Comparing maximum intercuspal contacts of virtual dental patients and mounted dental casts

Ralph DeLong, DDS, MS, PhD,[a] Ching-Chang Ko, DDS, MS, PhD,[b] Gary C. Anderson DDS, MS,[c] James S. Hodges, MA, PhD,[d] and W. H. Douglas BDS, MS, PhD[e]
School of Dentistry, University of Minnesota, Minneapolis, Minn.

Statement of problem. Quantitative measures of occlusal contacts are of paramount importance in the study of chewing dysfunction. A tool is needed to identify and quantify occlusal parameters without occlusal interference caused by the technique of analysis.

Purpose. This laboratory simulation study compared occlusal contacts constructed from 3-dimensional images of dental casts and interocclusal records with contacts found by use of conventional methods.

Material and methods. Dental casts of 10 completely dentate adults were mounted in a semi-adjustable Denar articulator. Maximum intercuspal contacts were marked on the casts using red film. Intercuspal records made with an experimental vinyl polysiloxane impression material recorded maximum intercuspation. Three-dimensional virtual models of the casts and interocclusal records were made using custom software and an optical scanner. Contacts were calculated between virtual casts aligned manually (CM), aligned with interocclusal records scanned seated on the mandibular casts (C1) or scanned independently (C2), and directly from virtual interocclusal records (IR). Sensitivity and specificity calculations used the marked contacts as the standard. Contact parameters were compared between method pairs. Statistical comparisons used analysis of variance and the Tukey-Kramer post hoc test ($P=<.05$).

Results. Sensitivities (range 0.76-0.89) did not differ significantly among the 4 methods ($P=.14$); however, specificities (range 0.89-0.98) were significantly lower for IR ($P=.0001$). Contact parameters of methods CM, C1, and C2 differed significantly from those of method IR ($P<.02$). The ranking based on method pair comparisons was C2/C1 > CM/C1 = CM/C2 > C2/IR > CM/IR > C1/IR, where ">" means "closer than."

Conclusion. Within the limits of this study, occlusal contacts calculated from aligned virtual casts accurately reproduce articulator contacts. (J Prosthet Dent 2002;88:622-30.)

CLINICAL IMPLICATIONS

A virtual dental patient assembled from scanned clinical records of a patient could provide quantitative information that will aid the dentist in assessing the patient's chewing function and in planning appropriate treatments.

Evaluation of the chewing system requires quantitative measures of occlusal interactions between the teeth. Of paramount importance are the number, location, and size of occlusal contacts and the forces applied at these contacts. The Prescale System,[1,2] Photoocclusion,[3,4] and the T-Scan[5,6] measure forces between the teeth using pressure sensitive recording materials. It has been implied that the thickness and stiffness of these recording materials affect the accuracy of the results.[2,5] None of these systems directly relate the location of contacts and forces to the occlusal anatomy.

The effects of occlusal force can be measured indirectly as volume loss of tooth material when the volume of material removed is measured using sequential 3-dimensional (3-D) computer models of the teeth.[7] This computer method provides a possible tool for noninvasively measuring occlusal interactions by use of 3-D computer renditions of dental arches. Digital images of the patient's hard and soft tissues would be correctly related to each other by use of computer software to create a "virtual dental patient" (VDP). Computer comparisons of sequential VDPs would identify and measure occlusal wear and changes in the patient's hard and soft tissues including occlusal contacts. The dentist would analyze the results through graphic representations visualized on 3-D images of the arches. Relationships be-

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[a]Professor, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science.
[b]Assistant Professor, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science
[c]Senior Associate Dean, Department of Diagnostic and Surgical Sciences.
[d]Senior Research Associate, Oral Health Clinical Research Center, Department of Preventive Sciences
[e]Professor and Director, Minnesota Dental Research Center for Biomaterials and Biomechanics, Department of Oral Science

tween contact parameters and occlusal forces estimated from the occlusal wear could provide quantitative, noninvasive measures of occlusal function that would aid the dentist in assessing restorative treatment outcomes and possibly diagnosing chewing dysfunction.

Crucial to the proposed technique is the ability to accurately align computer images of dental arches so that they reproduce the patient's occlusion. Therefore the purpose of this study was to test whether 3-D virtual images of maxillary and mandibular dental casts could be aligned by computer software to reproduce contacts measured in an articulator simulation with conventional clinical techniques.

MATERIAL AND METHODS

Existing maxillary and mandibular casts of 10 subjects were mounted in a semi-adjustable articulator (Denar Corp., Anaheim, Calif.) in maximal intercuspal position (ICP). Approval for secondary use of data was obtained from the University of Minnesota Human Subjects IRB. All casts were from subjects 18 years or older with full complements of teeth, no prosthetic or orthodontic appliances, no restorations, and minimal or no occlusal wear. Subjects with occlusal or temporomandibular joint problems or anterior or posterior open bite were not included.

Articulator simulated patients

The original full arch casts were duplicated with a 2-step impression technique by use of putty and light body vinyl polysiloxane impression materials (Express; 3M ESPE, St.Paul, Minn.) and disposable impression trays (SmartPractice, Phoenix, Ariz.). Replica casts were made with white Fujirock dental stone (GC Europe, Leuven, Belgium). Maxillary casts were mounted in the articulator centered on the articulator mounting ring with the occlusal plane parallel to, and 40 mm from, the base of the mounting ring. This orientation facilitated scanning of the casts. Mandibular casts were hand articulated to the maxillary cast and mounted with 2 separate pours of dental plaster to minimize the effects of setting expansion. Each set of casts was equilibrated to produce widely separated contacts. Contacts that held 0.01 mm shimstock were visualized with red marking film (Arti-Fol BK 25 Red; Dr. Jean Bausch, Kõln, Germany). The contacts marked on the casts were the standard for this study.

Virtual dental patient

An experimental vinyl polysiloxane registration material designed for use with optical 3-D scanners (3M, St. Paul, Minn.) recorded the occlusal surfaces in ICP (interocclusal record) in the articulator. Occlusal surfaces of the teeth were moistened to prevent the registration material from sticking. The material was expressed onto the occlusal surfaces of the mandibular teeth and the articulator was closed into ICP. A 0.6 kg weight was placed on top of the articulator while the material set. Before the registration material had set, a First Bite Disposable Impression Tray (Caulk/Densply International Inc., Milford, Del.) with the center gauze removed and with perforations placed uniformly around the rim was attached to the interocclusal record using additional impression material. The tray provided support during the scanning process. The material sat undisturbed for 10 minutes before being removed (manufacturer recommended setting time was 3 minutes).

A Comet 100 optical digitizing system (Steinbichler Optical Technologies, Neubeuern, Germany) scanned the dental casts and the interocclusal records. The Comet 100 has an XYZ measurement volume of 85 mm × 65 mm × 80 mm, a volume accuracy of 0.040 mm, and precision of 0.130 mm in the X and Y directions and 0.005 mm in the Z direction (parallel to the line of sight of the Comet). Multiple views were required to capture complete 3-D digitized images. Each Comet view was filtered using custom software (FilterAC) and aligned to all the other filtered views using PolyWorks (InnovMetric Software, Quebec, Canada). The filtered and aligned files were merged into a single data file with custom software (Stratus). Merged data files were rendered as 3-D surfaces and analyzed by use of the Virtual Dental Patient (VDP) software. (All custom software was developed in the Minnesota Dental Research Center for Biomaterials and Biomechanics, Minneapolis, Minn. under NIH/NIDCR grant R01 DE12225.)

For clarity, the merged data files of casts and interocclusal records used in the computer calculations are called virtual casts and virtual interocclusal records. Contacts calculated by the computer are referred to as virtual contacts, whereas those marked on the stone replica casts are the standard contacts.

Interocclusal records were scanned twice: once seated on the mandibular casts and once independently. Only the maxillary side of the interocclusal record was scanned when it was seated on the mandibular cast. Both sides were scanned when it was mounted independently in the Comet 100. The digital camera in the Comet 100 also recorded images of the standard contacts on the casts. Locations of the standard contacts were described qualitatively in terms of anatomical regions (Fig. 1).

Calculation of virtual contacts

In the VDP software, a contact between 2 opposing virtual surfaces, Mx and Mn, is a set of points C. C contains at least one point from Mx and one point from Mn, and the distance between the points is less than a specified distance (Tolerance). All the points from Mx (Mn) that are in C must be within a specified distance

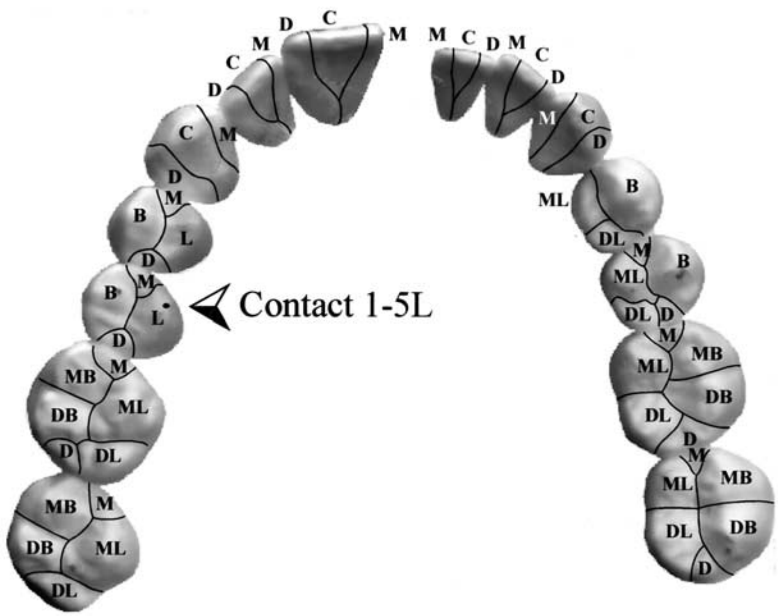

Fig. 1. Contact anatomic regions. Regions based on tooth anatomy qualitatively defined contact locations. Tooth number (International System) and region identified the contact *(arrow)*. Multiple contacts within the same region, were numbered sequentially. *B,* Buccal; *C,* central; *D,* distal; *L,* lingual; *M,* mesial.

(Range) of at least one other point from Mx (Mn) that is in C, or be the only point from Mx (Mn) that is in C. Tolerance was set at 0.050 mm to be slightly larger than the scanner accuracy. Range separates individual contacts. Two contacts are considered separate if all the points in 1 contact are at least 0.65 mm from all the points in the second contact. This value, which is 5 times the scanner XY resolution, was selected to separate contacts on adjacent interproximal marginal ridges.

Opposing virtual surfaces can be either the maxillary and mandibular virtual casts or the maxillary and mandibular sides of a virtual interocclusal record. The method for identifying contacts is the same for both. Virtual contacts are regions where distances between the 2 virtual casts or between the 2 sides of the virtual interocclusal record are less than the tolerance.

Three parameters described an occlusal contact (Fig. 2): area, centroid, and normal. Area is the 3-D surface area of the contact. Each point in a virtual cast or interocclusal record has a pre-assigned area. The area for the maxillary (mandibular) virtual contact is calculated as the sum of the areas for all the maxillary (mandibular) points in C. The centroid for the maxillary (mandibular) virtual contact is the center of mass for all the maxillary (mandibular) points in C. Normal is a unit vector at the centroid. Each point in a virtual cast or interocclusal record has a normal unit vector. This vector is at right angles to a plane tangent to the surface and points out from the surface at the point. The normal for the maxillary (mandibular) virtual contact is calculated by averaging the normals for all the maxillary (mandibular) points in C. The virtual contact normal is the average of the maxillary and mandibular virtual contact normals with 1 normal rotated 180-degrees. Its direction de-

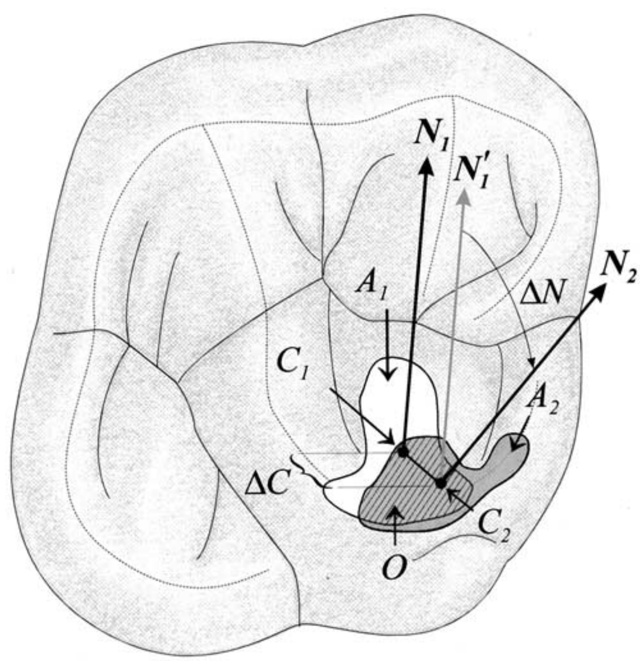

Fig. 2. Contact parameters. Area (*A*) is 3-D surface area of contact. Centroid (*C*) is center of mass of points in contact. Normal (*N*) is unit vector at centroid that points out perpendicular from contact. Corresponding contacts, A_1 and A_2, which were calculated with different methods, were compared by calculating difference in areas ($|A_1$-$A_2|$), distance between centroids (ΔC), angle between normals (ΔN), and percent overlap of A1 with A2 (*O*).

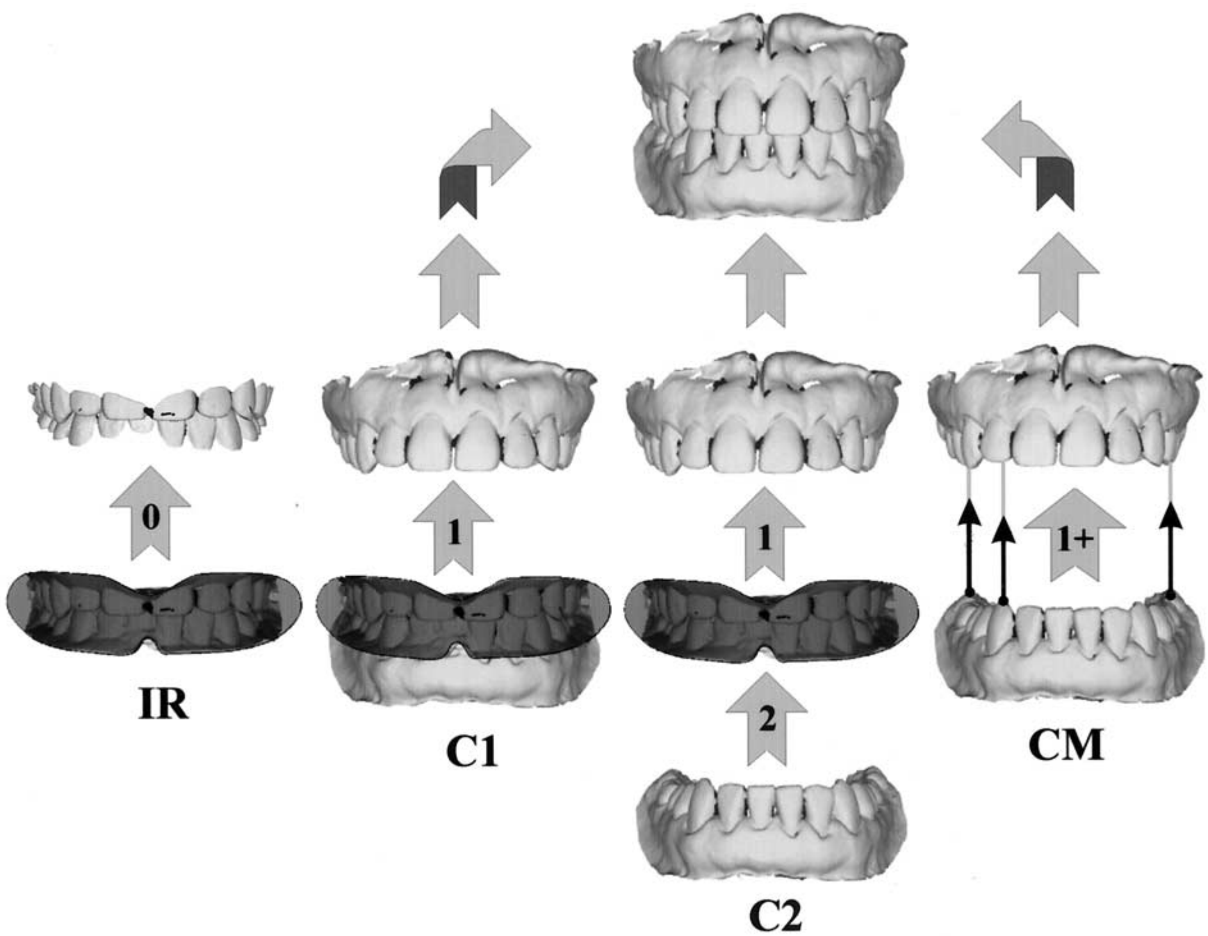

Fig. 3. Methods for aligning virtual surfaces. Interocclusal record *(IR)* recorded maxillary and mandibular occlusal surfaces in ICP. Computer "pours" positive virtual casts of these surfaces that have interocclusal relation recorded by the record. Virtual casts were aligned by manually selecting points located in opposing occlusal contacts *(CM)* and by computer using a virtual interocclusal record *(C1* and *C2)*. Interocclusal record was scanned, either seated on the mandibular cast C1, or independently C2.

pends on which surface (maxillary or mandibular) is being considered.

Four different methods were used to calculate the virtual contacts (Fig. 3). Three methods calculated contacts from virtual casts: 1) aligned manually (Method CM), 2) aligned using the interocclusal record that was scanned seated on the mandibular cast (Method C1), or 3) aligned using independently scanned interocclusal records (Method C2). The fourth method calculated virtual contacts directly from virtual interocclusal records (Method IR). The maxillary virtual cast defined the coordinate system for the subject for all 4 methods, thus enabling the virtual contacts from the different methods to be compared.

A crucial step in calculating virtual contacts is aligning the virtual interocclusal record with the corresponding virtual cast. This is similar to using the interocclusal record to mount dental casts. Two virtual surfaces were aligned by minimizing distances between common anatomical areas using an iterative algorithm.[8] The process starts with a set of points selected from one of the virtual surfaces. For every selected point, the closest point (nearest-neighbor) on the second virtual surface was found. After the nearest-neighbor pairs were determined, an optimal transformation matrix was calculated that aligned the points of the second virtual surface with the first.[9] A transformation matrix is a mathematical formula that when applied to the points describing a rigid body has the effect of moving the body from one position to another. The transformation matrix was applied to all the points of the second virtual surface. Because the alignment of the 2 virtual surfaces was different after the transformation, new nearest-neighbor pairings were identified and the process was repeated. When the smallest root mean squared distance between nearest-neighbor pairs was reached, the 2 virtual surfaces were considered to be in optimal alignment.

The first step for Methods C1 and C2 was aligning the virtual interocclusal record to the maxillary virtual cast. Maxillary cusp indents of the virtual interocclusal

Table I. Contact parameter differences by method pairs (mean ± SD; n = 10)

Method pair		Distance between Centroids (mm)	Angle between normals (deg)	Area difference (mm^2)	Area overlap (%)
First	Second				
C2	C1	0.12 ± 0.07	3.2 ± 1.2	0.12 ± 0.13	68.0 ± 11.6
CM	C1	0.13 ± 0.08	3.7 ± 1.6	0.11 ± 0.15	66.0 ± 15.4
CM	C2	0.13 ± 0.09	3.6 ± 2.5	0.13 ± 0.16	66.9 ± 14.4
C2	IR	0.25 ± 0.12	5.6 ± 2.1	0.26 ± 0.28	46.0 ± 11.5
CM	IR	0.27 ± 0.10	6.1 ± 1.8	0.29 ± 0.26	42.8 ± 11.8
C1	IR	0.30 ± 0.13	6.9 ± 2.8	0.35 ± 0.29	44.1 ± 12.1

Vertical lines indicate pairs that were not significantly different (Tukey-Kramer method, $P < .05$; n = 10).

record were aligned to the corresponding cusps of the maxillary virtual cast. The resulting transformation matrix was applied to the virtual interocclusal record, which aligned it with the maxillary virtual cast. For Method C1, which used the interocclusal record seated on the mandibular cast, the same transformation matrix moved the mandibular virtual cast into alignment with the maxillary virtual cast. Only one movement was required to align the mandibular and maxillary virtual casts. Method C2, which used the interocclusal record scanned independently, required a second movement. After the virtual interocclusal record was aligned to the maxillary virtual cast, the cusps of the mandibular virtual cast were aligned to their corresponding indents on the virtual interocclusal record, which aligned the mandibular virtual cast with the maxillary virtual cast.

Method IR, which calculates contacts directly from the virtual interocclusal records, also required alignment of the virtual interocclusal record with the maxillary virtual cast to align the 2 coordinate systems. The method for calculating virtual contacts treated the maxillary and mandibular sides of the virtual interocclusal record as if they were aligned maxillary and mandibular virtual casts. The distance between the 2 sides of the virtual interocclusal record (thickness) represented the distance between the opposing virtual surfaces. Virtual contacts were calculated by use of the same method used for the aligned virtual casts.

Method CM, which aligned the virtual casts manually, used the 3-point fitting algorithm of the VDP software. Three points that do not lie on a straight line describe the position of a rigid body in space. If 3 points are identified on 1 body and 3 points in the same spatial locations are found on a second body, then a transformation matrix can be found that optimizes the alignment of the 2 sets of 3 points, which aligns the 2 bodies to each other. Normally, this method is used for bodies with similar surface topography; however, it can be used with any 2 bodies such as the maxillary and mandibular virtual casts. Application of the 3-point method to the virtual casts required displaying their occlusal surfaces side-by-side. A mouse was used to select a set of 3 points on the maxillary virtual cast and a corresponding set of 3 points on the mandibular virtual cast. Digital camera images of the standard contacts guided the selection of alignment points. Each point on the maxillary virtual cast was selected in a region that corresponded to one of the standard contacts. The corresponding alignment point on the mandibular virtual cast was located in the opposing contact. The transformation matrix that brought the 2 sets of points into optimal alignment was applied to all the points of the mandibular virtual cast. The 3-point alignment method was repeated until the virtual contacts showed the best qualitative agreement with the standard contacts.

Alignments of the maxillary and mandibular virtual casts were refined to correct for penetration of one virtual surface into the other or for separation of the 2 virtual surfaces. The mandibular virtual cast was moved perpendicular to the maxillary occlusal plane to insure that no points in the mandibular virtual cast penetrated into the maxillary virtual cast by more than the contact Threshold (0.050 mm) and that at least 1 mandibular point was within the contact Threshold. Virtual contacts were then calculated from the aligned virtual casts.

Contact parameters and parameter differences between method pairs were calculated for each subject. Because of anatomic differences between subjects and differences in the number and location of contacts, it was considered inappropriate to compare contact parameters in 1 subject with contact parameters in a second subject. However, a comparison of changes in contact caused by similar interventions between subjects is valid. Virtual contact parameter differences were first averaged within each subject for each method pair, and then averaged over all subjects for each method pair. Averaging in this manner gave each subject equal weight. For pairs of methods, the difference in number of virtual contacts, the mean distance between centroids, the mean angle between normals, and the mean difference in areas were calculated. A fifth parameter, Overlap, which was the percent of overlap of the virtual contact areas for the selected pairs of methods, was also calculated. All 6 possible pairings of the 4 methods were compared.

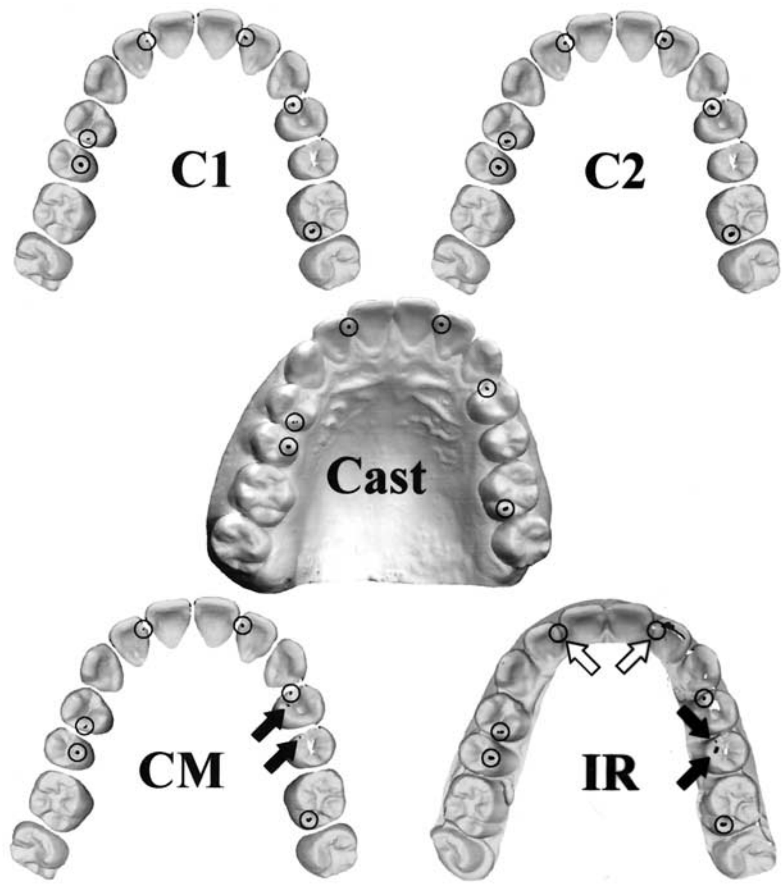

Fig. 4. Maxillary contacts from virtual images. Virtual contacts calculated using 4 different methods (CM, C1, C2, and IR; see Fig. 3) are shown on maxillary virtual casts for a typical subject. Corresponding standard contacts marked on stone cast with red marking film are shown for comparison *(Cast)*. *Black circles* indicate expected locations of standard contacts. Colored pixels of contacts were overlaid with black pixels for clarity. *Black arrows* indicate virtual contacts that do not correspond to standard contacts. *White arrows* indicate missing standard contacts.

Virtual contacts were defined according to their anatomic location following the same procedure that was used for the standard contacts. Sensitivity, specificity, positive predictive values, and negative predictive values were calculated for the four methods. The "Reference Standard" was the standard contacts marked with film.

Statistical analysis

Virtual contacts from the 4 methods defined by regions were compared to the standard contacts according to sensitivity and specificity using a repeated measures analysis of variance. The "subject" was a subject in the study, and the "repeated measures" on the subjects were the 4 methods of calculating virtual contacts.

Additional one-way analyses of variance were used to make virtual contact parameter comparisons of 6 different pairs of methods. Where significant differences existed ($P<.05$), pair comparisons were done with the Tukey-Kramer test to identify the significantly different pairs.

RESULTS

Six pairs of methods were considered: CM/C2, CM/C1, CM/IR, C2/C1, C2/IR, and C1/IR. The mean number of standard contacts was 14 ± 6 (mean ± SD; n = 10). The IR method identified the most virtual contacts, 17 ± 7, followed by C2, 15 ± 7, CM, 14 ± 5, and C1, 11 ± 6. The mean virtual contact areas for CM, C1, C2, and IR were 0.33 ± 0.35 mm^2, 0.27 ± 0.33 mm^2, 0.38 ± 0.44 mm^2, and 0.56 ± 0.80 mm^2, respectively. There were significant differences in the numbers of virtual contacts (P=.0004), distances between centroids (P=.0001), angles between the normals (P=.0003), differences in areas (P=.018), and area overlaps ($P<.0001$) for the different methods (Table I). A typical set of virtual contacts calculated using the 4 methods and the corresponding standard contacts are shown in Figure 4.

For each parameter, the method pairs were ranked from closest to most different. The median ranking for all parameter categories was used to describe the differ-

Table II. Comparison of occlusal contacts calculated using virtual models and film marked occlusal contacts (standard)

Method	Sensitivity	Specificity	Positive predictive values	Negative predictive values
C2	0.89	0.95	0.83	0.97
CM	0.86	0.96	0.83	0.96
C1	0.76	0.98	0.90	0.95
IR	0.80	0.89*	0.67*	0.96

*Significantly different ($P < .0001$; $n = 10$) from other values in column.

ent pairs. This aggregate ranking was C2/C1 > CM/C1 = CM/C2 > C2/IR > CM/IR > C1/IR, where ">" means "were closer than." The statistical analysis and this ranking imply that the interocclusal record method of calculating virtual contact parameters differed from the other methods more than the others differed among themselves.

The mean number of anatomic regions containing standard articulator contacts was 11 ± 4 (a region can have more than one contact). The mean number of regions containing virtual contacts for the CM, C1, C2, and IR methods were 11 ± 3, 9 ± 4, 12 ± 5, and 13 ± 7, respectively. Sensitivity, specificity, positive predictive values, and negative predictive values for the CM, C1, and C2 methods were similar, and they were better than those for the IR method (Table II).

There were no significant differences between the sensitivities (P=.14) or the negative predictive values (P=.27) for the 4 methods. Specificities of the methods differed (P=.0001); as did the positive predictive values (P<.0001). Specificity and positive predictive values for contacts found with virtual interocclusal records were significantly lower than those found using aligned virtual casts, which were not significantly different from each other.

DISCUSSION

This study showed in an articulator simulation that virtual models of dental casts could produce contacts equivalent to contacts marked on stone casts with a red marking film. Qualitative and quantitative evaluations found no noteworthy differences between the virtual contacts calculated from the virtual models of casts and standard contacts marked on the casts. Sensitivity and specificity for the virtual contacts met or exceeded clinical requirements for acceptance as a diagnostic test: sensitivity >0.7 and specificity >0.95.[10-12] Virtual contacts calculated directly from virtual models of the interocclusal records were not as good. Sensitivity and negative predictive values were equivalent to those of the virtual cast models; however, the specificity and positive predictive values were significantly less, and less than that required for clinical acceptance.

The 4 methods of calculating virtual contacts were compared in all possible pair combinations. Contact parameters for the manually aligned virtual casts (Method CM) were equivalent to those for the virtual casts aligned with the virtual interocclusal records (Methods C1 and C2). Statistically, virtual contact parameters calculated with the interocclusal record scanned seated on the mandibular cast (Method C1) or the independently scanned interocclusal record (Method C2) were equivalent; however, the mean number of virtual contacts found using Method C2 was closer to the mean number of standard contacts. Virtual contacts calculated directly for the virtual interocclusal record (Method IR) were significantly worse than those calculated with the virtual casts.

None of the methods for calculating virtual contacts had perfect agreement with the standard contacts, as indicated by sensitivity and specificity values less than 1.0. The accuracy of a virtual cast or interocclusal record is expected to be better than the 0.040 mm accuracy of the scanner because of the data filtering and averaging that occur during the creation of the merged data file.[13] Marking films have a measured thickness between 0.02 and 0.03 mm.[14] Setting the contact Tolerance variable closer to that of the thickness of the marking film rather than the accuracy of the scanner might improve the agreement. This is especially true for contacts calculated directly from the interocclusal record virtual models. Similarly, adjusting the contact range parameter might improve the agreement.

The disagreement between the virtual and marked contacts may not be entirely related to the accuracy and alignment of the virtual models. Marking ribbons and films are prone to making false positive marks.[15-17] Although every effort was made to confirm each marked contact, it was not possible to confirm all of them. False-positive contacts may partially explain why virtual contacts from the manually aligned virtual cast models did not always agree with the contacts marked on the casts.

The 4 methods for calculating virtual contacts were examined because they have different advantages and disadvantages. The manual alignment method (CM) does not require an interocclusal record or scanning of the record. It does require some reference to contact location, such as a digital image of the marked contacts, to confirm the location of the virtual contacts. Marking the teeth and recording contact locations may require significantly more time clinically than making an interocclusal record. Also, manual alignment of the virtual casts was time consuming, frequently taking hours. Manual alignment required selecting opposing points that are in contact on 2 anatomically different surfaces. Visual clues were provided from the digital images of the marked contacts; however, the corresponding regions on the virtual surfaces often contained hundreds of points, from which the correct one had to be found.

Selecting the correct point from one region, then finding the closest point on the opposing region was "trial and error." In a few instances, the final manual alignment was not as good as that achieved by the computer using virtual interocclusal records (Fig. 4). Aligning maxillary and mandibular virtual casts by use of the independently scanned interocclusal record (Method C2) takes about 5 minutes on a 1 MHZ PC. Method C1 takes about half as long. Because they require less operator input, these latter 2 methods are preferred. A disadvantage of Method C1 is the difficulty of reseating the interocclusal record on the mandibular cast. Although this is not a major problem for the articulator simulation used in this study, it may be significant when it is applied to patients in the clinic because problems similar to those experienced in mounting diagnostic or working casts will occur.[19]

Calculating virtual contacts directly from the virtual interocclusal record (Method IR) does not require any alignment time. A significant advantage of the direct calculation of virtual contacts from virtual interocclusal records is that full arch impressions are not required. This saves substantial clinical, laboratory, and scanning time. Unfortunately, under the conditions of this study, the resulting virtual contacts were not as good as those from the aligned virtual casts.

It was expected that virtual contacts calculated directly from virtual interocclusal records would show the best agreement with the standard contacts; however, more contacts with larger areas were found. Previous investigations that identified contacts using the translucency of black silicone also found significantly more contacts with the silicone than with marking paper.[18] The difference was attributed to silicone material 0.100 mm thick appearing translucent enough to be interpreted as a contact. The experimental vinyl polysiloxane impression material used in this study was translucent in the contact areas. If light from the scanner penetrated the surface more in translucent areas, then the calculated surface points would lie beneath the true surface. This would happen on both sides of the interocclusal record, effectively making it thinner in the translucent areas and producing more contacts with larger areas. Use of a smaller Tolerance may correct this effect. If the light penetrated too far, no surface points could be calculated and holes would appear in the surface. Holes can also occur from complete displacement of the material at the tooth contacts. Holes are not necessarily bad. They provide positive location of contacts. Filling in the holes with 3-D surface interpolation would enable calculation of the contact parameters.

A second possible cause of the increased number of contacts and contact areas of the virtual interocclusal record could be a failure to maintain the correct orientation of the maxillary and mandibular sides of the interocclusal record during the scanning or creation of its merged data file. If one side penetrated the other, this would have the effect of increasing the number and areas of the virtual contacts. A technique similar to that used to correct for the penetration of the virtual casts could be applied to the two sides of the virtual interocclusal record.

The clinical environment provides challenges not experienced in the laboratory. A limitation of this study is the rigid articulator simulation. Jaw flexure and tooth movement could not be considered. These non-rigid conditions could affect the quality of the results. This is especially true for the virtual casts. Nonrigid conditions that occur while the teeth are in contact differ from those present during full arch impressions. Clinically, calculating contacts directly from the interocclusal record is the preferred method because teeth experience occlusal forces when interocclusal records are made. Because of the many advantages in calculating virtual contacts from virtual interocclusal records, this method is being investigated further.

If the results of this study hold true in the clinical setting, this virtual method will provide a tool that can quantify occlusal contacts through a few easily obtained clinical records. Clinical application of this method requires access to an accurate 3-D scanner and the appropriate computer software. Quality 3-D scanners are expensive; however, scanning services are relatively inexpensive. A scanning service could scan the casts and interocclusal records outside of the dental office, then the dentist could do the analysis in the office. Advances in scanning technology are lowering the costs of scanners; thus they may soon be affordable for the dental office.

Besides providing a 3-D quantitative record of occlusal contacts, sequential comparisons of virtual contacts can identify changes in occlusion with time that may provide a method of assessing occlusal function. This study demonstrated that virtual contacts from two sources can be compared and differences in virtual contacts can be quantified. Changes in surface topology and tooth orientation can also be extracted from these same two records. Relationships between these data and comparisons to population norms derived from databases built on similar measurements may provide a powerful diagnostic and treatment assessment tool for dentists.

CONCLUSIONS

The results of this study in a laboratory simulation show that:

1. Valid occlusal contacts can be calculated from aligned virtual casts, and
2. The preferred method of calculating contacts uses virtual casts aligned with virtual interocclusal records.

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Reprint requests to:
Dr Ralph DeLong
University of Minnesota, School of Dentistry
Moos Health Science Tower
515 Delaware Street SE
Minneapolis, MN 55455
Fax: (612) 626-1484
E-mail: delon002@tc.umn.edu

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