Statistical evaluation of the learning curve in digital impression in different types of operators

Abstract

Aim
The objective of this study was to evaluate the learning curve associated with intraoral scanning using the CEREC system, comparing two groups: dental students and experienced clinicians. The study aimed to assess improvements in time, surface area acquired, and surface-time ratio (X) to determine the efficiency of repeated scanning.

Materials and Methods
A total of 50 participants were recruited for the study, divided into two groups: 25 dental students from the San Raffaele Faculty of Dentistry and 25 clinicians with at least 5 years of experience. Each participant performed four intraoral scans on a plaster model using the CEREC intraoral scanner. The scans were evaluated for time (T1-T4) in minutes, surface area (SUP) in pixel units, and surface-time ratio (X) as an efficiency metric. Statistical analysis was conducted using IBM SPSS Statistics (version 25) and MeshLab 2016 to assess the learning curve and compare the two groups.

Results
Both groups demonstrated a clear learning curve with significant improvements in time and surface-time ratio (X) over the four trials. For clinicians, the average time decreased from 1.399 minutes in T1 to 1.015 minutes in T4, while the surface-time ratio improved from 347.91 mm²/min to 447.77 mm²/min. Students showed a similar reduction in time, from 1.292 minutes in T1 to 1.001 minutes in T4, and an improvement in surface-time ratio from 343.96 mm²/min to 433.12 mm²/min. Clinicians consistently acquired more surface area than students, despite similar scan times, indicating that clinical experience plays a crucial role in scan accuracy.

Conclusion
The study highlights the importance of clinical experience in achieving more efficient and complete scans using intraoral scanners. Both groups improved with repetition, but clinicians demonstrated superior performance in terms of surface area acquired. The learning curve plateaued after the third trial, suggesting that sustained practice is necessary for mastery. Future training programs should focus on enhancing both technical proficiency and clinical judgment to optimize the use of digital scanning technology in dentistry.

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DOI

10.23805/JO.2025.698

Keywords

Intraoral Scanners, CAD-CAM Dentistry, Learning Curve, Dental Students, Digital Impression Technique.

INTRODUCTION

Over the course of the twentieth century, both dental materials and manufacturing technologies have significally advanced (1-3).

The evolution of dentistry has always been gradual and constant, driven above all by innovations and new treatment protocols, both on natural teeth and in fixed rehabilitation on dental implants, that have changed previous knowledge (4-9). Due to the patient's growing demand for accuracy of the product and the need to obtain aesthetically pleasing prosthetic solutions (10), several new ceramic materials have recently been introduced on the market. However, these materials have proven to require sophisticated processing technologies and new systems have been envisaged for the workflow between dentist and dental technician, aesthetic materials and implant prosthetic rehabilitations require precise maintenance follow-ups and methods suitable for correct conservation and duration over time and for the correct prevention of periodontal diseases resulting from inflammatory processes of a bacterial origin (11-19). A problem that can be related to traditional techniques is the "human error" variable: a prosthetic restoration with absolute precision is difficult to achieve with any traditional technique as these are affected by a cumulative error deriving from the sum of the errors of the individual steps (20-23).

The eye and the hand of man, even the most talented and experienced, are not predictable when it comes to measuring or analyzing the dimensions, angles, spaces and all the other variables necessary to obtain a satisfactory prosthetic result.

The recent development of digital technologies has produced a real revolution in all dental disciplines (24).

The idea of using them in the dental field dates to the early seventies when Dr. François Duret was the first to use the laser to take dental impressions and prepare prosthetic products.

Dental CAD / CAM was introduced in the 1980s. Initially, limited and conditioned by the materials and technologies available on the market, it had little development.

With the progress of technology, the use of new materials and the advent of increasingly sophisticated hardware and software systems, CAD / CAM has undergone an important evolution first in laboratories and then in dental practices.

This technique is based on three main moments: digital data acquisition and processing, digital design of the product (Computer Aided Design) and physical manufacturing of the same (Computer Aided Manufacturing). CAD / CAM technology was almost entirely limited to the laboratory, where conventional impressions were digitized in such a way as to be able to design and mill the new prosthetic products.

The rapid development of CAD / CAM systems in recent decades has increasingly reduced the distance from achieving the "perfect restoration".

CAD-CAM technology not only offers the possibility of designing directly on the computer and thus obtaining the product in an almost completely automated manner, but also offers advantages over conventional techniques in terms of speed, precision, and ease of use (25,26).

The prosthesis was certainly the most affected, thanks to the advent of CAD/CAM technologies and the continuous development of restorative materials (27,28).

The techniques "computer aided design" and "computer aided manufacturing", or CAD-CAM, were developed with the aim of reducing the deficits of traditional techniques and automating the production process for the quality of the restoration and the efficiency of the flow of work (29).

Digital dentistry and CAD / CAM restorations are now setting the standards of modern dentistry in terms of precision, predictability, and simplicity of production.

Already a century ago Albert Einstein stated, "Computers are incredibly fast, accurate and stupid, while men are incredibly slow, inaccurate and intelligent: the combination of the two constitutes an incalculable force" (30). CAD-CAM technology not only offers the possibility of designing directly on the computer and thus obtaining the product in an almost completely automated manner, but also offers advantages over conventional techniques in terms of speed, precision, and ease of use (31).

In dentistry, the digital world has made its appearance both in the management component of patients and in the clinical one, where digital acquisition through radiographic diagnostic systems and intraoral scanners allows you to create virtual models on which the diagnostic-therapeutic process can be developed. Modern dentistry is therefore an aesthetic, minimally invasive and digital dentistry. Achieving "beauty" with minimal

invasiveness passes more and more often through a "dental digital workflow", which is the adoption of modern principles and digital protocols in daily clinical practice (32,33).

To complete the professional technological development of recent years, "The intraoral digital impression" (I.O.S. Intra Oral Scanner) has appeared on the market.

The impression is a fundamental moment in the acquisition of intraoral data.

The traditional methods using the different impression materials, although widely tested and tested over the years, have some disadvantages, including the not always easy execution due to the reduced compliance of the patient linked to the objective discomfort caused by the procedures of the impression techniques. It is also necessary to consider the unpredictability of the result, sometimes the need for remaking and the problems relating to the stability

of the impression material and casting times (34).

Intraoral scanners are devices that allow the dentist to detect the oral anatomy of hard and soft tissues digitally,

or without the aid of normal impression materials, impression trays or registration waxes.
The introduction of intraoral scanners (IOS) on the market has almost totally changed the workflow: obtaining three-dimensional images of the oral apparatus directly in the specialist office, has facilitated the digitization process and solved both the known problems and the disadvantages concerning the conventional impressions.
The first benefit of Digital Scans is represented by precision: the accuracy of a project made on the computer is greater than that made with manual systems; the clinician can afford to deepen the details and refine the details (35).
The speed of acquisition is also important: intraoral scanners are potentially faster than a traditional impression, considering that the latter requires many more production stages before obtaining a model on which the technician can work.
There is also the reproducibility of the image: an artifact converted into a digital file can be duplicated indefinitely in an identical way to the original and will remain so over time, therefore it will not suffer the degradation intended for non-digital copies.
Another important advantage is to obtain a 3D simulation that allows you to view the three-dimensional image of the object in every smallest detail and from every angle.
The main advantages of digital systems will be listed below: minimal invasiveness, accuracy of the imprint, patient comfort, possibility of viewing, adjusting and possibly resuming the impression, simplification of the process and reduction of appointments, instant feedback, digital storage of the impression and high hygiene and cross-infection control.
The possibility of effectively replacing the traditional impression taking remains one of the major advantages of the optical impression, a goal on which all modern dentistry has been focusing in recent years.
However, the digital impression has not yet replaced the traditional impression, as scanners are expensive machines, with still a moderate risk of errors that limit the accuracy of the impression, do not always reduce the time compared to conventional impressions and have a specific learning curve.
From an analysis of the literature, most of the studies in the dentistry sector focus mainly on comparing the accuracy of the digital impression with the conventional one, but there is a lack of studies on the evaluation of learning curves for this new generation of equipment.
Recent studies have compared the preferences and working times of conventional and digital impression methods (36), but no studies have confirmed the improvement of skills in the repeated use of intraoral scanning. In one study, Lee and Gallucci (37) assessed the level of difficulty and perception between a group of students from the New York University School of Dentistry and one of experienced clinicians, while using digital and conventional techniques for taking footprint, based on a visual analog scale and a multiple questionnaire.
In their final evaluation, however, there was a lack of observation of the timing of the learning process by those who approached this new procedure for the first time.
The purpose of this study is to evaluate the learning curve in relation to the amount of surface acquired with the use of an intraoral scanner.

MATERIALS AND METHODS

Two different groups of operators were recruited for this study.
The first group is made up of 25 students of the San Raffaele Faculty of Dentistry between the fourth and sixth year of the course, who are already practicing practical training in the specialist department of the same San Raffaele Hospital.
In the second group, 25 dentists from the department were recruited, between 30 and 60 years of age with at least 5 years of work experience, who in their daily practice mainly use traditional techniques for taking the impression.
To avoid incorrect data, dental hygienists, dental technicians, and dental assistants were excluded from the office.
After several acquisition tests prior to the study, a porous material was chosen as the material for the model used for the acquisitions: thanks to its surface, the scanner was able to perfectly read all the details, as opposed to more shiny materials such as plastic that reflected the scanner light excessively (***Figure 1***).
A standard model of a full upper semi-jaw was created, which was then fixed with sticky wax on a training manikin. The reason for this choice is to evaluate and compare the competence of the scanner to obtain conditions as similar as possible to those that would occur during the taking of the impression on the patient, but without those potential disturbing factors, such as saliva, movement of the cheeks and the limited opening of the mouth, which would have given further variables (***Figure 1, Figure 2***).
Only one scanner was chosen for this study, CEREC, belonging to the Sirona group, again to obtain a standardized study.
Before the acquisition, each candidate was given a sheet with basic instructions on the use of the I.O.S.
In a single session, the operators had to consecutively take 4 complete fingerprints of the model inside the mannequin. An external operator, at each scan, was assigned to advise candidates on the best acquisition procedure.
The learning curve was assessed by measuring the time each operator completed the scan. To obtain images of a predetermined quality, the time until the image reached an appreciable level was evaluated: the scan was repeated until the standard requirements were met. If the change was not possible, the defective part was deleted, and the scan was re-scanned.

Fig. 1 Plaster model mounted on didactic manikin.

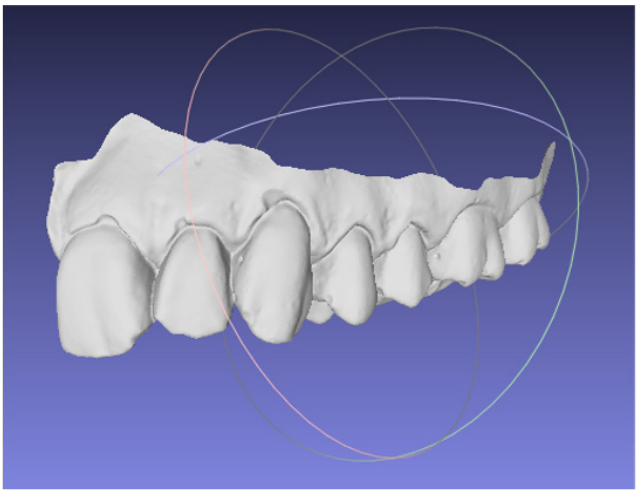

Fig. 2 Scan displayed via MeshLab software.

Time in minutes was documented for the learning curve. The standard requirements were as follows:
Accurate scan of the entire dentition, avoiding holes in the image

Scan at least 3 mm of apical gingiva at the gingival margin

Two values were considered in the evaluation.
The first is the time which, as mentioned, is important for evaluating the learning curve. It was calculated for all four scans of the plaster hemiarch model, to be able to subsequently define how each subject improved thanks to the repetitions.
The second data is the volume of the acquired area. Through a software (MeshLab 2016 Released) the volumes of all the scans were identified in pixel units (*Figure 2*).
These data were calculated both individually and in relation to each other, to also evaluate which group was more capable.
Since CEREC is a closed system, at the end of the acquisitions the files were sent to a laboratory associated with the Sirona group, which converted them into open STL files.

Statistical Analysis

The statistical analysis for this study was conducted using a systematic approach to evaluate and compare the learning curve of dentists and students in intraoral scanning. The analysis was focused on two main clinical outcomes: time and acquired surface area, as well as the surface-time ratio (X), which represents the efficiency of the scanning process.

1. Software Used

IBM SPSS Statistics (version 25): SPSS was used for all statistical testing, including descriptive statistics and significance testing.
Microsoft Excel (version 2016): Excel was employed to organize raw data, compute averages, standard deviations, and generate visual representations such as tables and graphs.
MeshLab 2016: This software was used to extract and analyze the surface area from the STL files generated by the intraoral scanner.

2. Tests Performed

Descriptive Statistics: Basic descriptive statistics, such as means and standard deviations, were calculated for each variable (time, surface area, and surface-time ratio) across the four trials (T1-T4) for both groups (dentists and students).
Paired Sample t-test: A paired t-test was performed to compare the values of time, surface area, and surface-time ratio (X) between consecutive scans (T1 vs. T2, T2 vs. T3, T3 vs. T4) within each group. The goal was to evaluate whether there was a statistically significant improvement in performance over time.
Independent Sample t-test: An independent t-test was applied to compare the performance of doctors and students at each time point (T1, T2, T3, T4) for all the evaluated metrics. This allowed for the identification of statistically significant differences in performance between the two groups.
Boxplot Analysis: Boxplots were used to visually assess the distribution and variability of the surface-time ratio (X) across the four time points. The boxplots provided a graphical representation of the median, quartiles, and potential outliers for each group, offering insights into the consistency and variability of performance.

3. Variables Analyzed

Time (T1, T2, T3, T4): The time required to complete each scan was measured in minutes. This variable was critical in assessing the learning curve of both groups, as a reduction in time across the four trials indicated improved proficiency with the scanning process.
Acquired Surface (SUP): The surface area captured

DOCTOR	T1	t	SUP.1	x	T2	t	SUP.2
1.	1.95.56	1.993	382.180	191.72554	3.1.61	1.5.63.83	264.65651
2.	1.47.61	1.792	446.494	268.33458	1.94.14	1.2.64	477.15
3.	1.05.93	1.116	541.135	401.4026	1.0.95	1.0.08	375.51883
4.	0.9.78	0.98	460.927	307.51401	1.09.08	1.061667	400.6452
5.	0.85.39	0.943	390.870	268.31537	0.98.11	1.006667	360.44387
6.	0.7.96	0.879	397.776	334.81374	0.9.66	0.951667	422.33407
7.	0.61.84	0.804	413.746	299.86604	0.92.5	0.901667	369.78245
8.	1.16.22	1.437	386.236	268.38442	0.42.37	1.006667	360.42705
9.	0.93.53	0.937	459.177	199.553	1.18.8	1.116667	462.84705
10.	2.05.56	2.093	811.440	281.80272	1.07.01	1.101	447.681
11.	0.5.21	0.661	439.621	141.497	0.50.84	0.911	401.82801
12.	3.09.9	3.01	474.489	455.71499	0.5.62	0.973333	450.80793
13.	0.34.53	0.88	389.489	491.40949	0.07.44	397.795	322.68342
14.	0.9.39	1.081	480.579	755.17921	0.97.96	349.706	437.33075
15.	2.8.71	3.18	449.895	497.19599	0.61.07	400.803	401.95375
16.	3.29.27	3.42	388.145	537.21895	0.1.29	0.955	362.584
17.	1.14.69	1.72	443.984	382.9077	1.63.1	412.36	406.323
18.	1.58.8	1.876	486.466	359.4097	1.96.1	432.546	433.781
19.	1.2.73	1.667	402.634	365.222	0.33.57	416.68	396.413
20.	0.6.51	0.951	443.949	423.12898	1.69.11	446.81	447.75813
21.	0.8.68	1.133	486.637	282.971	1.5.44	413.847	431.68721
22.	1.96.83	2.038	542.138	374.676	1.11.24	421.888	401.73891
23.	1.01.43	1.198	449.965	300.1469	0.25.64	402.612	340.142
24.	1.04.95	1.402	384.137	290.26582	0.58.64	0.957666	453.1746
25.	2.01.63	2.083833	409.822	202.3207	1.49.7	1.788333	405.452

DOCTOR	T1	t	SUP.1	x	T2	t	SUP.2
1.	1.12.23	2.083833	391.135	325.43873	1.04.3	1.238333	335.36674
2.	1.0.54	1.132	394.255	257.729	0.7.91	1.168333	396.893
3.	0.45.69	0.679	460.952	257.661	0.68.6	1.11	407.501
4.	0.56.09	0.935	480.632	289.6067	0.5.46	0.933	394.731
5.	1.08.16	1.193333	402.694	331.71796	0.60.09	394.487	379.76798
6.	0.45.96	0.876	432.356	276.119	0.59.7	0.99	377.669
7.	0.5.37	0.9	400.976	240.509	0.45.7	0.91	371.249
8.	0.54.29	0.978	432.059	271.154	0.5.87	1.06	429.154
9.	0.45.99	0.86	437.146	251.834	0.46.9	0.95	379.669
10.	1.09.84	1.176	461.851	312.873	0.88.67	0.971667	454.145
11.	0.8.16	1.016333	402.881	372.77099	1.02.17	0.966667	429.15231
12.	0.45.5	0.993333	460.295	409.67471	1.16.37	420.567	432.15451
13.	0.54.91	1.183	471.782	332.508	1.12.4	455.622	417.578
14.	0.5.37	0.916667	431.458	260.72785	0.45.79	405.974	392.435
15.	0.34.58	0.876	411.895	276.09783	0.7.31	451.889	350.267
16.	1.04.83	1.238333	423.56	301.837	1.16.37	443.57	433.06642
17.	1.68.13	1.333	400.213	306.884	0.07.5	419.84	436.6662
18.	1.04.83	1.183667	402.527	400.112	1.13.25	424.071	414.794
19.	1.08.84	1.116333	402.88	298.409	1.05.83	432.086	447.033
20.	1.05.57	1.076667	419.777	265.789	0.8.63	396.45	401.837
21.	0.57.98	0.933333	420.555	431.915	0.54.95	395.495	403.20055
22.	0.51.17	1.048167	419.178	282.48552	1.12.36	453.668	433.186
23.	0.54.91	1.216833	431.919	314.598	0.12.83	453.455	421.307
24.	1.07.64	1.126667	396.553	367.233	1.19.76	447.054	432.086
25.	0.57.17	1.466167	419.778	282.48552	1.13.66	454.333	301.343

Tab. 1 T1-2-3-4 Dentists' Scans.

STUDENT	T1	t	SUP.1	x	T2	SUP.2	x
1.	1.47.82	1.797	483.798	244.1836	1.22.99	1.381667	426.334
2.	1.00.79	1.013761	443.057	227.37582	1.01.82	1.083	389.647
3.	1.03.58	1.893	416.266	229.85795	1.01.08	1.003333	415.397
4.	0.57.89	0.784	413.452	229.35701	0.98.58	0.915	389.964
5.	2.11.18	2.816667	393.483	353.7718	1.05.6	1.175167	469.486
6.	1.17.53	1.826833	397.185	312.91025	1.09.16	1.286833	469.0107
7.	1.00.14	1.204667	402.282	354.1602	1.05.42	1.170667	390.869
8.	1.47.91	1.096667	480.125	452.4661	0.7.7033	0.914333	380.26
9.	1.07.0	1.458667	409.706	324.5025	1.07.54	1.5	456.82
10.	1.01.74	1.699333	509.798	380.6245	1.57.12	1.486667	380.287
11.	0.62.63	1.036843	380.7702	382.52395	0.5.42	0.834333	391.5696
12.	1.14.03	1.416667	422.3792	308.245	1.35.36	1.786333	508.642
13.	1.00.00	1.001667	442.774	372.7712	1.0.16	1.066667	463.87
14.	1.00.00	1.001667	422.774	304.7655	1.36.16	408.731	385.7711
15.	0.79.04	1.188	401.672	357.4031	1.01.66	1.066667	406.506
16.	0.87.79	1.376667	446.234	433.3922	0.35.57	1.006667	368.0726
17.	1.12.25	1.121	403.857	373.6095	1.06.36	1.26	414.59
18.	1.00.04	1.001667	422.774	304.8923	1.0.08	0.916667	371.6378
19.	1.09.57	1.456667	439.57	316.3456	1.56.94	1.886	456.769
20.	0.62.89	1.061167	421.895	314.6256	0.92.57	1.073333	356.0539
21.	0.94.63	1.513333	380.512	252.46295	1.00.85	1.068333	399.0039
22.	1.00.64	1.071667	380.649	324.6436	1.0.96	1.166667	406.194
23.	0.46.64	0.903333	382.136	268.6469	0.6.14	0.983143	413.476
24.	1.00.76	1.366	400.867	297.8213	1.55.9	1.4265	414.76
25.	1.20.76	1.364	400.867	297.8213	1.55.9	1.4265	414.76

Tab. 2 T1-2-3-4 Students' Scans.

during each scan was measured in pixel units using MeshLab. This variable was essential in evaluating the completeness and accuracy of each scan. Larger surface areas indicated that the operator had captured more of the model without leaving gaps.

Surface-Time Ratio (X): This ratio was calculated by dividing the surface area by the time taken for each scan (X = surface/time). It served as a key indicator of scanning efficiency, reflecting how effectively each operator was able to capture the surface area within a given time frame. A higher surface-time ratio indicated greater efficiency and proficiency.

4. Goals of the Analysis

The analysis aimed to:

Track Learning Progress: By comparing the time, surface area, and surface-time ratio across the four trials (T1-T4), the analysis sought to determine whether the operators (both doctors and students) improved their performance over time, thus indicating a learning curve.

Evaluate Efficiency: The surface-time ratio (X) was specifically analyzed to assess how efficiently the operators were able to complete the scans. The goal was to identify at which point the operators reached peak efficiency and whether this differed between the two groups.

Compare Groups: By using independent t-tests, the analysis aimed to identify significant differences between the doctors and students at each time point. This allowed for an understanding of how experience (doctors) versus learning (students) influenced the performance in intraoral scanning.

Assess Variability: Through boxplot analysis, the variability within each group was examined to determine whether the learning curve was consistent across all operators or whether some individuals exhibited greater improvement than others.

RESULTS

The analysis of this study is based on several critical outcomes related to the performance of **dentists** and **students** in using an intraoral scanner (IOS). The key metrics analyzed include **time** (T1-T4), **acquired surface** (SUP), and the **surface-time ratio (X)**, which is central to understanding the learning curve of both groups. The data are presented across several tables, offering detailed insight into the progression and performance improvements of both groups.

	T1			T2		
	time	surface	x	time	surface	x
Doctor Avg	1.399193	406.4966	347.908	1.170	406.4269	407.27
Student Avg	1.222	415.203	343.963	1.076	411.907	406.056
Doctor Std Dev	0.557273	20.6124	146.054	0.466444	26.60296	186.8661
Student Std Dev	0.387859	35.4648	84.89895	0.256998	28.19769	111.4653

	T3			T4		
	time	surface	x	time	surface	x
Doctor Avg	0.968	409.7356	455.486	1.015	445.2899	447.77
Student Avg	1.018	409.983	430.443	1.002	407.481	433.125
Doctor Std Dev	0.267529	14.87684	129.5547	0.305404	24.21387	140.4907
Student Std Dev	0.256282	25.44627	124.8018	0.26176	29.63379	114.5626

Tab. 3 Averages for doctors and students.

AVERAGE TIMES	T1	T2	T3	T4
DOCTORS	1.399193	1.16976	0.967607	1.015053
STUDENTS	1.292207	1.07574	1.018207	1.001887

Tab. 4 Average Doctor-Student Time.

AVERAGE SURFACE	T1	T2	T3	T4
DOCTORS	406.4696	406.2469	409.7356	415.2899
STUDENTS	415.2032	411.9067	409.9277	407.4812

Tab. 5 Average surface for doctor-students.

AVERAGE SURFACE/TIME RATIO (X)	T1	T2	T3	T4
DOCTORS	347.90759	407.27268	455.86091	447.76955
STUDENTS	343.96355	407.05621	430.44313	433.12497

Tab. 6 Average learning curve (X).

Raw Data of Time, Surface, and Efficiency for Doctors and Students

Table 1 (Doctors): This table shows the time, surface, and surface-time ratio (X) for each doctor across four scans (T1-T4). It reveals a significant improvement in both time and surface coverage over the repetitions. For example, the doctors' surface area increased from an average of 406.47 mm² in T1 to 415.29 mm² in T4, while the time decreased from 1.399 minutes in T1 to 1.015 minutes in T4. This reflects that with repeated practice, doctors were able to capture more data in less time, demonstrating their adaptation to the scanning process. The average surface-time ratio (X) also showed marked improvement, indicating a significant learning curve.

Table 2 (Students): Similarly, this table shows the corresponding values for the student group. The students demonstrated a more gradual learning curve, with less dramatic improvements in time and surface area compared to the doctors. For example, the students' surface area slightly decreased from 415.20 mm² in T1 to 407.48 mm² in T4, while their average scan time also reduced, from 1.292 minutes in T1 to 1.001 minutes in T4. The surface-time ratio (X) increased consistently, showing that students were improving their efficiency but at a slower rate than doctors.

Average Values for Time, Surface, and Surface-Time Ratio (X)

Table 3 summarizes the average values of time, surface, and surface-time ratio (X) across all four scans for both groups:

Doctors: The average time for doctors decreased consistently from 1.399 minutes in T1 to 1.015 minutes in T4. The surface area captured also increased from 406.47 mm² in T1 to 415.29 mm² in T4. The most significant change was in the surface-time ratio (X), which increased from 347.91 mm²/min in T1 to 447.77 mm²/min in T4, reflecting an overall improvement in efficiency.

Students: The students also showed a decrease in time, from 1.292 minutes in T1 to 1.001 minutes in T4. However, their surface area captured decreased slightly, from 415.20 mm² in T1 to 407.48 mm² in T4. The surface-time ratio (X) improved more gradually, from 343.96 mm²/min in T1 to 433.12 mm²/min in T4, suggesting steady progress.

Average Time Comparison Between Doctors and Students

Table 4 presents the average time taken for each scan across the four trials for both groups:

Doctors: The doctors showed a marked reduction in time, from 1.399 minutes in T1 to 0.968 minutes in T3,

DOCTORS	T1	T2	T3	T4
Value x				
	191.7255	264.6565	332.4385	315.3667
	248.3054	334.4676	419.1483	353.0867
	404.4041	375.5188	521.2484	535.0093
	470.6762	400.6452	531.6934	639.7076
	620.8474	422.3341	621.3441	670.7176
	288.5841	360.4439	549.6567	460.7805
	215.5824	369.7825	445.8351	381.8706
	268.3844	360.4271	355.8571	306.5244
	199.553	462.8471	381.4571	381.7599
	281.8027	447.681	459.6817	504.1456
	141.497	401.828	381.4571	391.716
	455.715	450.8079	457.8067	381.4571
	491.4095	322.6834	414.7667	431.7907
	755.1792	437.3308	659.7651	651.7816
	497.196	401.9538	437.7143	519.4546
	537.219	362.584	434.9571	481.7509
	382.9077	406.323	411.7625	380.2694
	359.4097	433.781	471.7651	481.679
	365.222	396.413	405.0214	430.5071
	423.129	447.7581	486.4571	527.0082
	282.971	431.6872	490.7809	451.6876
	374.676	401.7389	387.7509	431.7456
	300.147	340.142	380.8444	390.5848
	290.2658	453.1746	423.7651	466.0086
	202.3207	405.452	292.4529	321.1345

Tab. 7 Relationship between surface and time (DOCTORS)

followed by a slight increase to 1.015 minutes in T4. This indicates rapid adaptation and improvement in the first three scans, with some stabilization in the final scan.
Students: The students followed a similar trend but with a more gradual learning curve. Their time decreased from 1.292 minutes in T1 to 1.018 minutes in T3 and further decreased to 1.001 minutes in T4. This shows steady improvement, though less dramatic than that seen in the doctors' group.

Average Surface Acquired Comparison Between Doctors and Students

Table 5 compares the average surface area acquired by both groups:
Doctors: The surface area increased progressively across the scans, from 406.47 mm² in T1 to 415.29 mm² in T4. This indicates that doctors improved not only in speed but also in the completeness and accuracy of their scans.
Students: The students started with a slightly higher surface area in T1 (415.20 mm²) than the doctors, but their surface area slightly decreased over time to 407.48 mm² in T4. This suggests that while students improved their scanning speed, they may not have consistently captured as complete a scan as doctors.

Surface-Time Ratio (X) Comparison Between Doctors and Students

Table 6 is crucial in understanding the learning curve by examining the surface-time ratio (X), which combines both speed and precision:
Doctors: The surface-time ratio (X) showed a significant improvement from 347.91 mm²/min in T1 to 447.77 mm²/min in T4. The largest improvement occurred between T2 and T3, reflecting the doctors' increased efficiency as they became more familiar with the scanning process.
Students: The students also improved their surface-time ratio, though their progression was more gradual. Their ratio increased from 343.96 mm²/min in T1 to 433.12 mm²/min in T4. While students achieved steady improvements, they did not reach the same level of efficiency as the doctors.

Relationship Between Surface and Time for Doctors (Boxplot Analysis)

Table 7 provides a more detailed analysis of the variability in performance among doctors across the four scans:
The boxplot for doctors shows a high degree of variability in the first scan (T1), with some doctors achieving very high efficiency and others struggling. By the third scan (T3), the variability had decreased significantly, indicating that most doctors had reached a consistent level of proficiency. However, by T4, the variability slightly increased, suggesting that some doctors may have struggled to maintain their improved performance.

Relationship Between Surface and Time for Students (Boxplot Analysis)

Table 8 offers a similar boxplot analysis for students:
The boxplot for students shows less variability overall compared to doctors, suggesting that students followed a more uniform learning curve. However, their peak efficiency, represented by the surface-time ratio (X), was lower than that of the doctors. This indicates that while students demonstrated consistency, they did not reach the same level of mastery as the more experienced doctors.

DISCUSSION

Dentistry, like other branches of medicine, is undergoing continuous evolution. The advent of new technologies and clinical protocols is progressively transforming traditional dental practices. In particular, the introduction of CAD-CAM techniques has represented a significant technological leap in the dental field.
The origins of CAD-CAM technology date back to the early 1960s with the development of the first graphical interface. However, it was not until 1983 that François Duret applied this technology in dentistry, introducing the first prosthetic restoration utilizing CAD-CAM methods (38). Two years later, in 1985, Dr. Werner Mörmann and engineer Marco Brandestini introduced an optical dental

STUDENTS	T1	T2	T3	T4
Value x				
	244.1836	334.9806	354.1687	263.2484
	437.8471	370.8611	450.2509	490.4090
	219.8925	403.8567	389.3954	435.7091
	180.1013	380.6393	354.3393	393.0194
	130.8736	298.0195	359.6919	419.1048
	460.4243	420.9354	456.6949	473.7012
	388.2695	399.6639	438.4561	400.9707
	328.6935	260.5659	421.3129	421.9794
	525.9689	281.9737	432.9243	444.7907
	308.4255	290.3345	419.8464	401.7590
	322.7465	261.5051	481.6341	414.7607
	328.1527	302.6235	486.3126	442.5907
	367.5935	368.7967	441.8164	476.1516
	443.6094	509.7982	449.9582	439.7554
	380.7702	382.5239	390.4535	391.5696
	422.3792	308.2450	437.7651	508.6423
	401.6724	357.4031	399.8564	406.5060
	446.2341	433.3922	446.4571	368.0726
	403.8571	373.6095	471.7651	414.5976
	380.6492	324.6436	406.4571	406.1943
	421.8952	314.6256	487.7509	356.0539
	441.0049	370.8611	395.9582	393.7554
	281.8054	276.0627	407.8055	420.2163
	441.4297	276.0627	420.3058	462.0130
	350.3012	340.4373	442.3456	464.6795
	339.3042	260.5659	459.9341	494.0970
	236.6634	374.8765	347.3376	362.0419
	329.6441	428.8826	346.0467	396.5241
	297.8213	286.6466	347.3376	362.0419

Tab. 8 Relationship between surface and time (STUDENTS).

scanning system, CEREC, which revolutionized intraoral scanning and prosthetic dentistry (38).
CAD-CAM technology was developed with the goal of designing and producing prosthetic structures with uniform quality, using standardized, codified, and reproducible procedures. With advances in hardware and software, the use of CAD-CAM evolved from dental laboratories to dental practices, establishing itself as a critical component of modern dentistry.
The most recent technological innovation in this progression is the Intraoral Scanner (I.O.S.), a device designed to capture digital impressions directly from the oral cavity. The introduction and widespread adoption of various I.O.S. devices has fundamentally altered the impression-taking process. The term "intraoral scanner" distinguishes this technology from extraoral and laboratory-based scanners.
The success of a prosthetic restoration largely depends on the accuracy of the initial impression, as any inaccuracies can lead to suboptimal clinical outcomes (39). The accuracy of a digital system is influenced by three critical stages: impression precision, digital design, and production (40).
Precision, defined as the repeatability of data, plays a fundamental role in determining the reliability of a scanner. A precise scanner generates consistent, repeatable data across multiple scans, with minimal variance from the mean. In contrast, a scanner that exhibits significant variability across repeated scans lacks precision. In essence, a scanner's precision is measured by the degree of "convergence" or "dispersion" of the data from the average, often quantified through statistical measures such as variance or standard deviation.
While the precision and accuracy of intraoral scanners have improved significantly, challenges remain in achieving completely error-free scans. Errors can arise due to various factors, including insufficient point density, misalignment of point clouds, outliers or missing data, suboptimal scanning devices, inadequate device calibration (41), improper positioning of the scanner tip (36), interference from reflective materials such as saliva (42), and most critically for this study, operator inexperience (43).
Understanding the learning curve associated with intraoral scanners is critical. A learning curve refers to the gradual improvement in performance that occurs with repeated practice, typically characterized by rapid initial improvement followed by a more gradual enhancement until performance plateaus (44).
Three-dimensional intraoral scanning is gaining traction across various fields of dentistry, and to fully capitalize on the advantages of this technology, clinicians must invest time in mastering its use. The learning process, characterized by behavioral changes induced by repeated practice, is necessary to achieve high-quality results.
In medicine, various studies have explored the learning curves associated with the introduction of new technologies. However, in dentistry, most research has focused on comparing the accuracy of digital versus conventional impressions, with limited focus on assessing the learning curve for new devices (45).
Recent studies have examined the preferences and working times between digital and conventional impression methods (46), but few have quantitatively assessed the improvement in proficiency through repeated intraoral scanning. A recent study evaluated the learning curve for two digital intraoral scanners by measuring how scanning times decreased with repeated use (47). However, these studies often lack a comprehensive evaluation of the surface area acquired during the scans, which is a key factor in assessing the completeness and accuracy of the impression.
The present study aims to fill this gap by evaluating the learning curve of intraoral scanning with the CEREC system among two groups: dental students from the San Raffaele

Faculty of Dentistry and clinicians with at least five years of experience. Unlike previous studies that focused only on subjective preferences (48) or scanning times (49), this study also analyzes the surface area captured during each scan. The results indicate that repeated practice significantly improved the performance of both groups, as evidenced by the reduction in average scan times and the improvement in the surface-time ratio (X). This phenomenon mirrors findings in other fields, such as laparoscopic surgery, where repeated practice led to faster suture times (50). However, unlike the cited work, which focused solely on the final quality of the procedure, our study integrates both time and surface data, providing a more holistic view of performance improvement. A study by Jisun et al. evaluated the learning curve by measuring scan times with two different scanners but did not account for the surface area acquired (51). In contrast, our study analyzed both scan time and surface area using MeshLab 2016 software to quantify the amount of data captured during each scan.

CONCLUSION

This study aimed to evaluate the learning curve associated with intraoral scanning using the CEREC system, comparing two distinct groups: dental students and experienced clinicians. The results revealed significant improvements in scanning performance for both groups, with reductions in time, increases in surface area captured, and improvements in the surface-time ratio (X), which reflects scanning efficiency. The most notable finding was the clear advantage that clinical experience provided. Although both groups showed similar reductions in time after repeated practice, clinicians consistently outperformed students in terms of surface area acquired. This suggests that, while students adapted well to the technical aspects of the scanner, clinicians' broader procedural knowledge and familiarity with dental anatomy allowed them to perform more accurate and complete scans. The learning curve was steepest in the initial trials, with both groups showing rapid improvement, followed by a plateau after the third trial (T3). This reflects a common pattern seen in procedural learning, where initial exposure and repetition yield the most dramatic improvements, but further refinement requires sustained practice to achieve marginal gains in efficiency and precision.

Clinicians, despite being less familiar with digital tools, demonstrated their capacity to integrate new technologies effectively, benefitting from their extensive practical experience. In contrast, students, while quick to grasp the technical usage of the scanner, did not achieve the same level of proficiency in acquiring comprehensive surface data, likely due to their more limited clinical experience.

These findings suggest that while intraoral scanning is accessible to both novice and experienced users, the combination of repetition and clinical expertise is critical for optimizing the use of this technology. Therefore, training programs should emphasize not only repeated practice but also the development of clinical judgment to fully leverage the potential of digital impression systems.

Future studies should explore the long-term retention of these skills, as well as the role of enhanced training protocols in further reducing the learning curve for both dental students and practitioners. Additionally, examining the impact of different scanning systems and their interfaces on the learning process could provide valuable insights into how intraoral scanning can be more effectively integrated into dental education and practice.

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