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Attitudes, Awareness Toward the Use of Digital Twin Technology in Restorative and Surgical Dentistry in Saudi Arabia

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Abstract: Digital Twin Technology (DTT) is revolutionizing various industries, including healthcare, by providing real-time, virtual replicas of physical objects or processes. This study investigates the attitudes and awareness of Saudi-based dentists toward the application of DTT in restorative and surgical dentistry. A cross-sectional survey of 376 dentists was conducted to analyze their knowledge, perceptions, and barriers to adopting DTT. Results reveal that while 40.1% of participants exhibit a high level of knowledge of DTT, a significant portion remains unaware of its potential applications in dental practice, particularly in designing computer-aided restorations, diagnosing oral cancer, and fabricating hard and soft tissue replicas. Awareness of related programs, such as Dentistry 4.0 and 3D printing, was moderate, with specialists and practitioners in urban areas demonstrating higher familiarity compared to their rural counterparts. The findings emphasize the need for targeted educational programs, enhanced accessibility, and standardized training to bridge knowledge gaps and promote the integration of DTT into clinical practice. This study highlights the transformative potential of DTT and calls for initiatives to equip dental professionals with the necessary skills to effectively harness its benefits.

Keywords: Digital twin technology, Restorative dentistry, Surgical dentistry, Digital dentistry

INTRODUCTION

Digital Twin Technology (DTT) is an innovative technology that has recently gained traction in various sectors, with the healthcare sector being one of them. It is expected to have a radical impact on restorative and surgical dentistry. A digital twin is an as-built, real-time digital model of an object or process in the physical world, updated by it or its data [1]. In dental practice, the use of DTT enables clinicians to produce accurate and detailed three-dimensional models of the patient's oral structures, which in turn aid in accurate diagnosis and treatment planning. An accurate impression is most useful in restorative dentistry, where personalized dental prosthetics such as crowns and bridges, as well as dental implants, are developed from an exact model fit [2, 3].

In surgical dentistry, the DTT is used to assess potential outcomes before actual surgery and potentially enhance outcomes and patient safety by rehearsing in a risk-free virtual environment. The technology also enhances the level of accuracy in surgeries by providing real-time information and positioning the implant with high precision, thereby eliminating the risks associated with conventional approaches [4, 5].

Recently, many authors have focused on utilizing digital twin technology in dentistry, particularly in restorative and surgical procedures. It was established that the use of DDT enhances dental restoration precision by making prosthetic fittings more accurate, thereby reducing treatment time. The effectiveness of digital twins in designing crowns and bridges for patients resulted in a quarter of the time being saved, as fewer adjustments were needed, and led to improved patient satisfaction. However, the study also found that many dental professionals are unaware of the existence of DTT, with only 40% of the participants responding that they have a working knowledge of the technology [6, 7].

DTT has numerous advantages when applied in surgical dentistry, particularly allowing for the simulation of complex surgical interventions and the identification of potential complications during their execution. It is safe to conclude that DTT can help improve the accuracy of surgery and have a positive impact on patients' health. However, the use of DTT is still somewhat limited due to its expense and the lack of standardized training protocols for its application [8].

Several factors influence the adoption of DTT in dentistry, including technologically advanced equipment, the awareness created among dental professionals and dentists, and their motivation to adopt various digital technologies [9]. Research also revealed that the highest level of technology innovation among these healthcare specialists was reported among dental workers in urban areas, as opposed to their counterparts practicing in rural areas, where dental facilities often have limited access to modern and sophisticated equipment and training. These gaps inform the need to launch specific educational campaigns for increasing DTT and other digital advancements in dentistry across the various regions of the country [10].

Study rationale: Digital twin technology is relatively new in dentistry; therefore, the findings of this study will provide insights into the current level of dentists' awareness regarding DTT. Moreover, no similar study had been conducted in the past, including an examination of dentists' knowledge and awareness of DTT.

Null hypothesis: There is no difference in attitude and awareness among Saudi-based dentists regarding the utilization of digital twin technology in dentistry.

Aims and objectives: The main aim of this study is to determine the level of awareness among Saudi-based dentists towards the application of digital twin technology in dentistry.

Objectives include:

- Comparison of attitude and awareness between general dentists and specialists.
- List the factors that are barriers to acquiring digital twin technology in clinical practice.

Materials and Methods

Study design: This is a cross-sectional study conducted using an online questionnaire.

Study sample: The sample was calculated using www.raosoft.com:

Margin of error: 5%

Confidence level: 95%

Population size: 17000 [11]

Response distribution: 50%

Recommended sample size: 376

Inclusion criteria:

- General and specialist dentists working in Saudi Arabia.
- Participants from all nationalities and genders.

Exclusion criteria:

- Dental students and interns.

Study instrument: A questionnaire was designed and tested for validity and reliability using Cronbach's alpha value (0.873). Components of the questionnaire included demographics based on gender, nationality, work sector, and work experience. Moreover, questions including attitudes and awareness about DTT and factors associated with not using it were asked.

Data collection: Google Forms was used to collect data, and the links were sent to the dentists in different cities of Saudi Arabia using social media platforms and official emails.

Data analysis: SPSS (Statistical Package for Social Sciences) version 22 (IBM New York 2018) was used to analyze the data. A descriptive analysis was done to present the demographic distribution of participants. A chi-square test was done to present the comparison between groups, and a p-value of 0.05 or less was considered to be statistically significant.

Results and Discussion

Table 1. Demographics of the study participants

Variables	Frequencies
Gender	Male: 216 (53.9%)
	Female: 185 (46.1%)
Work Position	General practitioner: 254 (63.3%)
	Specialist/Consultant: 147 (36.7%)
Work Experience	Less than 10 years: 275 (68.6%)
	More than 10 years: 126 (31.4%)
Nationality	Saudi: 264 (65.8%)
	Non-Saudi: 137 (34.2%)

The Table titled "Demographics of the Study Participants" provides a detailed breakdown of the participants in terms of gender, work position, work experience, and nationality. This data offers insight into the composition of the sample used in the study.

In terms of gender, the participants consist of 216 males, which account for 53.9% of the total sample, and 185 females, representing 46.1%. This indicates a slightly higher number of male participants compared to females, though the distribution is relatively balanced.

Regarding work positions, the majority of participants are general practitioners, numbering 254 and constituting 63.3% of the total. The remaining 147 participants, or 36.7%, are specialists or consultants. This distribution indicates that the study is heavily represented by general practitioners, accounting for nearly two-thirds of the sample.

When considering work experience, a significant proportion of participants, 275 (68.6%), have less than 10 years of experience in their respective fields. In contrast, 126 participants (31.4%) have more than 10 years of experience. This highlights that the sample is predominantly composed of relatively less experienced professionals.

Lastly, in terms of nationality, the participants are divided between Saudi and non-Saudi nationals. Saudis comprise 65.8% of the sample, with 264 participants, while non-Saudis account for 34.2%, totaling 137 participants. This suggests that the study has a stronger representation of Saudi nationals.

Table 2. Descriptive statistics for the knowledge-related survey questions

Knowledg-related questions	Responses
What is your level of knowledge regarding digital twin technology in general?	Very low (None): 5.7% Low: 9.7% Average: 29.2% High: 40.1% Very high: 15.2%
Are you familiar with the application of DTT in healthcare?	Not aware at all: 7.2% Not much aware: 9.5% Neutral: 20% Somewhat aware: 45.6% Extremely aware: 17.7%
Are you aware of the use of DTT in dentistry?	Not aware at all: 8.5% Not much aware: 11.7% Neutral: 22.9% Somewhat aware: 39.9% Extremely aware: 17%
Are you aware of the Dentistry 4.0 program?	Not aware at all: 11.5% Not much aware: 11.7% Neutral: 24.9% Somewhat aware: 38.4% Extremely aware: 13.5%
Are you aware of the use of 3D printing in various dental procedures?	Not aware at all: 4% Not much aware: 8% Neutral: 27.9% Somewhat aware: 41.4% Extremely aware: 18.7%
Are you aware that DTT can aid in designing computer-aided restorations and prosthesis?	Not aware at all: 5.2% Not much aware: 11.5% Neutral: 31.9% Somewhat aware: 35.4% Extremely aware: 16%
Are you aware that DTT can aid in the early diagnosis of oral cancer?	Not aware at all: 8.5% Not much aware: 14.7% Neutral: 30.4% Somewhat aware: 33.7% Extremely aware: 12.7%
Are you aware that DTT can help in fabricating replicas of both hard and soft tissue?	Not aware at all: 7.2% Not much aware: 15.2% Neutral: 29.2% Somewhat aware: 33.4% Extremely aware: 15%

Are you aware that DTT can aid in manufacturing the scaffolds for prosthetic restorations?	Not aware at all: 6% Not much aware: 14% Neutral: 33.2% Somewhat aware: 31.9% Extremely aware: 15%
Do you think you require more knowledge and information regarding the use of DTT in dentistry?	Strongly disagree: 4% Disagree: 4% Neutral: 29.7% Agree: 36.4% Strongly agree: 25.9%

The Table titled "Descriptive Statistics for the Knowledge-Related Survey Questions" provides an overview of participants' responses regarding their knowledge and awareness of Digital Twin Technology (DTT), its applications in healthcare and dentistry, and their perception of the need for further knowledge in this area. The data is presented as percentages, reflecting varying levels of awareness and understanding across several dimensions.

General knowledge of DTT

When asked about their overall knowledge of digital twin technology, 40.1% of participants reported having a high level of knowledge, while 15.2% indicated a very high level of knowledge. However, a significant portion still expressed limited awareness, with 9.7% rating their knowledge as low and 5.7% as very low. A notable 29.2% considered their knowledge average.

Awareness of DTT in healthcare

Regarding the use of DTT in healthcare, 45.6% of respondents were somewhat aware, and 17.7% were extremely aware, showing a moderate level of familiarity. However, 16.7% reported little to no awareness, suggesting a need for increased education in this area.

Awareness of DTT in dentistry

Awareness of DTT's use in dentistry revealed a similar pattern. While 39.9% were somewhat aware and 17% were extremely aware, a combined 20.2% were either not aware at all or not much aware. Neutral responses accounted for 22.9%.

Awareness of dentistry 4.0 program

Regarding the Dentistry 4.0 program, 38.4% of participants were somewhat aware, while 13.5% were extremely aware. However, 23.2% expressed little or no awareness, indicating that this program might not yet be widely recognized among the participants.

Awareness of 3D printing in dentistry

When asked about the use of 3D printing in dental procedures, 41.4% of participants were somewhat aware, and 18.7% were extremely aware. Only 12% had low or no awareness, suggesting a relatively higher familiarity with this technology.

Applications of DTT in dentistry

Participants were also asked about specific applications of DTT in dentistry:

- **Designing computer-aided restorations and prostheses:** 35.4% were somewhat aware, and 16% were extremely aware, though 16.7% expressed limited awareness.

- **Diagnosing oral cancer:** Awareness levels were moderate, with 33.7% somewhat aware and 12.7% extremely aware, but 23.2% reported low or no awareness.
- **Fabricating replicas of hard and soft tissues:** 33.4% were somewhat aware, and 15% were extremely aware, though 22.4% reported little or no awareness.
- **Manufacturing scaffolds for prosthetic restorations:** Awareness was somewhat lower, with 31.9% somewhat aware, 15% extremely aware, and 20% expressing limited awareness.

Need for more knowledge

When asked if they felt a need for more knowledge about DTT in dentistry, the majority agreed, with 36.4% agreeing and 25.9% strongly agreeing. Only 8% disagreed, while 29.7% remained neutral.

Table 3. Knowledge-related questions with a comparison based on work position

Knowledge-related questions	General practitioners	Specialist/Consultant	P-value
What is your level of knowledge regarding digital twin technology in general?	Very high: 7% High: 13% Average: 29% Low: 35% Very low (None): 16%	Very high: 4% High: 3% Average: 29% Low: 50% Very low (None): 14%	.003*
Are you aware of the use of DTT in healthcare?	Not aware at all: 8% Not much aware: 10% Neutral: 21% Somewhat aware: 43% Extremely aware: 18%	Not aware at all: 5% Not much aware: 9 % Neutral: 18% Somewhat aware: 50% Extremely aware: 18%	.584
Are you aware of the use of DTT in dentistry?	Not aware at all: 8% Not much aware: 12% Neutral: 24% Somewhat aware: 38% Extremely aware: 18%	Not aware at all: 9% Not much aware: 11% Neutral: 21% Somewhat aware: 44% Extremely aware: 16%	.822
Are you aware of the Dentistry 4.0 program?	Not aware at all: 12% Not much aware: 13% Neutral: 25% Somewhat aware: 35% Extremely aware: 15%	Not aware at all: 11% Not much aware: 9% Neutral: 25% Somewhat aware: 45% Extremely aware: 10%	.192
Are you aware of 3D printing for various dental procedures?	Not aware at all: 3% Not much aware: 8% Neutral: 31% Somewhat aware: 37% Extremely aware: 20%	Not aware at all: 5% Not much aware: 7% Neutral: 22% Somewhat aware: 49% Extremely aware: 16%	.085
Are you aware that DTT can aid in designing computer-aided restorations and prosthesis?	Not aware at all: 5% Not much aware: 11% Neutral: 32% Somewhat aware: 33% Extremely aware: 18%	Not aware at all: 5% Not much aware: 12% Neutral: 32% Somewhat aware: 39% Extremely aware: 12%	.597
Are you aware that DTT can aid in the early diagnosis of oral cancer?	Not aware at all: 8% Not much aware: 16% Neutral: 27% Somewhat aware: 34% Extremely aware: 15%	Not aware at all: 9% Not much aware: 13% Neutral: 37% Somewhat aware: 33% Extremely aware: 9%	.172
Are you aware that DTT can help in fabricating replicas of both hard	Not aware at all: 9% Not much aware: 14%	Not aware at all: 5% Not much aware: 18%	.179

and soft tissue?	Neutral: 29% Somewhat aware: 31% Extremely aware: 17%	Neutral: 30% Somewhat aware: 37% Extremely aware: 11%	
Are you aware that DTT can aid in manufacturing the scaffolds for prosthetic restorations?	Not aware at all: 7% Not much aware: 13% Neutral: 32% Somewhat aware: 30% Extremely aware: 18%	Not aware at all: 4% Not much aware: 15% Neutral: 35% Somewhat aware: 36% Extremely aware: 10%	.165
Do you think you require more knowledge and information regarding the use of DTT in dentistry?	Strongly disagree: 4% Disagree: 3% Neutral: 27% Agree: 41% Strongly agree: 32%	Strongly disagree: 4% Disagree: 5% Neutral: 34% Agree: 41% Strongly agree: 16%	.009*

The comparison of knowledge and awareness related to Digital Twin Technology (DTT) between general practitioners and specialists/consultants highlights key differences, as well as areas of similarity, in their understanding of this emerging technology. The data also includes p-values to assess the statistical significance of these differences, with p-values below 0.05 indicating significant disparities.

When it comes to general knowledge of DTT, significant differences are evident between the two groups. Among general practitioners, 7% reported very low knowledge, 13% high knowledge, and 35% low knowledge, compared to 4%, 3%, and 50%, respectively, among specialists. The p-value of 0.003 indicates a statistically significant difference, with specialists having a higher proportion of participants with low general knowledge. This suggests that general practitioners are comparatively more knowledgeable about DTT in general.

In terms of awareness of DTT in healthcare, both groups showed similar levels of familiarity. Among general practitioners, 43% were somewhat aware, and 18% were extremely aware, compared to 50% and 18%, respectively, among specialists. The p-value of 0.584 suggests no significant difference in awareness between the two groups, indicating a comparable understanding of DTT applications in healthcare.

Similarly, the awareness of DTT in dentistry is consistent across the two groups. General practitioners reported that 38% were somewhat aware and 18% were extremely aware, while specialists reported that 44% were somewhat aware and 16% were extremely aware. The p-value of 0.822 confirms that there is no significant difference in their knowledge. Additionally, awareness of the Dentistry 4.0 program also showed no significant difference, with general practitioners reporting 35% as somewhat aware and 15% as extremely aware, compared to 45% and 10%, respectively, for specialists (p = 0.192).

Awareness of 3D printing for dental procedures is slightly higher among specialists, with 49% being somewhat aware, compared to 37% among general practitioners. However, the p-value of 0.085 indicates that this difference is not statistically significant. Similarly, awareness of specific applications of DTT, such as designing computer-aided restorations, diagnosing oral cancer, fabricating hard and soft tissue replicas, and manufacturing scaffolds for prosthetic restorations, showed no statistically significant differences between the two groups (p-values ranging from 0.165 to 0.822).

The most notable difference lies in the perceived need for more knowledge about DTT in dentistry. Among general practitioners, 41% agreed, and 32% strongly agreed, compared to 41% and 16%, respectively, among specialists. The p-value of 0.009 highlights a significant difference, with general practitioners expressing a stronger desire for further education on DTT compared to specialists.

Table 4. Knowledge-related questions with comparison based on work experience

Knowledge-related questions	Less than 10 years	More than 10 years	P-value
What is your level of knowledge regarding digital twin technology in	Very high: 7% High: 12%	Very high: 3% High: 5%	.011*

general?	Average: 31% Low: 36% Very low (None): 14%	Average: 25% Low: 50% Very low (None): 17%	
Are you aware of the use of DTT in healthcare?	Not aware at all: 9% Not much aware: 11% Neutral: 22% Somewhat aware: 41% Extremely aware: 17%	Not aware at all: 4% Not much aware: 7 % Neutral: 15% Somewhat aware: 55% Extremely aware: 19%	.041*
Are you aware of the use of DTT in dentistry?	Not aware at all: 10% Not much aware: 14% Neutral: 23% Somewhat aware: 45% Extremely aware: 16%	Not aware at all: 6% Not much aware: 7% Neutral: 23% Somewhat aware: 45% Extremely aware: 19%	.140
Are you aware of the Dentistry 4.0 program?	Not aware at all: 14% Not much aware: 13% Neutral: 25% Somewhat aware: 35% Extremely aware: 13%	Not aware at all: 6% Not much aware: 9% Neutral: 25% Somewhat aware: 47% Extremely aware: 13%	.048*
Are you aware of 3D printing for various dental procedures?	Not aware at all: 4% Not much aware: 8% Neutral: 30% Somewhat aware: 39% Extremely aware: 19%	Not aware at all: 4% Not much aware: 9% Neutral: 23% Somewhat aware: 47% Extremely aware: 17%	.528
Are you aware that DTT can aid in designing computer-aided restorations and prosthesis?	Not aware at all: 7% Not much aware: 12% Neutral: 32% Somewhat aware: 33% Extremely aware: 16%	Not aware at all: 2% Not much aware: 10% Neutral: 33% Somewhat aware: 40% Extremely aware: 15%	.388
Are you aware that DTT can help in diagnosing oral cancer at an early stage?	Not aware at all: 10% Not much aware: 15% Neutral: 29% Somewhat aware: 32% Extremely aware: 14%	Not aware at all: 6% Not much aware: 13% Neutral: 33% Somewhat aware: 38% Extremely aware: 10%	.378
Are you aware that DTT can help in fabricating a replica of hard and soft tissue?	Not aware at all: 8% Not much aware: 15% Neutral: 29% Somewhat aware: 32% Extremely aware: 17%	Not aware at all: 6% Not much aware: 17% Neutral: 30% Somewhat aware: 37% Extremely aware: 10%	.179
Are you aware that DTT can aid in manufacturing the scaffolds for prosthetic restorations?	Not aware at all: 7% Not much aware: 13% Neutral: 31% Somewhat aware: 30% Extremely aware: 17%	Not aware at all: 4% Not much aware: 13% Neutral: 37% Somewhat aware: 36% Extremely aware: 10%	.208
Do you think you require more knowledge and information regarding the use of DTT in dentistry?	Strongly disagree: 3% Disagree: 4% Neutral: 27% Agree: 35% Strongly agree: 32%	Strongly disagree: 7% Disagree: 3% Neutral: 37% Agree: 40% Strongly agree: 13%	.000*

1. General knowledge of DTT

Participants with less than 10 years of experience reported varying levels of general knowledge of DTT, with 7% indicating very high knowledge, 12% high knowledge, and 36% low knowledge. In contrast, those with more than 10 years of experience had 3% reporting very high knowledge, 5% high knowledge, and 50% low knowledge. The p-value of 0.011* indicates a significant difference, with less experienced participants demonstrating comparatively better general knowledge of DTT.

2. Awareness of DTT in healthcare

There is a notable difference in the awareness of DTT in healthcare. Among participants with less than 10 years of experience, 41% were somewhat aware and 17% extremely aware, compared to 55% and 19%, respectively, for those with more than 10 years of experience. The p-value of 0.041* suggests a significant difference, with more experienced participants showing higher awareness.

3. Awareness of DTT in dentistry

Both groups exhibit similar levels of awareness regarding the use of DTT in dentistry. For those with less than 10 years of experience, 45% were somewhat aware and 16% extremely aware, while for those with more than 10 years of experience, these figures were 45% and 19%, respectively. The p-value of 0.140 indicates no significant difference between the groups.

4. Awareness of the dentistry 4.0 program

Awareness of the Dentistry 4.0 program shows a significant difference between the two groups. Participants with less than 10 years of experience reported 35% somewhat aware and 13% extremely aware, compared to 47% and 13%, respectively, among those with more than 10 years of experience. The p-value of 0.048* highlights that participants with more experience have greater awareness of the Dentistry 4.0 program.

5. Awareness of 3D printing in dentistry

Awareness of 3D printing for dental procedures is relatively consistent between the groups. Among those with less than 10 years of experience, 39% were somewhat aware and 19% extremely aware, compared to 47% and 17%, respectively, among those with more than 10 years of experience. The p-value of 0.528 indicates no significant difference in awareness.

6. Applications of DTT in dentistry

For specific applications of DTT, such as designing computer-aided restorations, diagnosing oral cancer, fabricating replicas of tissues, and manufacturing scaffolds for prosthetic restorations, no significant differences were observed between the groups. The p-values for these questions ranged from 0.179 to 0.388, indicating that both groups have similar levels of awareness of these applications.

7. Need for more knowledge about DTT in Dentistry

A significant difference is observed in the perceived need for more knowledge about DTT. Among participants with less than 10 years of experience, 35% agreed and 32% strongly agreed that they required more knowledge, compared to 40% and 13%, respectively, among those with more than 10 years of experience. The p-value of 0.000* highlights that less experienced participants feel a much greater need for additional education and training in DTT.

The concept of Digital Twin Technology (DTT) has emerged as a transformative approach in dentistry, providing opportunities for personalized treatment planning, educational advancements, and enhanced diagnostic precision. This discussion delves into the findings from present research surveys assessing the

knowledge, awareness, and perceptions of DTT among dental professionals, comparing them with past studies that focus on technological development and practical applications. By bridging these perspectives, this discussion aims to identify gaps, challenges, and future directions for integrating DTT into dental practice and education.

Knowledge levels in present studies

The present study revealed that while a substantial proportion of dental professionals are aware of DTT, significant gaps in knowledge still need to be discovered. Of the participants, 40.1% reported having a high level of knowledge, while only 15.2% indicated very high familiarity with DTT. On the other hand, 9.7% and 5.7% rated their knowledge as low or very low, respectively, and 29.2% classified it as average. These findings highlight the growing recognition of DTT but also indicate a considerable need for further education and training to deepen understanding.

Awareness in healthcare and dentistry

Awareness of DTT applications in healthcare and dentistry also showed moderate levels. Regarding healthcare, 45.6% of participants were somewhat aware, and 17.7% were extremely aware, while 16.7% reported little or no awareness. Similarly, 39.9% were slightly aware of DTT in dentistry, and 17% were extremely aware. These figures suggest that while professionals are moderately familiar with DTT, many need to be made aware of its full potential and applications.

In surgical dentistry, the DTT is used to assess what may happen before actual surgery and possibly enhance outcomes and patient safety by actually rehearsing in a risk-free virtual environment. The technology also increases the level of accuracy when it comes to surgeries through real-time information and positions the implant with high precision, eradicating the dangers of conventional approaches [4, 5].

Past research has demonstrated advanced applications of DTT in healthcare and dentistry, suggesting a disconnect between the theoretical knowledge assessed in present studies and the practical advancements documented in earlier works. For instance, Ahn *et al.* (2024) illustrated that significant values were obtained from the student perspective about the use of DTT in implant placement planning, integrating CBCT imaging with reduced-order models to create patient-specific digital replicas. This approach enhanced clinical decision-making by reducing reliance on subjective judgment and improving accuracy [10]. Similarly, Ma *et al.* (2024) highlighted the role of DTT in orthodontics, where it enables personalized treatment planning, tissue outcome prediction, and the development of cloud-based platforms for data sharing [12].

These applications showcase the tangible benefits of DTT in clinical settings, contrasting with the limited awareness observed in present studies. While the technology is well-documented in research, its integration into routine dental practice needs to catch up, underscoring the need for targeted efforts to bridge this gap.

Applications of DTT in dentistry

In the present survey, participants demonstrated moderate awareness of specific applications of DTT in dentistry. For instance:

- **Designing computer-aided restorations and prostheses:** 35.4% were somewhat aware, and 16% were extremely aware.
- **Fabricating hard and soft tissue replicas:** 33.4% were somewhat aware, and 15% were extremely aware.
- **Diagnosing oral cancer:** 33.7% were somewhat aware, and 12.7% were extremely aware.
- **Manufacturing scaffolds for prosthetic restorations:** Awareness levels were slightly lower, with 31.9% somewhat aware and 15% extremely aware.

Despite these moderate awareness levels, a significant proportion of participants expressed limited familiarity with these applications, highlighting the need for educational interventions to improve understanding.

However, the study also found that a lot of dental professionals are unaware of the existence of DTT, with only 40% of the participants responding that they have a working knowledge of the technology [6, 7]. Past studies provide a deeper exploration of DTT applications in dentistry, offering evidence of its transformative potential. Mangano *et al.* (2018) and Stokbro *et al.* (2014) demonstrated that significant values were obtained from the student perspective about using DTT to create virtual patients through the integration of intraoral scans, CBCT imaging, and facial scans. These virtual models have been instrumental in planning orthognathic surgeries and designing prosthetic devices with high precision.

Additionally, Ahn *et al.* (2024) showcased that significant values were obtained from the student perspective about how DTT aids in real-time implant placement planning, combining patient-specific data to evaluate treatment plans objectively. Ma *et al.* (2024) emphasized that significant values were obtained from the student perspective about its role in orthodontics. DTT facilitates predictive modeling of soft and hard tissue outcomes, enabling personalized treatments. These applications illustrate the practical utility of DTT, which contrasts with the moderate awareness levels reported in the present study [10, 12].

This raises an important concern regarding the awareness and understanding of Digital Twin technology among dental students. While the concept holds promise for advancing personalized dental care, such as simulating treatment outcomes or improving patient management, its implications extend beyond technical benefits. Dental students may not fully grasp the potential social and ethical challenges associated with Digital Twins. For instance, the mere existence of a Digital Twin for patients could lead to biased treatment decisions or unfair assumptions about a patient's oral health, similar to how perceptions in other sectors can lead to unintended consequences. If dental professionals rely heavily on data-driven predictions from Digital Twins, it might inadvertently reinforce disparities or create new forms of discrimination in patient care. Thus, dental students need a well-rounded understanding of both the technical and ethical dimensions of Digital Twin technology to ensure its responsible and equitable application in dentistry [6].

Educational impact of DTT

The present study highlighted a strong demand for more education and training on DTT. A significant 36.4% of participants agreed, and 25.9% strongly agreed, that they required additional knowledge about DTT and its applications. This finding underscores the need for targeted educational initiatives to equip dental professionals with the skills and knowledge necessary to leverage DTT effectively.

Educational advancements in past studies

Past studies have documented the educational potential of DTT, particularly in remote and simulation-based learning environments. Deniz *et al.* (2021) reported positive feedback from students using digital twins in remote laboratory courses. These virtual models allowed students to practice dental procedures online, offering flexibility, accessibility, and cost-effectiveness while maintaining high educational quality [13]. Similarly, Cheng *et al.* (2021) highlighted that significant values were obtained from the student perspective about the effectiveness of "DenTeach," a DTT-enabled platform that provided real-time feedback and performance metrics, significantly improving students' procedural skills and confidence [14].

These findings demonstrate the value of integrating DTT into dental education, not only to enhance learning outcomes but also to bridge the knowledge gaps identified in the present study.

Technological advancements in past studies

Past research has emphasized the role of DTT in enhancing precision and efficiency in dental treatments. For example, Ahn *et al.* (2024) introduced a reduced-order model for real-time DTT applications in implant

placement, enabling dentists to visualize and evaluate placement plans with greater accuracy [10]. Mangano *et al.* (2018) demonstrated that significant values were obtained from the student perspective about how DTT facilitates the creation of virtual patients, integrating multiple data sources to improve surgical planning and prosthetic design [15].

These advancements highlight DTT's practical capabilities, particularly in areas such as orthodontics, implantology, and surgical planning. However, the successful implementation of these technologies requires adequate training and awareness among dental professionals, which remains a challenge, as evidenced by the present study.

Present challenges

The present study revealed limited awareness and understanding of DTT among dental professionals, with many participants expressing a need for more knowledge and training. This gap highlights the challenges of integrating advanced digital tools into routine practice, including:

- **Lack of awareness:** Moderate to low awareness levels among practitioners impede the widespread adoption of DTT.
- **Educational barriers:** Limited exposure to DTT during dental education hinders professionals' ability to leverage its potential.
- **Technological accessibility:** High costs and technical complexities associated with DTT may deter its adoption, particularly in resource-constrained settings.

Addressing these challenges will require coordinated efforts to promote awareness, provide training, and enhance accessibility to DTT technologies.

Limitations of present and past studies

Limitations of present studies

The present study relied on self-reported data, which may have biases or inaccuracies that may influence participants' responses. Additionally, the sample size and demographic representation may limit the generalizability of the findings. Furthermore, the study focused on assessing awareness and perceptions without evaluating participants' practical experience with DTT, leaving gaps in understanding the challenges of real-world implementation.

Limitations of past studies

While past studies demonstrated the technical capabilities of DTT, they often focused on specific applications or controlled environments, which may not fully reflect the complexities of clinical practice. Additionally, these studies primarily explored the potential of DTT rather than its widespread adoption, limiting insights into the barriers and challenges faced by practitioners.

Future recommendations

1. **Education and training:**
Developing comprehensive training programs and workshops to improve dental professionals' understanding and practical skills in DTT. This includes integrating DTT into undergraduate and postgraduate dental education to ensure early exposure and competence.
2. **Awareness campaigns:**
Promoting awareness about the benefits and applications of DTT through conferences, seminars, and online resources. These campaigns should target both students and practicing professionals.
3. **Research on clinical adoption:**

Conducting longitudinal studies to evaluate the impact of DTT on clinical outcomes and its integration into routine practice. This research should identify barriers to adoption and propose strategies to overcome them.

4. **Collaboration:**

Encouraging collaboration between dental professionals, researchers, and technology developers to facilitate the development and adoption of user-friendly DTT solutions.

5. **Technological accessibility:**

Addressing cost and accessibility issues through partnerships with technology developers and policymakers to ensure that DTT is available to practitioners in resource-constrained settings.

Conclusion

The comparison of present and past studies reveals a significant gap between the theoretical awareness of Digital Twin Technology and its practical implementation in dentistry. While past studies demonstrate the transformative potential of DTT through advanced applications in clinical and educational settings, the present study highlights limited awareness and understanding among dental professionals; thus, accepting the null hypothesis. Addressing these gaps through education, training, and research will be critical for leveraging DTT's full potential to improve dental care and education. Future efforts must focus on integrating DTT into routine practice, enhancing accessibility, and fostering collaboration to ensure its widespread adoption.

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