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# The Accuracy of Optical Scanning: Influence of Convergence and Die Preparation

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### Clinical Relevance

Although studies about computer-aided design/computer-aided manufacturing (CAD/CAM) marginal discrepancy are common, studies about the accuracy of optical measurement of the CAD/CAM system are rare. With this study, clinicians will be aware of the error inherent in the data acquisition and modeling process of the CAD/CAM procedure.

## SUMMARY

**The purpose of this study was to determine the reliability of the data acquisition and modeling process of laser and white light scanners by evaluating the reproducibility of digitized simulated crowns with different convergences. A secondary purpose was to analyze the influence of die preparation by testing this hypothesis with a set of dies without ditching compared with a set with well-defined margins. Ditching or trimming the die defines the position of the margin and acts as a guide to gingival contour when the restoration is being waxed. Two light scanners (a white light optical scanner [Steinbichler Gmbh, Neubeuern, Germany] and red laser light scanner [Turbo-Dent System, Taichung, Taiwan]) were evaluated. Two sets of simulated crowns were fabricated as cone frustrum models with a total occlusal convergence (TOC) of 0°, 5°, 10°, 15°, 20°, and 25° and a 9-mm base and 3-mm height using a precision milling machine and computer-aided design/computer-aided manufacturing (CAD/CAM) technique. One set of the dies was ditched immediately below the finish line to enhance marginal definition. Each die was optically digitized five times directly with**

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**the two different measuring systems. The area of each triangle in the scan that is occlusal to the margin line was calculated and summed to produce the final surface area measurement provided. The digitizing error was compared with the computed surface area of the original master die sets and compared with a paired *t*-test (df=4; 95% CI). There was no difference in accuracy of the untrimmed dies between the two systems evaluated. We also did not find any difference in the 0° (*p*=0.12) and 5° degree (*p*=0.21) groups among the ditched dies. However, when the TOC exceeded 5°, there was a significant difference between the two groups, with the laser groups having a smaller error percentage. Three-dimensional light scanning was not affected by the convergence angle except in the 0°-5° range. Trimming the dies greatly affected the accuracy of scanning.**

## INTRODUCTION

Recently, three-dimensional (3D) computer-aided design/computer-aided manufacturing (CAD/CAM) technology applied in the manufacturing of dental restorations has become popular due to patient acceptance and fewer clinical visits.[1,2] This technology also has the potential to eliminate potential sources of error in the conventional lost-wax casting procedure. CAD/CAM systems typically consist of a scanning system (data acquisition), design software (modeling), and a fabrication machine (milling).[3] During the entire CAD/CAM process, each sequential step will add to final inaccuracies. Therefore, any procedural step that minimizes cumulative error of the CAD/CAM procedure is of significant clinical interest.

A long-standing concern with CAD/CAM restorations is accuracy. Much of the literature on the use of CAD/CAM in the manufacturing of crowns and bridges has been about the internal fit and gap size of dental restorations.[4-10] The cavosurface gap widths produced via CAD/CAM have been shown in some earlier studies to approach or exceed 270 μm.[11] Thus the fit of earlier CAD/CAM restorations is considered very poor. The mean marginal discrepancies of the latest system can still be in the range from 74 to 99 μm.[12] Because the sources of error are cumulative throughout the production process (ie, data acquisition error, modeling error, and fabrication error), clinicians and manufacturers are at a loss as to where to focus on improving the procedures.[13]

In dentistry, 3D scanners can generally be classified as contact and noncontact. Contact 3D scanners probe the subject through physical touch and can be very precise. Procera (Nobel Biocare GmbH, Germany) is an example of a contact 3D scanner. The disadvantage is that it requires contact with the object being scanned. Thus, the act of scanning the object might modify or damage it. Another disadvantage is the relatively slow speed of this scanner. The fastest probe can only operate on a few hundred hertz. Scanning time of a typical metal-free coping for the Procera system (Nobel Biocare) is reported to be approximately five to seven minutes. In contrast, noncontact 3D scanners like a laser scanner can operate from 10 up to 500 kHz. For example, a laser-type scanner can scan a typical metal-free coping in 25 seconds.

Noncontact 3D scanners can be broadly classified into active and passive types. Passive scanners do not emit any kind of radiation themselves, but instead rely on detecting reflected ambient radiation. Currently, they are not used in dental applications. In dentistry, noncontact 3D scanners are the active type; ie, they emit some kind of radiation (light, ultrasound, or x-ray) and detect its reflection in order to probe an object or environment. Light sources currently used in 3D CAD/CAM include white light, infrared, and blue light. They are relatively inexpensive and measurement takes less time than with a contact probe. However, it is one order less accurate than a mechanical touch probe. Because the reflected light from the object must be recognized by a sensor, the precision decreases with the effects of diffusion. In addition, the resolution of the charge-coupled device (CCD) camera also affects the precision.

The purpose of this study was to determine the reliability of the data acquisition and modeling process of laser and white light scanners by evaluating the reproducibility of digitized simulated crowns with different convergence. A secondary purpose was to analyze the influence of die preparation by testing this hypothesis with a set of dies without "ditching" compared with a set with well-defined margins.

## MATERIALS AND METHODS

Two noncontact active scanners were evaluated: a white light optical scanner (Steinbichler Gmbh, Germany) and red laser scanner (TurboDent System [TDS] LSC-200, Pou Yu Biotechnology Co Ltd, Taiwan). The white light optical scanner projects a line grid at a prescribed angle onto the object to be measured, and the CCD camera records the resultant pattern. Evaluation of the projected pattern was performed with the phase-shift method. From the geometric relationships in a triangle, the object coordinates for each individual pixel were determined. The scanner's accuracy is between 20 and 40 μm. As expressed in linear height, the percent error was calculated to be from 0.5%-1.33%. The TDS Scanner is a customized red-line laser scanner that uses the diffuse reflections of a projected laser beam from the part surface to establish the 3D data also by triangulation. The scanning time for a single stump is less than 60 seconds and its accuracy is claimed to be ±10 μm. It can scan 131 lines per face, eight faces, 1000 points per line. The total scan area (length × width × height) is reported to be 80 × 80 × 30. The laser is in the range of 635 to 1550 nm and has power up to 200 mW.

Two sets of simulated crowns were fabricated as cone frustrum models (Figure 1) with the total occlusal convergence (TOC) of 0°, 5°, 10°, 15°, 20°, and 25° and a 9-mm base and 3-mm height. One set of the dies was precision machined from stainless steel stock models and the other set comprised their identical virtual models (CAD models). The stainless steel dies were more difficult to be ditched, so the CAD models were ditched immediately below the finish line to enhance marginal definition. The ditch height and ditch depth were 2 mm and 0.5 mm, respectively. It is recognized that the CAD models may not be exactly the same as the stainless dies. Because the CAD models will be evaluated by both systems, the bias will be the same. Each die was optically digitized five times directly with the two different measuring systems. The area of each triangle in the scan that was "above" the margin line was calculated and summed to produce the final surface area measurement provided. The digitizing error was compared with the computed surface area of the original master die sets and compared with a paired $t$-test (df=4; 95% CI). The total surface areas of the cone frustrum models have been reported previously.[14]

## RESULTS

The results are tabulated in Table 1. A mathematically generated surface area was used as the gold standard. The Delta E (ΔE) between the calculated data surface area and the scanned data for the untrimmed dies was from 2.88-6.47 mm$^2$. The acquisition error of the untrimmed dies amounted to 2.28%-5.7%. The error percentage for each optical system was large, and we did not find significance difference between the two systems ($p>0.05$).

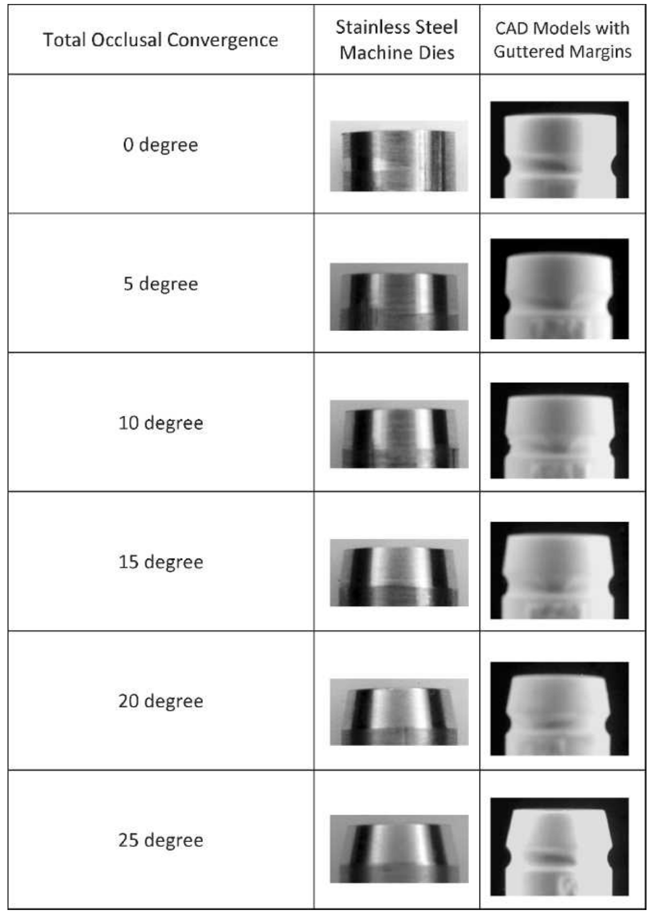


Figure 1. *Stainless steel dies and CAD models.*

The ΔE between the calculated data surface area and the scanned data for the ditched dies was from 1.44-3.66 mm$^2$. The error of the trimmed dies amounted to 1.14%-2.27%. We did not find any difference in the 0° ($p$=0.12) and 5° ($p$=0.21) groups among the ditched dies. However, when the TOC exceeded 5°, there was a significance difference between the two groups, with the laser groups having a smaller error percentage.

The preparation convergence was not found to be a dominant factor for the achievable data acquisition and modeling precision, except for 0° in both the ditched and unditched groups. Qualitative analysis revealed the largest deviations in dies with 0° convergence. Statistical analysis showed that the percentage of error was influenced by die preparation (ditching).

## DISCUSSION

Our results showed that for both ditched and unditched models with 0° convergence, either the readings cannot be validated or they have a higher percentage of error. For the unditched stainless steel dies, the use of an opaque agent was required to pretreat the dies prior to scanning. This opaque agent is a nonreflective material and should be used sparingly. Any excess buildup or areas on the die that are not covered can be an error source. In order for the optical scanner to read properly, it is important to have the medium being scanned to be in good contrast with the incident light. Modified or scattered light will result in a poor reading by the CCD camera and create noise in the point cloud. One way to avoid this error is to check the point cloud of the final 3D image that is produced. The final image should be smooth and free of defects.

The high error percentage can also be seen in ditched dies with 0° margins. This can be explained by the fact that most software used for scanning the dies has an automatic margin marking feature. The algorithm behind it searches for the apex of the angle between the shoulder and the ditch on the scanned die. Given that the 0° dies have an absent or unpronounced shoulder, this probably causes the relatively large margin of error for these dies. Other studies also point out that corner precision is particularly difficult to obtain.[15,16] For this reason, ditching, either virtually or physically, is recommended. Such a recommendation can be supported by the results of our study, which showed the maximum error for the scanning to be around 5.7% for unditched dies but as low as 1.14% for ditched dies.

In a study that compared the same laser model and cone beam computed tomography in scanning plaster, it was shown that laser scanning resulted in an average 0.72% error in length measurements.[17] Using the estimation of measurement uncertainty as a multiple to the first power, the percentage uncertainty in surface area equals (percentage uncertainty in height) plus (percentage uncertainty

Table 1: *Calculated Die Surface Area ($mm^2$) and Measurement of the Two Scanners With and Without Die Trimming (Ditching)*

| | Total Occlusal Convergence (TOC) | | | | | |
|---|---|---|---|---|---|---|
| | 0° | 5° | 10° | 15° | 20° | 25° |
| Calculated area ($mm^2$) | 148.44 | 143.64 | 139.07 | 134.74 | 130.61 | 126.28 |
| Laser scanner ($mm^2$) Untrimmed die | NA | 137.17 | 134.32 | 127.05 | 125.62 | 123.34 |
| ΔE ($mm^2$) (calculated–scanned) | NA | 6.47 | 4.75 | 7.69 | 4.98 | 2.94 |
| % error | NA | 4.5 | 3.42 | 5.7 | 3.82 | 2.33 |
| Laser scanner ($mm^2$) Ditched die | 145.08 | 141.43 | 137.32 | 133.10 | 128.94 | 124.84 |
| ΔE ($mm^2$) (calculated–scanned) | 3.36 | 2.21 | 1.75 | 1.64 | 1.67 | 1.44 |
| % error | 2.27 | 1.53 | 1.26 | 1.22 | 1.28 | 1.14 |
| White light scanner ($mm^2$) Untrimmed die | NA | 138.27 | 135.62 | 131.51 | 126.34 | 123.40 |
| ΔE ($mm^2$) (calculated–scanned) | NA | 5.37 | 3.45 | 3.23 | 4.27 | 2.88 |
| % Error | NA | 3.74 | 2.48 | 2.39 | 3.26 | 2.28 |
| White light scanner ($mm^2$) Ditched die | 145.56 | 141.15 | 136.66 | 132.45 | 128.41 | 124.40 |
| ΔE (calculated–scanned) | 2.88 | 2.49 | 2.41 | 2.29 | 2.20 | 1.88 |
| % Error | 1.94 | 1.73 | 1.74 | 1.76 | 1.69 | 1.78 |

in base), or 0.72% + 0.72% = 1.44%. This value agrees with our finding of 1.14%-1.53% for trimmed dies. We can therefore deduce that the linear uncertainty in the two systems tested is approximately 0.6%-0.80%. This is in agreement with one of the manufacturer's reports of 0.5%-1.33% error expressed in linear height. Our result also partially supports the accuracy claims of both manufacturers. The white light scanner's accuracy is reported to be between 20 and 40 μm, whereas the laser scanner is claimed to be ±10 μm. The same magnitude of accuracy can be seen in our measurements. Wavelength resolution has been indicated as a possible source for accuracy improvement.

Earlier studies on the CAD/CAM procedure have expressed that the data acquisition and modeling account for as high as 70% of the cumulative error. Obviously much has improved since the last decade for the data acquisition and modeling process. Most studies reported error in terms of microns. Although we expressed our error in terms of percentage of total surface area, our deduced percentage uncertainty in height of 0.6%-0.80% will produce a marginal gap of 18–32 μm in a typical crown height between 3 and 4 mm. Our results are in agreement with another study of single-tooth images that reported an accuracy up to 19 μm.[18] It is safe to conclude that current optical scanner systems will produce restorations with acceptable margins. Manufacturers include theoretical numbers that represent the maximal possible accuracy of their instruments; however, these typically do not include a combination of potential error rates for both scanning and modeling. With this study, clinicians will be aware of the error inherent in the data-acquisition and modeling processes.

It is interesting to note that the scanned data from both systems are lower than the calculated value (Table 1). The slight underestimation could partially be explained by an optical phenomenon governed by the angle of incidence that occurs at the edge of an object. When the incidence plane exceeds a certain angle (70°) from normal, the perceived thickness of the line is altered, making it difficult for the software to delineate the true edge of the object. If a single surface scan was used, this edge was most likely removed as noise in the modeling process. An underestimation would produce a smaller die during the CAM procedure. To overcome this problem, a statistical software compensation technique, which is more cost effective than hardware compensation, can be used to improve the overall accuracy. Without this modeling compensation, the discrepancy will result in a tight-fitting restoration at the time of delivery, producing a gap at the margins. Routine fit checking for internal fit for CAD/CAM restorations is strongly recommended.

We evaluated convergence (taper) and its relationship to visual interference. It has been reported that one of the errors associated with optical impressions by intraoral cameras was attributable to visual interference that occurred when the camera tilt angle exceeded the axial wall angle of divergence (ie, 7°).[19] In the case of crown preparations, the top occlusal cavosurface can be visually "blocked out" to the gingival margins; the same can be said for inlay/onlay preparations where occlusal cavosurface margins can be visually blocked out to the ends of the preparation box. It can be assumed that preparations made with more vertical walls are more susceptible to camera misalignment errors. The reason for the error of the acute angle can again be explained by both light and software limitations.

We define *taper* as the angle between a single preparation wall and the long axis of the preparation. Hence, TOC will be twice the taper as defined. Our study showed that convergence does not affect the data acquisition and modeling for 3D scanners as long as the TOC is larger than 5°.[20,21] Because convergence angles between 6° and 12° appear to be optimum for tooth crown preparation, our results showed that optimal preparation will not be affected by visual interferences. Thus extraoral scans have less limitation than intraoral systems.[22] This can be explained by the fact that in 3D CAD/CAM, multiple scans from many different directions are usually required to obtain information about all sides of the subject. These scans have to be brought in a common reference system, a process that is usually called *alignment* or *registration*, and then merged to create a complete model.

In our study, the CAM processing precision was not evaluated. Other studies have reported that the error in the milling was small.[3,23] The error in the measurement process would be greater than the error in the milling process, especially with the availability of five-axis milling machines. It would seem logical for manufacturers to devote their attention to the data acquisition process. We only evaluated a single die for simulated crowns. For multiple framework use, the error will be larger than a single crown. Future systems should integrate multiple laser heads and CCDs for accurate and rapid contour measurement of all the identified important surface sections.

## CONCLUSION

1. There is no difference in accuracy between the two systems evaluated when evaluating unditched dies. However, ditched dies showed a difference in the groups greater than 5°.
2. 3D scanning is not affected by convergence angle except in the 0° range.
3. Based on our findings, it is recommended that dies should be ditched in an appropriate fashion before scanning.
4. Both 3D scanners produced data acquisition and modeling error of less than 2.27% with the trimmed dies.

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