3DISC Heron IOS	25	3.64	3.52	3.68	4.29	4.00
Dexis Carestream CS 3600	17	3.47	3.18	3.29	4.20	3.00
iTero Element 5D	17	3.94	4.06	3.88	4.50	3.17
Straumann Virtuo Vivo	16	3.86	3.56	3.94	4.44	4.44
Planmeca Emerald S	13	4.00	3.92	4.31	4.17	3.17
Eighteeth Helios 600	12	4.25	4.25	4.00	4.38	4.13
iTero Element Flex	11	4.27	4.36	4.27	4.60	4.00
Panda P2	11	4.09	4.09	3.91	4.22	4.33
Planmeca Emerald	11	3.90	3.82	4.36	4.20	3.30
3Shape TRIOS 5	10	4.00	3.90	3.70	3.50	3.17

For speed, the highest-rated scanners were Medit i700 Wireless, 4.77; Dentsply Sirona Primescan, 4.52; and Medit i700, 4.47. The highest support ratings were reported for Medit i700 Wireless, 4.61; Planmeca Emerald, 4.36; and Medit i600, 4.31. Accessibility was rated highest for iTero Element Flex, 4.60; iTero Element 5D, 4.50; and Medit i700 Wireless, 4.45. Regarding price satisfaction, the highest scores were recorded for Medit i700 Wireless, 4.55; Straumann Virtuo Vivo, 4.44; and Panda P2, 4.33.

The most frequently reported disadvantage of the selected intraoral scanner was price, reported by 29.8% (n = 333) of respondents. Other disadvantages included scanning speed, 13.9% (n = 155); software quality, 10.3% (n = 115); support service, 8.0% (n = 89); and the provided training course, 7.1% (n = 80). In contrast, 17.6% (n = 197) of respondents reported no major disadvantage and stated that they were satisfied with their purchased IOS.

Annual maintenance costs related to intraoral scanner ownership varied substantially. More than half of the respondents, 53.1% (n = 595), reported no annual maintenance cost. Maintenance expenses of USD 101–250 were reported by 5.3% (n = 60), USD 251–500 by 5.9% (n = 66), USD 500–1000 by 7.51% (n = 84), USD 1001–2000 by 8.31% (n = 93), USD 2001–5000 by 9.4% (n = 106), and more than USD 5000 by 2.5% (n = 28).

In the 3D printing study, the most commonly owned post-processing tools were UV curing units, 22.9% (n = 323), and wash stations, 20.7% (n = 292). These were followed by finishing tools, 15.8% (n = 223); hand polishers, 12.8% (n = 180); staining and glazing equipment, 11.6% (n = 164); and ultrasonic cleaners, 9.9% (n = 140).

Among respondents who owned both washing and curing units (n = 363), most had purchased these units from the same brand, 67.8% (n = 246; $p < 0.05$). Most users followed the manufacturer's post-processing guidelines, 89.5% (n = 324). Post-processing was completed within 60 minutes by 97.0% of users. Specifically, 30.7% (n = 103) reported post-processing times below 15 minutes, 42.4% (n = 142) reported 15–30 minutes, and 23.9% (n = 80) reported 30–60 minutes.

Separate equipment for biocompatible materials was used by 45.3% (n = 156), while 32.0% (n = 110) used the same equipment for all material types. A further 22.7% did not use biocompatible materials. Among respondents using isopropyl alcohol (n = 351), only 19.7% reported recycling it, whereas 58.7% did not; the remaining respondents were uncertain about recycling practices.

The most frequently reported concerns related to 3D printing were long-term stability, 24.7% (n = 369); possible toxicity or allergic reactions associated with resins, 19.8% (n = 269); and biocompatibility issues, 17.3% (n = 259) (Figure 11).

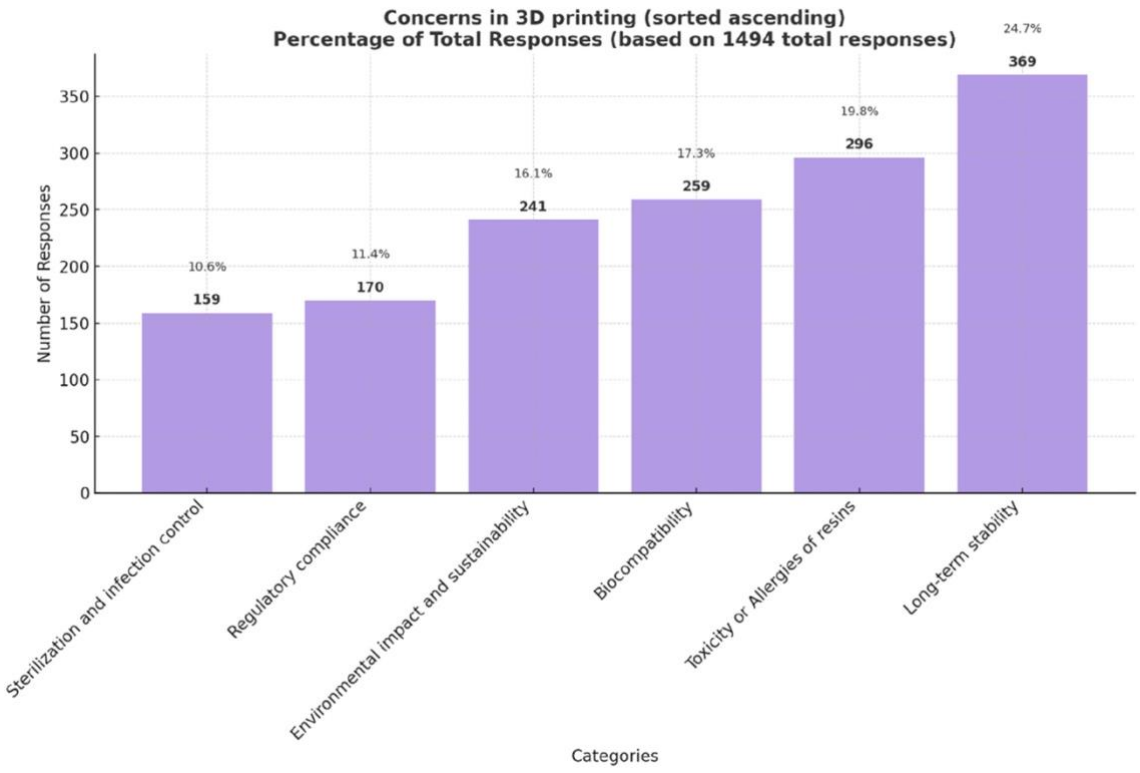


Figure 11: Key concerns in 3D printing, according to the multiple-choice question (87)

A subgroup of 291 respondents provided information about the brands and models of 3D printers they owned. Among them, 188 respondents also provided detailed information on their reasons for choosing specific models and their overall satisfaction. SprintRay was the most frequently reported 3D printer brand, 21.0% (n = 61), followed by Phrozen, 16.8% (n = 49), and Formlabs, 12.4% (n = 36). Commonly reported models included Pro 55 S, Form 3B+, and Sonic Mini 4K.

The most important factors influencing the purchase of a 3D printer were ease of use, 44.0%; print quality and accuracy, 37.2%; brand reputation, 35.1%; price, 29.8%; resin options, 22.9%; availability of consumables and spare parts, 22.9%; and print speed, 14.9%.

The mean reported price of a 3D printer was USD 7790 ± 6440. The highest reported model price was USD 22,140 for Primeprint, whereas the lowest was USD 250 for Photon Mono 4K. Performance ratings on a scale from 1 to 5 showed that Primeprint received the highest score, 4.22, followed by Form 4B, 4.12, and Pro 55 S, 4.04. Lower average scores were reported for Mighty 8K, 3.39; AccuFab-L4D/L4K, 3.32; and Photon Mono 4K, 3.25 (Figure 12).



Figure 12: A bar chart depicting the average user satisfaction scores of selected 3D printer models: (a higher rating (darker shades) indicates increased user satisfaction) (87)

V. DISCUSSION

The present thesis investigated the everyday use of intraoral scanners and 3D printing systems in dentistry. These technologies represent two closely related stages of the digital workflow: intraoral scanners collect clinical data, while 3D printers convert digitally designed data into physical dental products. By examining both areas, the studies provided insight into how dental professionals select, introduce and use digital technologies outside controlled laboratory conditions.

Overall, respondents had a favourable opinion of both technologies. Intraoral scanners were frequently used in everyday practice, and 3D printing was applied across a broad range of clinical and laboratory indications. Most participants also considered digital methods more accurate than conventional alternatives. At the same time, the results showed that successful implementation was influenced by more than the technical performance of the equipment. Purchase price, software, training, maintenance, technical support, post-processing and compatibility with the existing workflow all contributed to the user experience.

Laboratory investigations are essential for determining precision, material properties and manufacturing accuracy of 3D printed dental products. However, these studies cannot fully describe how a system performs in an everyday dental practice. A device may produce accurate results under fully controlled situations but still be difficult to introduce because of complicated software, insufficient training, high operating costs or unreliable support. User experience therefore provides a different type of information and complements technical and clinical investigations that can be valuable for general dentists.

The accuracy reported in the two surveys should be considered with caution. Neither study objectively measured trueness, precision, marginal fit or long-term clinical performance. The responses instead reflected the confidence that users placed in the technologies. This difference is important, although perceived accuracy remains clinically relevant because it may influence purchasing decisions, frequency of use and willingness to extend a digital workflow to new indications.

V/1. INTRAORAL SCANNERS IN EVERYDAY DENTAL PRACTICE

The intraoral scanner study showed that optical impression-taking was already well established among the respondents. Most IOS users applied the technology regularly, and approximately half reported daily use. Fixed prosthodontic restorations were the most common indication, which is consistent with the established role of digital impressions in restorative and prosthodontic digital dental workflows. Digital impressions may reduce impression-taking time, avoid errors related to impression materials and gypsum casts, improve communication with the dental laboratory and increase patient comfort, particularly among patients with a pronounced gag reflex (29, 30, 32, 33).

Frequent IOS use should not be interpreted as the complete replacement of conventional impressions. Available evidence indicates that digital impressions perform well for single restorations and short-span prostheses, while complete-arch, edentulous and multiple-implant situations may remain more difficult (34, 38-40, 46, 47). Accuracy may also be influenced by the scanner model, scanning strategy, operator experience, saliva, reflective surfaces and restricted intraoral access (41-45). The favourable opinion of the respondents therefore reflects general confidence in digital impression-taking, but it does not mean that all scanners or all clinical indications provide the same level of predictability.

Experience and training are also relevant. A substantial proportion of respondents had used IOS technology for fewer than three years, and almost one-third described themselves as beginners. Previous investigations have shown that scanning efficiency improves with practice and that the learning curve may differ between systems (31). The transition to digital impression-taking therefore involves the development of a new clinical skill rather than simply replacing one piece of equipment with another. Training before purchase and instruction provided by the distributor may help clinicians understand scanning strategy, software operation and the limitations of the selected device.

The expectation that digital technology will continue to improve was almost universal. This is understandable because scanner hardware and software are regularly updated by manufacturers, and a newer scanner may offer improved complete-arch accuracy (45, 47). AI-supported functions may also assist in recognising scanning defects, removing unwanted structures and improving the digital model (48, 49). However, software

processing cannot eliminate every source of clinical error. Automated correction may improve the appearance of a mesh without necessarily reproducing missing anatomical information accurately. Continued independent evaluation is more than required when new scanners or software functions are introduced.

The purchasing data demonstrated that scanner selection was a multidimensional decision. Recommendations from colleagues were the most frequently reported reason for choosing a system, followed by accuracy, brand reputation, price and software design. Individual recommendations may be particularly influential in a rapidly changing market where systems have similar advertised specifications but are different in their software, service models and operating costs. Experiences shared by colleagues can provide practical information that is not always available in technical documentation.

At the same time, reliance on individual feedback has limitations. A scanner that performs well in one practice may not be the most appropriate option in another. The required indications, relationship with the dental laboratory, preferred software, number of users and expected case volume may all differ. Selection should therefore be based on the intended workflow rather than on brand reputation or a single device characteristic.

The results also showed that IOS adoption did not always lead to a completely in-house digital workflow. Fewer respondents performed CAD or CAM procedures in their own practice than used an intraoral scanner. This suggests that digitalisation often happens gradually. A dental practice can first introduce IOS and continue sending files to an external laboratory without investing immediately in design software, milling equipment, 3D printers and post-processing units. In-house manufacturing may be introduced later when the number of digital cases, professional experience and financial conditions allow further development.

Software formed an important part of the scanner experience. The practical value of an IOS depends not only on the camera itself but also on STL file export, laboratory communication, software updates, integration with different design programs. Closed systems or recurring software fees may restrict flexibility, while open file formats can make cooperation with different laboratories easier. Consequently, the scanner should be evaluated as part of a wider digital environment rather than as an isolated device.

Price was the most frequently reported disadvantage of IOS systems. Although more than half of respondents reported no annual maintenance cost, others reported considerable

yearly expenses. This difference reported by individuals probably shows differences in service contracts, subscriptions, software licences, distributor policies and geographical markets. The initial purchase price therefore gives only a partial picture of the financial burden. Upgrade fees, repairs, support services and required computer hardware may also contribute to the total cost of ownership.

The financial relevance of these costs is likely to have a difference between dental practices. A dental clinic with a high number of prosthodontic or orthodontic cases may use the scanner frequently enough to validate the investment, meanwhile the same system may be less economical in a practice with limited demand. The present study did not include a formal cost-effectiveness analysis, so no conclusion can be drawn regarding the financial superiority of digital over conventional impression-taking. The results show that transparent information about both purchase and ongoing costs is necessary before a system is selected.

Users rated their scanners separately for overall satisfaction, speed, support, accessibility and price. The variation between these categories indicates that scanner quality cannot be represented by a single aspect. Some systems received favourable ratings for speed but lower ratings for price or support, while others were valued for accessibility. The final opinion of the user therefore reflects a combination of hardware, software and service-related experiences.

The device-specific ratings should not be interpreted as a definitive ranking. The numbers of respondents differed considerably between scanner models. Some systems were evaluated by more than one hundred users, whereas others only reached the minimum inclusion criteria. Ratings were also not adjusted for professional experience, clinical indication, purchase year, local distributor or regional price differences. It is more appropriate to state that certain devices received high satisfaction scores within the investigated population than to identify one system as objectively superior.

V/2. ADOPTION AND CLINICAL INTEGRATION OF 3D PRINTING

The 3D printing study showed that additive manufacturing had been introduced into a wide range of dental workflows. Night guards and surgical guides were the most frequently reported applications, but temporary restorations, prosthodontic models,

complete dentures, definitive restorations and full-arch prostheses were also produced. This broad range reflects the rapid development of printable materials and the expansion of dental indications described in the literature (67-72).

The applications reported by the participants differed in their clinical complexity. The manufacture of models and surgical guides is already supported by established digital procedures, while definitive restorations require greater confidence in material properties, post-processing and long-term behaviour. The reported use of permanent restorations is therefore an important sign of technological development.

Most participants considered 3D printing more accurate than conventional manufacturing methods. As in the IOS study, this represents self-reported user experience rather than an objective comparison. Additive manufacturing accuracy is affected by several stages of the workflow, including digital design, slicing, printing orientation, layer thickness, support placement, washing, curing and finishing. Printer resolution alone does not determine the final accuracy of a dental product. For this reason, the complete production procedure must be considered when evaluating the reliability of a system.

A large proportion of respondents owned 3D printers, and many also owned milling machines. Future investment intentions followed a similar pathway, with greater interest in 3D printing than in milling alone and interest in having both technologies. These results suggest that additive and subtractive manufacturing are not viewed simply as competing methods. Instead, they can fulfil different roles within the same digital workflow.

Milling remains important for established restorative materials such as zirconia, glass ceramics and PMMA. Three-dimensional printing offers advantages for complex geometries, customised appliances and the simultaneous production of several objects.

The complementary role of additive and subtractive manufacturing is also supported by the findings of Packaeser et al. (89). Their scoping review indicated that 3D printing may offer lower material costs, lower initial investment and less material waste than milling, particularly in high-volume production, whereas milling may remain advantageous when high precision and mechanical strength are required. The appropriate manufacturing process depends on the indication, material requirements, desired mechanical properties and production volume. Rather than replacing milling in every area, additive manufacturing appears to extend the range of procedures that can be performed in-house.

Equipment cost was the most frequently reported limitation among respondents who had not invested in in-house manufacturing. Lack of skilled personnel, insufficient training and unreliable support were also relevant facts. These findings demonstrate that access to the printer alone is not sufficient. A successful workflow requires personnel who can perform digital design, prepare files, operate the equipment, carry out post-processing and assess the quality of the final product.

The presence of equipment does not necessarily mean that it will be used efficiently. In-house production may reduce dependence on an external laboratory and make shorter certain workflows, but it also increases the responsibility for the manufacturing process within the dental practice or laboratory. Staff time, material storage, equipment cleaning, failed prints, maintenance and quality control must all be considered. For practices with a limited number of suitable cases, outsourcing will still be the first choice.

Muhetaer et al. reported that the main barriers to the adoption of 3D-printed implant surgical guides were high initial costs, complex and time-consuming digital design, and a lack of expertise (90). These findings are consistent with the present results, in which equipment costs, insufficient training, lack of skilled and unreliable technical support were among the most frequently reported obstacles to in-house manufacturing. The agreement between the studies indicates that the successful implementation of additive manufacturing depends not only on access to a printer but also on the availability of trained personnel and an adequately supported digital workflow.

Uncertainty regarding return on investment was also reported by respondents who were not planning to purchase equipment. The economic value of in-house manufacturing is likely to depend on case volume, outsourcing fees, material consumption, labour requirements and the proportion of unsuccessful production attempts. As these factors were not calculated in the study, the results cannot establish whether purchasing a printer is more economical than continuing to use external production services.

The availability of validated workflows had a marked influence on investment confidence. Most respondents indicated that they would be more confident or more likely to invest if validated procedures were available. This suggests that uncertainty is not limited to the selection of a certain 3D printer. Users also need predictable compatibility between the printer, the software, the material and the post-processing equipment.

A validated workflow should define the relevant production parameters, including printing orientation, layer thickness, support structures, washing, drying, post-curing and finishing. Changing one component can affect accuracy, lifespan and biocompatibility. Results achieved with one combination of equipment and material cannot automatically be transferred to another 3D printing device. Clear protocols are particularly important for products that are intended for permanent clinical use.

Similar barriers were identified by Hatamleh et al., who found that the wider adoption of digital dentistry was restricted by high costs, limited training, material unavailability and insufficient in-house expertise (91). Their findings support the present observation that access to validated workflows may increase investment confidence. A validated workflow can reduce uncertainty by defining compatible combinations of printers, materials and post-processing procedures, although it cannot replace the need for appropriate professional training.

The ease of use was one of the most important factors influencing printer selection, together with print quality, presumed accuracy, brand reputation and price. This result highlights the practical requirements of routine manufacturing. A technically advanced printer may have limited value when the usage of software is difficult, materials are unavailable or post-processing is complicated. A system with a straightforward workflow may be attractive even when it does not provide the highest quality outcome.

Material availability was also important. The range of compatible resins determines which clinical indications can be produced with a system. Open-material systems may provide greater flexibility, whereas closed systems may offer simplified validation and support. These approaches involve different advantages and limitations, and the preferred option depends on the user's experience, intended applications and willingness to manage production parameters independently.

The reported price of 3D printers varied considerably, ranging from relatively inexpensive desktop units to integrated professional systems. Direct comparison based only on purchase price may be confusing. More expensive systems may include dedicated software, automated functions, validated materials and integrated post-processing. Lower-cost devices may provide greater flexibility but require more control and user experience. Additional expenses include washing and curing units, consumables, ventilation, maintenance and finishing equipment.

Similar to the IOS results, the printer-specific satisfaction scores should be considered exploratory. The evaluated models differed in price, automation, intended use and number of responses. A high average rating does not necessarily demonstrate greater accuracy or clinical performance. It reflects satisfaction among the users who selected and evaluated that particular device.

V/3. POST-PROCESSING, SAFETY AND SUSTAINABILITY

Post-processing is an integral part of additive manufacturing. Printed objects generally require washing to remove uncured resin, followed by post-curing to complete polymerisation and achieve the intended material properties (61, 62). Finishing, polishing and glazing may also be required according to the clinical indication. The quality of the final product therefore depends on more than the printing stage itself.

Most respondents reported following the manufacturer's post-processing recommendations.

Variations in washing time, curing temperature, light intensity and object orientation may influence the properties of the final product.

Post-processing was generally completed within 60 minutes. This suggests that the procedure can be easily integrated into routine clinical or laboratory work. However, the reported time may not have included every related task, such as removal of support structures, cleaning of equipment, replacement of solvent, polishing and quality control. The actual working hour requirement may therefore be greater than the curing or washing time alone.

Most respondents who owned both washing and curing units had purchased them from the same manufacturer. This may reflect a preference for integrated systems in which the individual components are designed and validated together. Such systems can simplify material selection and reduce uncertainty about compatibility. At the same time, dependence on one manufacturer may reduce flexibility and increase the cost of materials and equipment. The present study did not compare the performance of same-brand and mixed-brand workflows, so no conclusion can be drawn regarding their relative quality.

The use of separate equipment for biocompatible materials varied between participants. Some respondents used dedicated equipment, while others used the same washing and

curing units for different material types. This finding indicates a need for clearer guidance regarding cleaning, material separation and the prevention of cross-contamination. However, the questionnaire did not assess the cleaning procedures used, and it cannot be concluded that shared equipment resulted in unsafe products.

The importance of following the recommended washing protocol is supported by Hwangbo et al., who demonstrated that washing time and washing solution influenced both the biocompatibility and mechanical properties of 3D-printed dental resins (92). Increasing the washing time improved cell viability and reduced cytotoxicity, although excessively prolonged washing adversely affected certain mechanical properties.

Long-term stability was the most frequently reported concern, followed by possible resin toxicity, allergic reactions and biocompatibility. These responses describe uncertainty among users rather than confirmed adverse effects. Nevertheless, they show that the expansion of printed definitive restorations has occurred alongside continued concern about their long-term clinical behaviour.

These issues are particularly relevant for 3D printing materials because their final properties depend on resin composition and the degree of polymerisation. Inadequate washing or curing may influence residual monomer content, surface quality and mechanical properties. Independent clinical studies and long-term follow-up are therefore required, especially for printed restorations intended for permanent use.

Sustainability was another area in which practices differed. Only a minority of participants using isopropyl alcohol reported recycling it. Additive manufacturing also produces support structures, failed objects, resin-contaminated materials and disposable containers. Although printing may use less bulk material than subtractive manufacturing for certain objects, the environmental effect of the complete workflow cannot be judged from material efficiency alone (73-75).

Shinkai et al. also identified material waste, residual chemicals, single-use materials and inappropriate disposal as important sustainability challenges in prosthodontic workflows (93). The present finding that only 19.7% of respondents using isopropyl alcohol reported recycling it provides practice-based support for these broader concerns.

Waste reduction, correct disposal and prevention of failed prints should therefore be included in the development of dental printing protocols. The studies did not measure

actual waste production, energy consumption or emissions. Its findings identify variation in reported practice rather than quantify the environmental impact of dental 3D printing.

V/4. IMPLICATIONS FOR DIGITAL DENTAL WORKFLOWS

A common finding of both studies was that users evaluated more than the physical device. Satisfaction with an IOS was affected by software, technical support, accessibility and maintenance costs. The implementation of 3D printing was influenced by material availability, post-processing, training and validated procedures. Digital equipment should therefore be assessed as part of a complete workflow.

The individual user remains a central component of this workflow. Training and experience affect whether the technical capabilities of the equipment can be achieved in practice. Introducing new hardware without sufficient education may produce unsatisfactory results even when the device itself is capable of high performance. Training should cover not only basic operation but also clinical indications, limitations, maintenance and quality control.

For many practices digitalisation may be more realistic than the immediate introduction of a complete in-house workflow. Intraoral scanning can be adopted while design and manufacturing remain outsourced. This approach may reduce financial risk and allow the dental team to develop digital competence over time.

The most suitable workflow is unlikely to be the same for every setting. A small general dental practice, a multidisciplinary clinic and a dental laboratory have different case volumes and production requirements. Purchasing decisions should therefore begin with the intended applications and available personnel rather than with the advertised performance of a particular system.

Manufacturer information is necessary for understanding technical specifications and validated indications, but it cannot describe every aspect of routine use. Independent user feedback may reveal practical barriers such as unexpected operating costs, inadequate training, software limitations and difficulties with support.

User experience, laboratory testing and clinical research should be considered together when digital technologies are evaluated.

V/5. STRENGTHS AND LIMITATIONS

A major strength of the thesis is the international outreach of the two studies. The IOS survey included respondents from 109 countries, while participants from 80 countries were represented in the 3D printing study. This allowed experiences to be collected from different professional and economic environments rather than from a single institution or country.

Another strength is the practical focus of the questionnaires. In addition to general use, the studies addressed purchasing decisions, costs, software, training, maintenance, support, post-processing and satisfaction with individual systems. These aspects are relevant to everyday practice but are rarely captured by laboratory investigations. Considering both intraoral scanning and manufacturing also provided a broader view of digital workflow integration.

Several limitations should also be acknowledged. Both investigations were cross-sectional and based on self-reported data. Responses may have been influenced by recall bias, personal expectations and differences in the interpretation of questions. Device ownership, purchase costs, professional experience and workflow practices were not independently verified.

Participants were recruited through newsletters of IDD, professional networks and social media. Individuals who followed digital dentistry platforms or had an interest in these technologies may have been more likely to respond. High-level users and early adopters may therefore have been overrepresented, while professionals with little experience or a negative attitude towards digital dentistry may have been less likely to participate.

Although the studies included respondents from many countries, their geographical distribution was unequal. A limited number of countries contributed a relatively large proportion of responses, while some countries were represented by only a few participants. The findings should consequently be described as international rather than globally representative.

Both questionnaires were distributed in English. This allowed standardised data collection but may have limited participation among professionals with insufficient

English-language proficiency. General dentists also formed the largest professional group in both studies, meaning that the findings may reflect the priorities of general clinical practice more strongly than those of dental laboratories or individual specialties.

Desired accuracy was approached through the opinion of the participants and was not supported by objective measurements. Similarly, satisfaction ratings describe the experience of the respondents but do not establish the technical superiority of one system over another.

The number of evaluations differed considerably between scanner and printer models. Device-specific scores based on small groups are less stable and more sensitive to individual experiences.

The cross-sectional design captured experience at a particular point in time. It cannot determine whether satisfaction changes as users gain experience, whether planned investments are completed or whether digital adoption improves clinical outcomes. Rapid technological development is also relevant, as software updates and newer device generations may change user experience after data collection.

Finally, the two studies were conducted at different times and used different questionnaires and analytical methods. Their results can be interpreted as complementary parts of the same research topic.

Future research should combine user-reported experience with objective measures of accuracy, production time, restoration quality, failure rates and clinical outcomes.

In vitro or clinical studies could investigate whether satisfaction changes with increasing experience and whether stated investment intentions result in actual purchases. Economic evaluations should include equipment, software, materials, maintenance, staff time, unsuccessful production and outsourcing costs.

Further IOS research should examine how experience is affected by clinical indication, scanning frequency, software openness and service model. Studies of 3D printing should focus on validated indication-specific workflows, the long-term behaviour of definitive materials, post-processing compliance, occupational safety and environmental impact. Standardised questionnaires would also improve comparisons between countries, professions and future generations of digital equipment.

VI. CONCLUSIONS

This PhD thesis intends to provide an international overview of the user experience of intraoral scanners and 3D printing systems in dentistry. The two published studies that are included in this work are the largest international cross-sectional studies carried out so far.

We can conclude that both technologies were generally perceived positively and had already been incorporated into a wide range of clinical and laboratory workflows in everyday dental practices. Intraoral scanners were primarily used for the acquisition of digital impressions, whereas 3D printing supported the in-house production of several prosthetic, surgical and diagnostic applications.

The findings demonstrate that the successful introduction of digital technology depends on more than technical specifications and data provided by the manufacturers.

Purchase and continued use were influenced by cost, usability, software, training, maintenance, technical support and compatibility with the existing workflow. In additive manufacturing, post-processing and the availability of validated protocols were also important, while uncertainty remained regarding long-term material stability, biocompatibility and sustainability.

Overall, real-world user experience provides information that cannot be obtained solely from laboratory investigations. Intraoral scanning and 3D printing should therefore be evaluated as complete workflows rather than isolated devices. Further development should focus on predictable clinical performance, accessible training, transparent costs, standardised procedures and independent long-term evidence.

VII. SUMMARY

Digital technologies are now part of everyday dental practice, but their value cannot be judged only from technical specifications or manufacturer information. This thesis examined how intraoral scanners and 3D printers are used and perceived by dental professionals in routine clinical and laboratory settings.

The dissertation was based on two international, cross-sectional questionnaire studies. The intraoral scanner survey included 1072 respondents from 109 countries, while the 3D printing survey included 499 completed questionnaires from 80 countries. The studies assessed professional experience, frequency of use, perceived accuracy, purchasing decisions, costs, workflow integration, satisfaction, and the main limitations reported by users.

In the intraoral scanner study, 78.8% of respondents used an IOS in their daily work, most often for fixed prosthodontic restorations. Most participants (81.9%) considered digital methods more accurate than conventional techniques. Scanner selection was influenced by colleague recommendations, expected accuracy, brand reputation, price, and software. Satisfaction was generally high, although ratings differed between devices, especially in terms of speed, support, accessibility, and cost. Price was the most frequently reported disadvantage.

In the 3D printing study, 75.6% of respondents considered additive manufacturing more accurate than traditional workflows. The most common applications were night guards, surgical guides, temporary restorations, prosthodontic models, and permanent restorations. Ease of use, print quality, brand reputation, price, and material availability were the main factors affecting printer selection. Interest in future investment was high, particularly when validated workflows were available. However, equipment costs, limited training, technical support, and uncertainty about return on investment remained important barriers.

The findings show that successful implementation depends on more than the device itself. Software, training, maintenance, technical support, post-processing, and reliable workflows all influence everyday use. User feedback therefore provides important information alongside laboratory studies and manufacturer data. Further research is needed on long-term clinical performance, safety, cost-effectiveness, and sustainability.

VIII. REFERENCES

1. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: current status and future perspectives from 20 years of experience. Dental Materials Journal. 2009;28(1):44-56.
2. Duret F, Preston JD. CAD/CAM imaging in dentistry. Curr Opin Dent. 1991;1(2):150-4.
3. Spitznagel FA, Boldt J, Gierthmuehlen PC. CAD/CAM Ceramic Restorative Materials for Natural Teeth. J Dent Res. 2018;97(10):1082-91.
4. Sannino G, Germano F, Arcuri L, Bigelli E, Arcuri C, Barlattani A. CEREC CAD/CAM Chairside System. Oral Implantol (Rome). 2014;7(3):57-70.
5. Davidowitz G, Kotick PG. The Use of CAD/CAM in Dentistry. Dental Clinics of North America. 2011;55(3):559-70.
6. Galhano G, Pellizzer EP, Mazaro JV. Optical impression systems for CAD-CAM restorations. J Craniofac Surg. 2012;23(6):e575-9.
7. Alghazzawi TF. Advancements in CAD/CAM technology: Options for practical implementation. Journal of Prosthodontic Research. 2016;60(2):72-84.
8. Alammar A, Kois JC, Revilla-León M, Att W. Additive Manufacturing Technologies: Current Status and Future Perspectives. Journal of Prosthodontics. 2022;31(S1):4-12.
9. Revilla-León M, Özcan M. Additive Manufacturing Technologies Used for Processing Polymers: Current Status and Potential Application in Prosthetic Dentistry. J Prosthodont. 2019;28(2):146-58.
10. Thakur J, Parlani S, Shivakumar S, Jajoo K. Accuracy of marginal fit of an implant-supported framework fabricated by 3D printing versus subtractive manufacturing technique: A systematic review and meta-analysis. The Journal of Prosthetic Dentistry. 2023;129(2):301-9.
11. Schwendicke F, Samek W, Krois J. Artificial Intelligence in Dentistry: Chances and Challenges. Journal of Dental Research. 2020;99(7):769-74.
12. Shan T, Tay FR, Gu L. Application of Artificial Intelligence in Dentistry. Journal of Dental Research. 2021;100(3):232-44.

13. Lee SJ, Poon J, Jindarojanakul A, Huang C-C, Viera O, Cheong CW, et al. Artificial intelligence in dentistry: Exploring emerging applications and future prospects. J DENTISTRY. 2025;155:105648.
14. Lee SJ, Chung D, Asano A, Sasaki D, Maeno M, Ishida Y, et al. Diagnosis of Tooth Prognosis Using Artificial Intelligence. Diagnostics (Basel). 2022;12(6).
15. Schropp L, Sørensen APS, Devlin H, Matzen LH. Use of artificial intelligence software in dental education: A study on assisted proximal caries assessment in bitewing radiographs. European Journal of Dental Education. 2024;28(2):490-6.
16. Sabri H, Saleh MHA, Hazrati P, Merchant K, Misch J, Kumar PS, et al. Performance of three artificial intelligence (AI)-based large language models in standardized testing; implications for AI-assisted dental education. J Periodontal Res. 2025;60(2):121-33.
17. Rutkūnas V, Auškalnis L, Pletkus J. Intraoral scanners in implant prosthodontics. A narrative review. J DENTISTRY. 2024;148:105152.
18. Mangano F, Gandolfi A, Luongo G, Logozzo S. Intraoral scanners in dentistry: a review of the current literature. BMC Oral Health. 2017;17(1):149.
19. Martin CB, Chalmers EV, McIntyre GT, Cochrane H, Mossey PA. Orthodontic scanners: what's available? Journal of Orthodontics. 2015;42(2):136-43.
20. Imburgia M, Logozzo S, Hauschild U, Veronesi G, Mangano C, Mangano FG. Accuracy of four intraoral scanners in oral implantology: a comparative in vitro study. BMC Oral Health. 2017;17(1):92.
21. Aragón MLC, Pontes LF, Bichara LM, Flores-Mir C, Normando D. Validity and reliability of intraoral scanners compared to conventional gypsum models measurements: a systematic review. European Journal of Orthodontics. 2016;38(4):429-34.
22. Zimmermann M, Mehl A, Mörmann WH, Reich S. Intraoral scanning systems - a current overview. Int J Comput Dent. 2015;18(2):101-29.
23. Richert R, Goujat A, Venet L, Viguie G, Viennot S, Robinson P, et al. Intraoral Scanner Technologies: A Review to Make a Successful Impression. J Healthc Eng. 2017;2017:8427595.
24. Baba NZ, Goodacre BJ, Goodacre CJ, Müller F, Wagner S. CAD/CAM Complete Denture Systems and Physical Properties: A Review of the Literature. Journal of Prosthodontics. 2021;30(S2):113-24.

25. Anderson J, Wealleans J, Ray J. Endodontic applications of 3D printing. International Endodontic Journal. 2018;51(9):1005-18.
26. Charavet C, Van Hede D, Maes N, Albert A, Lambert F. Disentangling the effects of CAD/CAM customized appliances and piezocision in orthodontic treatment. Angle Orthod. 2021;91(6):764-71.
27. Kapos T, Evans C. CAD/CAM technology for implant abutments, crowns, and superstructures. Int J Oral Maxillofac Implants. 2014;29 Suppl:117-36.
28. Elnagar MH, Aronovich S, Kusnoto B. Digital Workflow for Combined Orthodontics and Orthognathic Surgery. Oral and Maxillofacial Surgery Clinics of North America. 2020;32(1):1-14.
29. Yuzbasioglu E, Kurt H, Turunc R, Bilir H. Comparison of digital and conventional impression techniques: evaluation of patients' perception, treatment comfort, effectiveness and clinical outcomes. BMC Oral Health. 2014;14(1):10.
30. Sampaio-Fernandes MA, Pinto RJ, Almeida PR, Sampaio-Fernandes MM, Silva Marques DN, Figueiral MH. Direct vs. Indirect Digital Implant Impressions: A Time and Cost Analysis. DENT J-BASEL. 2024;12(11):340.
31. Róth I, Hermann P, Vitai V, Joós-Kovács GL, Géczi Z, Borbély J. Comparison of the learning curve of intraoral scanning with two different intraoral scanners based on scanning time. BMC Oral Health. 2023;23(1):267.
32. Patzelt SBM, Lamprinos C, Stampf S, Att W. The time efficiency of intraoral scanners: An in vitro comparative study. The Journal of the American Dental Association. 2014;145(6):542-51.
33. Londono J, Abreu A, Baker PS, Furness AR. Fabrication of a definitive obturator from a 3D cast with a chairside digital scanner for a patient with severe gag reflex: a clinical report. J Prosthet Dent. 2015;114(5):735-8.
34. Mangano FG, Veronesi G, Hauschild U, Mijiritsky E, Mangano C. Trueness and Precision of Four Intraoral Scanners in Oral Implantology: A Comparative in Vitro Study. PLoS One. 2016;11(9):e0163107.
35. Róth I, Czigola A, Fehér D, Vitai V, Joós-Kovács GL, Hermann P, et al. Digital intraoral scanner devices: a validation study based on common evaluation criteria. BMC Oral Health. 2022;22(1):140.

36. Pera P, Gilodi S, Bassi F, Carossa S. In vitro marginal adaptation of alumina porcelain ceramic crowns. J Prosthet Dent. 1994;72(6):585-90.
37. De Bièvre P. The 2012 International Vocabulary of Metrology: “VIM”. Accreditation and Quality Assurance. 2012;17(2):231-2.
38. Boeddinghaus M, Breloer ES, Rehmann P, Wöstmann B. Accuracy of single-tooth restorations based on intraoral digital and conventional impressions in patients. Clinical Oral Investigations. 2015;19(8):2027-34.
39. Chochlidakis KM, Papaspyridakos P, Geminiani A, Chen CJ, Feng IJ, Ercoli C. Digital versus conventional impressions for fixed prosthodontics: A systematic review and meta-analysis. J Prosthet Dent. 2016;116(2):184-90.e12.
40. Goujat A, Abouelleil H, Colon P, Jeannin C, Pradelle N, Seux D, et al. Marginal and internal fit of CAD-CAM inlay/onlay restorations: A systematic review of in vitro studies. J Prosthet Dent. 2019;121(4):590-7.e3.
41. Nedelcu RG, Persson AS. Scanning accuracy and precision in 4 intraoral scanners: an in vitro comparison based on 3-dimensional analysis. J Prosthet Dent. 2014;112(6):1461-71.
42. Mehl A, Ender A, Mörmann W, Attin T. Accuracy testing of a new intraoral 3D camera. Int J Comput Dent. 2009;12(1):11-28.
43. Ting-shu S, Jian S. Intraoral Digital Impression Technique: A Review. Journal of Prosthodontics. 2015;24(4):313-21.
44. Kravitz ND, Groth C, Jones PE, Graham JW, Redmond WR. Intraoral digital scanners. J Clin Orthod. 2014;48(6):337-47.
45. Schmalzl J, Róth I, Borbély J, Hermann P, Vecsei B. The effect of generation change on the accuracy of full arch digital impressions. BMC Oral Health. 2023;23(1):766.
46. Kim J-E, Amelya A, Shin Y, Shim J-S. Accuracy of intraoral digital impressions using an artificial landmark. The Journal of Prosthetic Dentistry. 2017;117(6):755-61.
47. Mangano FG, Admakin O, Bonacina M, Lerner H, Rutkunas V, Mangano C. Trueness of 12 intraoral scanners in the full-arch implant impression: A comparative in vitro study. BMC Oral Health. 2020;20(1).

48. Eggmann F, Blatz MB. Recent Advances in Intraoral Scanners. J Dent Res. 2024;103(13):1349-57.

49. Róth I, Géczi Z, Végh DC, Hegedüs T, Pál A, Hermann P, et al. The role of artificial intelligence in intraoral scanning for complete-arch digital impressions: An in vitro study. J DENTISTRY. 2025;156:105717.

50. Lukić M, Clarke J, Tuck C, Whittow W, Wells G. Printability of elastomer latex for additive manufacturing or 3D printing. Journal of Applied Polymer Science. 2016;133(4).

51. Vukicevic M, Mosadegh B, Min James K, Little Stephen H. Cardiac 3D Printing and its Future Directions. JACC: Cardiovascular Imaging. 2017;10(2):171-84.

52. Schweiger J, Edelhoff D, Güth JF. 3D Printing in Digital Prosthetic Dentistry: An Overview of Recent Developments in Additive Manufacturing. J CLIN MED. 2021;10(9).

53. Lin L, Fang Y, Liao Y, Chen G, Gao C, Zhu P. 3D Printing and Digital Processing Techniques in Dentistry: A Review of Literature. Advanced Engineering Materials. 2019;21(6):1801013.

54. Schubert C, van Langeveld MC, Donoso LA. Innovations in 3D printing: a 3D overview from optics to organs. British Journal of Ophthalmology. 2014;98(2):159.

55. Manapat JZ, Chen Q, Ye P, Advincula RC. 3D Printing of Polymer Nanocomposites via Stereolithography. Macromolecular Materials and Engineering. 2017;302(9):1600553.

56. https://formlabs.com/3d-printers/form-4b/ [Available from: https://formlabs.com/3d-printers/form-4b/.

57. Kessler A, Hickel R, Reymus M. 3D Printing in Dentistry-State of the Art. Oper Dent. 2020;45(1):30-40.

58. Hofmann M. 3D printing gets a boost and opportunities with polymer materials. ACS Publications; 2014.

59. Stansbury JW, Idacavage MJ. 3D printing with polymers: Challenges among expanding options and opportunities. Dental Materials. 2016;32(1):54-64.

60. Hoy MB. 3D Printing: Making Things at the Library. Medical Reference Services Quarterly. 2013;32(1):93-9.

61. Mertz L. Dream It, Design It, Print It in 3-D: What Can 3-D Printing Do for You? IEEE Pulse. 2013;4(6):15-21.
62. Andjela L, Abdurahmanovich VM, Vladimirovna SN, Mikhailovna GI, Yurievich DD, Alekseevna MY. A review on Vat Photopolymerization 3D-printing processes for dental application. Dent Mater. 2022;38(11):e284-e96.
63. Pagac M, Hajnys J, Ma QP, Jancar L, Jansa J, Stefek P, et al. A Review of Vat Photopolymerization Technology: Materials, Applications, Challenges, and Future Trends of 3D Printing. Polymers (Basel). 2021;13(4).
64. Bora PV, Sayed Ahmed A, Alford A, Pitttman K, Thomas V, Lawson NC. Characterization of materials used for 3D printing dental crowns and hybrid prostheses. Journal of Esthetic and Restorative Dentistry. 2024;36(1):220-30.
65. Bora PV. Crown Fatigue Resistance And Enamel Wear Of 3D Printed Resin Compared To Lithium Disilicate: The University of Alabama at Birmingham; 2024.
66. Strub JR, Rekow ED, Witkowski S. Computer-aided design and fabrication of dental restorations: Current systems and future possibilities. The Journal of the American Dental Association. 2006;137(9):1289-96.
67. Kurenov SN, Ionita C, Sammons D, Demmy TL. Three-dimensional printing to facilitate anatomic study, device development, simulation, and planning in thoracic surgery. J Thorac Cardiovasc Surg. 2015;149(4):973-9.e1.
68. Dawood A, Marti BM, Sauret-Jackson V, Darwood A. 3D printing in dentistry. British Dental Journal. 2015;219(11):521-9.
69. Javaid M, Haleem A. Current status and applications of additive manufacturing in dentistry: A literature-based review. Journal of Oral Biology and Craniofacial Research. 2019;9(3):179-85.
70. Anadioti E, Musharbash L, Blatz MB, Papavasiliou G, Kamposiora P. 3D printed complete removable dental prostheses: a narrative review. BMC Oral Health. 2020;20(1):343.
71. Cousley RR. Introducing 3D printing in your orthodontic practice. J Orthod. 2020;47(3):265-72.
72. Elliott T, Hamilton A, Griseto N, Gallucci GO. Additively Manufactured Surgical Implant Guides: A Review. J Prosthodont. 2022;31(S1):38-46.

73. Maroulakos M, Kamperos G, Tayebi L, Halazonetis D, Ren Y. Applications of 3D printing on craniofacial bone repair: A systematic review. J DENTISTRY. 2019;80:1-14.
74. Khosravani MR, Reinicke T. On the environmental impacts of 3D printing technology. Applied Materials Today. 2020;20:100689.
75. Shuaib M, Haleem A, Kumar S, Javaid M. Impact of 3D Printing on the environment: A literature-based study. Sustainable Operations and Computers. 2021;2:57-63.
76. Rejeski D, Zhao F, Huang Y. Research needs and recommendations on environmental implications of additive manufacturing. Additive Manufacturing. 2018;19:21-8.
77. Harte R, Glynn L, Rodríguez-Molinero A, Baker PM, Scharf T, Quinlan LR, et al. A Human-Centered Design Methodology to Enhance the Usability, Human Factors, and User Experience of Connected Health Systems: A Three-Phase Methodology. JMIR Hum Factors. 2017;4(1):e8.
78. Hegedus T, Kreuter P, Kismarczi-Antalffy AA, Demeter T, Banyai D, Vegh A, et al. User Experience and Sustainability of 3D Printing in Dentistry. Int J Environ Res Public Health. 2022;19(4).
79. Krastev T, Payer M, Krastev Z, Cardelles JFP, Vegh A, Banyai D, et al. The Utilisation of CAD/CAM Technology Amongst Austrian Dentists: A Pilot Study. INT DENT J. 2023;73(3):430-4.
80. Nassani MZ, Ibraheem S, Shamsy E, Darwish M, Faden A, Kujan O. A Survey of Dentists' Perception of Chair-Side CAD/CAM Technology. Healthcare (Basel). 2021;9(1).
81. Tran D, Nesbit M, Petridis H. Survey of UK dentists regarding the use of CAD/CAM technology. Br Dent J. 2016;221(10):639-44.
82. Ahlholm P, Lappalainen R, Lappalainen J, Tarvonen PL, Sipilä K. Challenges of the Direct Filling Technique, Adoption of CAD/CAM Techniques, and Attitudes Toward 3D Printing for Restorative Treatments Among Finnish Dentists. Int J Prosthodont. 2019;32(5):402-10.
83. Kelley K, Clark B, Brown V, Sitzia J. Good practice in the conduct and reporting of survey research. Int J Qual Health Care. 2003;15(3):261-6.

84. Burns KE, Duffett M, Kho ME, Meade MO, Adhikari NK, Sinuff T, et al. A guide for the design and conduct of self-administered surveys of clinicians. Cmaj. 2008;179(3):245-52.
85. Artino AR, Jr., La Rochelle JS, Dezee KJ, Gehlbach H. Developing questionnaires for educational research: AMEE Guide No. 87. Med Teach. 2014;36(6):463-74.
86. Eysenbach G. Improving the quality of Web surveys: the Checklist for Reporting Results of Internet E-Surveys (CHERRIES). J Med Internet Res. 2004;6(3):e34.
87. Hegedus T, Al-Hassiny A, Dickie J, Bencze B, Samaranayake L, Geczi Z, et al. User experience of 3D printing in dentistry: A transnational questionnaire survey. J Dent. 2025;163:106200.
88. Al-Hassiny A, Vegh D, Banyai D, Vegh A, Geczi Z, Borbely J, et al. User Experience of Intraoral Scanners in Dentistry: Transnational Questionnaire Study. INT DENT J. 2023;73(5):754-9.
89. Packaeser MG, AM DEODP, Kleverlaan CJ, Mendes Tribst JP. Economic aspects of 3D printing in restorative dentistry: a scoping review. Minerva Dent Oral Sci. 2026;75(3):200-13.
90. Muhetaer A, Yang H, Liu Y, Huang C. Three-dimensionally printed implant surgical guide-related experience, knowledge, attitude, and professional behaviors among 2028 dentists in China: A cross-sectional study. J Prosthet Dent. 2023;129(3):448.e1-.e8.
91. Hatamleh MM, Saleh SA, Radwan OI, Shamma HRA. Adoption and challenges of digital dentistry among dentists and dental technicians: A cross-sectional study. J Prosthodont. 2025;34(9):913-7.
92. Hwangbo NK, Nam NE, Choi JH, Kim JE. Effects of the Washing Time and Washing Solution on the Biocompatibility and Mechanical Properties of 3D Printed Dental Resin Materials. Polymers (Basel). 2021;13(24).
93. Shinkai RSA, Biazevic MGH, Michel-Crosato E, de Campos TT. Environmental sustainability related to dental materials and procedures in prosthodontics: A critical review. J Prosthet Dent. 2025;133(6):1466-73.

IX. BIBLIOGRAPHY OF THE CANDIDATE'S PUBLICATIONS

PUBLICATIONS RELATED TO THE DISSERTATION

1. Hegedüs T, Al-Hassiny A, Dickie J, Bencze B, Samaranayake L, Géczi Z, et al. User experience of 3D printing in dentistry: a transnational questionnaire survey. J Dent. 2025;163:106200. doi:10.1016/j.jdent.2025.106200.
2. Al-Hassiny A, Végh D, Bányai D, Végh Á, Géczi Z, Borbély J, et al. User experience of intraoral scanners in dentistry: transnational questionnaire study. Int Dent J. 2023;73(5):754–759. doi:10.1016/j.identj.2023.04.002.

OTHER PUBLICATIONS

1. Róna V, Bencze B, Agócs G, Hegyi P, Kelemen K, Hegedüs T, et al. Antimicrobial efficacy of chitosan vs. sodium hypochlorite against *Enterococcus faecalis*: a systematic review and meta-analysis. Medicina (Kaunas). 2026;62(8):1491. doi:10.3390/medicina62081491.
2. Bencze B, Sokolowski A, Lee JH, Hermann P, Hegedüs T, Kozuma W, et al. Comparing manual and ChatGPT deep research on systematic search and selection in the PubMed database on the topic of dental implantology. Int J Dent. 2025;2025:2677641. doi:10.1155/ijod/2677641.
3. Haba KS, Bencze B, Kammerhofer G, Ujpál M, Bányai D, Hermann P, et al. Locally delivered 1% metformin gel improves periodontal parameters: a systematic review and meta-analysis. Saudi Dent J. 2025;37(7–9):40. doi:10.1007/s44445-025-00045-8.
4. Lipták L, Lipták K, Hermann P, Rózsa NK, Somogyi KS, Végh Á, et al. Fogászati szűrővizsgálat fontossága a cukorbetegek ellátásában: a Semmelweis Egyetem Diabéteszes Fogászati Munkacsoportjának szerepe. Diabetol Hung. 2025;33(5):369–377. doi:10.24121/dh.2025.28.
5. Róth I, Géczi Z, Végh DC, Hegedüs T, Pál A, Hermann P, et al. The role of artificial intelligence in intraoral scanning for complete-arch digital impressions: an in vitro study. J Dent. 2025;156:105717. doi:10.1016/j.jdent.2025.105717.

6. Kammerhofer G, Végh D, Bányai D, Végh Á, Joób-Fancsaly Á, Hermann P, et al. Association between hyperglycemia and medication-related osteonecrosis of the jaw (MRONJ). J Clin Med. 2023;12(8):2976. doi:10.3390/jcm12082976.
7. Somogyi A, Végh D, Róth I, Hegedüs T, Schmidt P, Hermann P, et al. Therapy for temporomandibular disorders: 3D-printed splints from planning to evaluation. Dent J (Basel). 2023;11(5):126. doi:10.3390/dj11050126.
8. Bányai D, Végh Á, Biczó Z, Barone MTU, Hegedüs T, Végh D. Oral health knowledge and habits of people with type 1 and type 2 diabetes. Int Dent J. 2022;72(3):407–413. doi:10.1016/j.identj.2021.07.003.
9. Hegedüs T, Kreuter P, Kismarczi-Antalffy AA, Demeter T, Bányai D, Végh Á, et al. User experience and sustainability of 3D printing in dentistry. Int J Environ Res Public Health. 2022;19(4):1921. doi:10.3390/ijerph19041921.

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