Tuned Aperture Computed Tomography (TACT®)

An investigation on the factors associated with its image quality for caries detection

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DECLARATION

I, Murillo José Nunes de Abreu Junior, the undersigned, hereby declare that the work contained in this dissertation is my own work and that I have not previously in its entirety or in part submitted it at any university for a degree.

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OPSOMMING

Die doel van hierdie proefskrif was om die veelvuldige veranderlikes wat betrokke is by gewysigde spleet rekenaartomografie (Tuned Aperture Computed Tomography (TACT)) te ondersoek in 'n poging om die beeldingsmodaliteit te optimaliseer in die diagnostiese opsporing van primêre karies. Die proefskrif bestaan uit 'n ekstensiewe literatuur oorsig en word in 7 fases aangebied waarin die veranderlikes individueel geevalueer word. Tande is in gips ingebed en radiografiese opnames is gemaak met behulp van 'n digitale radiografiese sensor. As 'n voorvereiste vir TACT beelding is veelvuldige beelde uit verskillende projeksiehoeke van die tande gemaak. Die resulterende basisbeelde is dan gebruik om TACT snitte te produseer. Veranderlikes wat in die proefskrif getoets is, sluit die volgende in: 'n aantal herhalende herstellings waaraan die snitte blootgestel is, die aantal basisbeelde, die hoek gevorm tussen die basisbeelde, die 2 en 3 dimensionele verspeiding van die basis projeksies in die ruimte en die metodes waardeur die snitte gerekonstrueer is. In alle fases is waarnemers gevra om die teenwoordigheid of afwesigheid van primêre karies te evalueer wat met TACT afgeneem is met in ag neming van die verskillende veranderlikes. Ten slotte, om te bepaal of die beste kombinasie van veranderlikes 'n aansienlike verbetering in diagnostiese prestasies sou meebring, is 'n vergelyking met konvensionele digitale radiografiese beelding uitgevoer. Geen statistiese beduidende verskille is waargeneem in die opsporing van karies tussen TACT snitte wat blootgestel is aan verskillende aantal herhalende herstellings, rekonstruksie van basis beelding met verskillende hoek veranderinge, ruimtelike verspreiding (beide 2 en 3 dimensioneel) of deur verskillende rekonstruksie metodes nie. 'n Statistiese beduidende verskil is waargeneem tussen TACT snitte wat van 'n verskeidenheid basis projeksies gerekonstrueer is. Die finale vergelyking het aangetoon dat TACT nie statisties beter is as konvensionele radiografie in die opsporing van karies nie.

Die resultate van hierdie proefskrif het getoon dat alhoewel TACT bruikbaar is in vele prosedures wat in die tandheelkunde uitgevoer word, is die toepassing daarvan in die diagnose van karies nie noodsaaklik nie, omdat daar in die tandheelkunde modaliteite beskikbaar is, wat meer eenvoudig, meer prakties en goedkoper is, met 'n laer stralingsdosis vir die pasiënt.

SUMMARY

The purpose of this investigation was to explore the multiple variables involved in TACT® image generation in an attempt to optimize this imaging modality for the diagnostic task of primary dental caries detection. The work is divided in seven phases in which the variables are evaluated individually. Teeth from the study samples were mounted in dental stone and imaged with a solid state digital radiography sensor. As a requisite of TACT® imaging, multiple images of the teeth were acquired from different projection angles. These resulting basis images were then used to generate TACT® slices. Variables tested in the investigation included the number of iterative restorations to which the slices were submitted, the number of basis images, the angle formed between the basis images, the two- and three-dimensional distribution of the basis projections in space, and the method through which the slices were reconstructed. For all phases, observers were asked to assess the presence or absence of primary caries in the teeth imaged using the TACT® slices treated with the different variables. Finally, to determine whether the best combination of variables produced a significant improvement in diagnostic performance, a comparison with conventional digital radiography images was carried out. No statistically significant differences were found in caries detection between TACT® slices submitted to different numbers of iterative restorations, reconstructed from basis images bearing different angular disparities, spatial distributions (in both two and three dimensions), or through different reconstruction methods. A statistically significant difference was detected between TACT® slices reconstructed from different numbers of basis projections. The final comparison showed that TACT® was not statistically superior to conventional digital radiography for the task of caries detection. The results of this investigation suggest that, although TACT® has been shown to be useful in many tasks performed in dentistry, its application in caries detection is not essential inasmuch as there are modalities that are simpler, more practical, less expensive, and that submit the patient to smaller radiation doses.

Keywords: TACT, tomosynthesis, image reconstruction, digital radiography, caries detection, ROC analysis, analysis of variance

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GLOSSARY

basis (component, source) images (projections)	Planar projection images formed by viewing and imaging the same object from different perspectives, where the perspective is changed by moving one or more of the x-ray source, object of interest, and image receptor
tomosynthesis	A method to create images representing planar sections of an object by combining multiple separate two-dimensional projections of the object taken from different perspectives; synthesis from multiple discrete images as opposed to continuous tomography
TACT	Tuned Aperture Computed Tomography; a reconstruction method based on tomosynthesis; relies on information contained in the basis images to determine the architecture of the exposure system (*a posteriori* vs. *a priori*)
slices (slice images)	The planar images formed by applying the TACT algorithms to the basis images
slice stack, image stack, or stack of slices	A set of slice images representing neighboring parallel planes in the object of interest
fiducial marker, fiducial reference marker	A marker that is attached to the object of interest to provide a means of identifying one or more unique points in space
source	The source of radiation that is used to generate an image
object	The object of interest that is to be imaged
detector, sensor	A device that is capable of sensing the source's radiation and forming an image based on the intensity of radiation that is received at any given point on the sensor

source position, point source position	Position occupied in space by the x-ray focal spot, at the time of exposure, to acquire a basis image
TACT reconstruction methods	The utilization of different algorithms (computer calculations) to produce TACT images (slices)

CHAPTER I

INTRODUCTION AND REVIEW OF THE LITERATURE

The widespread use of fluoride has caused a decrease in the incidence of dental caries as well as a change in its behavior and progression pattern in western countries in the last two to three decades.[1] The most common methods used to diagnose dental caries continue to be the visual examination and conventional bitewing radiographs. Clinically, proximal caries continues to be a diagnostic challenge inasmuch as direct visualization of proximal surfaces is only occasionally possible. Occlusal lesions, once thought to be easily diagnosed by clinical examination alone, may be passing undetected during such an examination as dentinal lesions may be hidden under a remineralized outer enamel surface.[2] Radiographically, the reduced prevalence of caries puts a higher demand on imaging modalities to detect those lesions that are actually present and to avoid misinterpreting sound surfaces as carious. However, conventional radiographic methods for caries detection such as bitewing radiographs have been shown to provide only moderate sensitivity.[3,4] The introduction of digital radiography in the late eighties has not helped to solve the problem.[5] Present circumstances therefore remind us of the important role radiography still plays in caries diagnosis at the same time as they reinforce the need to continue searching for alternative imaging modalities that help raise the diagnostic yield. Apparently simple and undemanding, caries diagnosis deserves further research efforts also because caries, along with periodontal disease, represents that group of pathologic conditions having the greatest economic impact in the field of dentistry. A practical dental imaging system should be designed around effective management of dental caries and periodontal disease.[6]

While some of the attributes necessary to better diagnose dental caries can only be achieved with imaging systems that possess high sensitivity, others can only be attained with systems that are capable of providing some form of three-dimensional information about the object or anatomic region being evaluated. None of the radiographic systems commonly used in dentistry completely fulfills these requirements. Three-dimensional structures are typically represented as a two-dimensional image plane. This lack of a sense of depth has historically represented a major challenge in conventional radiography. On the other hand, the more advanced imaging systems that do provide three-dimensional information, such as computed tomography and magnetic resonance imaging, besides being expensive and not readily available, may not exactly satisfy the needs of the more ordinary diagnostic tasks performed by the general dental practitioner. In the face of these circumstances, a continuing search for technologies that can yield some improvement over the current status is warranted.

Tuned aperture computed tomography (TACT®) is a relatively new diagnostic imaging tool with the potential to fulfill some or all of the attributes outlined above. TACT® is a three-dimensional radiographic data acquisition scheme based on optical aperture theory and derived from a laminographic process called "tomosynthesis".[7-10] A complete review of the theory underlying TACT® has been published elsewhere.[11] For the sake of simplicity, TACT® can be envisioned as a software package that is added to a digital radiographic system, conferring a tomographic capability to this system.[12] In TACT®, multiple images of the same object – known as *basis* or *component* images - are taken from different projection angles. These images serve as the input for a personal computer to reconstruct multiple tomogram-like slices through the object under examination. In reality, basis images are digitally added and shifted until there is complete coincidence or superimposition ("registration") of the structures lying in the plane to be reconstructed.[13] In this way, images of elements within the tomographic plane are reinforced and appear sharper than images of elements located in all other planes. Structures outside the plane of interest appear more or less blurred in the final reconstructed slices depending on their position relative to the in-focus plane, their size, and their degree of radiopacity, among other factors. Enhancement procedures can alleviate the detrimental effects caused by the blurring of other planes on the reconstructed slices.[14-16]

The concepts underlying TACT® and its precursor, circular tomosynthesis, occupy the middle ground between computed tomography on the one side, and conventional transmission radiography on the other.[11] With TACT®, disease processes or other structures of interest can be assessed without the interference of the most buccal (facial) and lingual anatomical planes. This advantage supposedly makes the difference between TACT® and conventional imaging greatest for diagnostic tasks that require depth information such as lesion-location. Detection tasks, nevertheless, are also likely to benefit from the absence of or reduction in superimpositions of the overlying anatomical structures. The ability to acquire spatial information in three dimensions using TACT® should influence in a positive way the diagnosis and management of diseases and abnormalities in the oral and maxillofacial region, including the most common dento-alveolar problems.

Previous studies using TACT® in particular, or tomosynthesis in general, have demonstrated its usefulness as a diagnostic tool for a multitude of tasks.[17-31] Webber *et al* have shown that TACT® slices and TACT® subtracted slices enhance the ability of clinicians to detect crestal defects around endosseous titanium implants over conventional two-dimensional imaging modalities.[18] Horton *et al*,[19] employing TACT® in the axial direction ("occlusal" view) also demonstrated that TACT® can accurately detect bone changes around implants. In a new imaging approach to the simultaneous assessment of multiple implant sites, Liang *et al* have shown *in vitro* that TACT® can produce true cross-sectional slices of the jaws using simple radiographic machinery.[24] The latter may serve as an alternative to the more expensive and complex tomography units where such equipment is not available.

Nair *et al* have shown that TACT® slices are significantly better than conventional digital and film images for the detection of simulated recurrent carious lesions.[17] Nair and colleagues also evaluated the effectiveness of TACT® in monitoring tissue-engineered bone graft-assisted healing of osseous defects in rabbit mandibles.[23] They concluded that radiometric measurements using TACT® correlated well with the results of the histological examination, and that TACT®, therefore, can provide a reliable means to quantitatively assess bone healing of tissue-engineered bone graft on a routine basis. Regarding periapical pathoses, Vandre *et al* have suggested that TACT® may be superior to two-dimensional D-speed film images for the detection of nodular osseous jaw lesions.[20] Comparing conventional extra-oral images (panoramic and lateral-oblique films) with TACT® for the detection of known mandibular fractures, Johnson *et al* reported that TACT® provides a more accurate assessment of fractures than conventional and more commonly used extra-oral modalities.[22]

Engelke and colleagues, experimenting with new diagnostic methods for the examination of osseous lesions in the temporomandibular joint, reported that tomosynthesis (TACT®'s progenitor) was able to show the reshaping of the condylar head and a fracture in the condyle that was not visible even with subtraction radiography.[25] For endodontic applications, TACT® has been shown to be superior to conventional film in the detection of the correct number of root canals contained in extracted human molars.[29] Similarly, it was found to be statistically superior to conventional radiographs in the diagnosis of simulated external root resorption.[30]

Two other studies recently concluded demonstrated the value of TACT® for periodontal applications. Chai-U-Dom *et al* showed that TACT® subtracted slices were more accurate than conventional digital subtraction radiography in the assessment of simulated peri-crestal bone gain in dry human jaw specimens.[27] Ramesh *et al*, also simulating lesions in dry cadaver specimens, found that TACT® performed significantly better than conventional film images for the detection of interproximal periodontal defects in the posterior segments of the jaws.[26]

In an *in vivo* utilization of the TACT® methodology, Webber and Messura showed that TACT® displays were more diagnostic than film-based x-ray imaging modalities and that TACT® was capable of significantly altering perceived treatment outcomes and increasing diagnostic confidence compared to film radiography without TACT®.[28] In medicine, the use of TACT® or tomosynthesis has already been reported in the field of mammography, where it has also been shown to produce promising results.[21,31]

Apparently the only diagnostic task examined in which TACT® has not excelled is in the detection of primary caries. In the two previous studies reported in the literature that assessed detection of primary caries, the three-dimensional attributes offered by TACT® failed to significantly improve the diagnostic performance over that achieved with conventional two-dimensional film or digital radiography.[32,33] Tyndall and colleagues, the first investigators to explore TACT® imaging for caries detection, recognized that they used what is now an outdated digital sensor for the acquisition of basis images.[32] Although they used two identical sets of eight basis projections taken in a square pattern to produce TACT® slices, they did not specify the angular disparity used during the acquisition of the images. Angular disparity is the angle subtended at the object irradiated by the most extreme or opposite x-ray source positions used to acquire the basis images. Angular disparity, together with the size of the object under examination, controls the thickness of the reconstructed slice. Angular disparity may not have been ideal in their experiment. Another variable that was not specified in their study was the number of iterative restorations used during the generation of slices. Iterative restoration is an enhancement procedure that tries to remove the inherent blur associated with TACT® or tomosynthetic reconstructions. It works like a filter removing low spatial frequencies from the desired slices. The number of iterations may also influence the quality of slices in a significant way.

Abreu and colleagues, using a currently state-of-the-art digital sensor were again unable to show that TACT® improves diagnostic performance in caries detection over conventional modalities.[33] In their study, they used an intra-oral (dental) x-ray source to acquire the images to simulate a clinical application of TACT®. However, this simulation represented a non-strict acquisition of basis projections, with the source-to-image receptor distance varying from exposure to exposure. Since a prerequisite for generating TACT® slices is that basis images be taken either from the same plane in space or from a relatively long source-to-image receptor distance (to avoid significant discrepancies in magnification), this experimental variable may have partly reduced the quality of the slices used in their study. Similarly, the unconstrained method of image acquisition may have led to excessive and uncontrolled overlaps between the proximal surfaces of the teeth imaged. This may have reduced the diagnostic value of TACT® for caries detection. Due to the use of hand-controlled angles, no accurate means of determining the angular disparity was available, and therefore it was not reported in their study.

More than in conventional radiography, many factors or variables are associated with the image quality in TACT®. Therefore it is possible that neither of the studies just described used the best combination of variables for the task of caries detection. In TACT®, while the tomosynthetic plane remains in sharp focus, the images of details located outside that plane do not coincide exactly because successive images are slightly displaced. This circumstance causes blurred images of anatomic details, which are mainly of low frequency, lying outside the plane of interest to be superimposed on the image of the plane "in focus".[16] Niklason and colleagues, in explaining this phenomenon, clarify that although we use the term "blurring", the images of structures outside the in-focus plane are essentially repeated in the direction of the x-ray source motion used to acquire them.[21] TACT® reconstructions, therefore, look blurred and have reduced contrast due to the inherent tomosynthetic process.[7] This is detrimental to image quality and may prevent proper image interpretation.

To achieve a partial removal of the "blur" associated with tomosynthetic reconstruction, enhance the image, and provide better slice separation, one of two methods is generally used: the application of linear spatial-frequency filtration (high-pass filter), or an iterative deconvolution technique.[15] High-pass filtration provides a better slice separation but yields images with fewer gray levels. Furthermore, it may be more difficult to orient oneself within the image when compared with full-contrast images.[14] Iterative restoration, on the other hand, provides a reasonable slice separation while maintaining a contrast level that approximates more closely that of the original basis images.[34] This latter method, which is computationally more intense, mitigates the undesired contribution of details lying outside the focal plane by subtracting from the slice to be restored a set of properly blurred replicas of planes (slices) located at various distances from the desired plane (slice of interest), therefore producing sharper images.[13,35]

Iterative restoration is currently utilized in TACT® imaging because it has been shown to provide superior diagnostic quality compared to non-iterated slices.[17] Theoretically, this process may be repeated indefinitely to maximize the elimination of blur. In practice, however, the build-up of image noise limits the number of iterations that can be used. It is generally considered that three or four is the maximum number of repetitions that should be used.[16] To date, the optimal number of iterative restorations to be used in different diagnostic tasks has not been established.

As in tomography, where the image layer thickness is determined by the tomographic angle, in both TACT® and tomosynthesis the slice "thickness" is determined by the angle subtended at the object of interest by the most extreme and opposite x-ray source point positions used to acquire the images.[11,36,37] This "angular disparity" set by the imaging geometry determines the amount of blurring of out-of-focus structures within the object. Together with the number of images utilized, it determines the quality of the final reconstructed slices.[7,9,10,13] A small angular disparity yields less blurring, resulting in a sharper picture of a thicker layer. It also requires fewer images to produce the reconstructions, but the resolution in the direction of the depth of the object is lower.[7,11,13] Conversely, with greater angular disparities, more blurring of unwanted structures can be expected, and consequently "thinner" slices are obtained. However, more basis images are required to reduce quantization artifacts to an acceptable level.[7,11,13,16,36] Quantization effects arise from the approximation of the object by a limited number of planes, and the discrete nature of tomosynthetic techniques themselves, which produce reconstructions from a very limited number of focal spot positions.[16]

The selection of the number of projections and angular disparity to be used in TACT® or tomosynthetic reconstructions should be governed by the diagnostic task to be accomplished. This general rule, however, is rather unspecific and has been followed mostly in an empirical manner.[17,20,21,24,38,39] Optimal angular disparities to be used in most dental diagnostic tasks have not yet been established. Only two studies in the English language literature seem to have addressed the latter issue.[40,41] Yamamoto *et al* compared the accuracy in depth discrimination provided by different angular disparities and concluded that, for tasks of this type, *total* angular disparities of 30° or more should be used.[40] However, determining the position of a highly radiopaque lead sphere inside an alveolus relative to two others positioned on the facial and lingual cortices, as assessed in their study, may have limited usefulness in a clinical setting. Chai-U-Dom *et al* compared observer detection of simulated periodontal bone gain using digitally subtracted TACT® slices generated from different angular disparities. They concluded that smaller angular disparities, i.e. 10°, provide better detection of bone gain in buccal and lingual but not in proximal periodontal defects.[41]

No previous study has investigated whether the angular disparity of basis images used for TACT® slice generation has an influence on observer performance in primary caries detection when the number of projections is kept constant. The optimal angular disparity to be used in this task and data regarding the flexibility of the reconstruction procedure in accepting progressively wider angles while keeping comparable diagnostic quality are lacking in the literature.

As described earlier, the number of basis images for use with TACT® determines the distribution of blur inherent to the tomosynthetic process and the signal-to-noise ratio of the reconstructed slices. In a scenario where the angular disparity is kept constant, additional basis images lead to a better distribution of the blur and an increase in the signal-to-noise ratio of the generated slices.[10] The number and angular disparity of basis images can be planned to address the diagnostic task at hand. As far as the number of basis images is concerned, eight have been recommended based on subjective assessments of image quality by investigators themselves rather than on objective scientific evidence.[7,9,11,36] In practice, varying numbers of images ranging up to thirty-two have been used,[17,21,24,32,42] but no specific guidelines have been presented. It was not possible to find more than two studies in the English language literature that have assessed the variable ‘number of basis images’ in the generation of TACT® slices.[40,43]

These two studies were carried out by the same group of investigators and made use of a task requiring depth discrimination to test their hypotheses. The first study was that of Yamamoto *et al* mentioned above.[40] The second study was a repetition of the first, but the investigators replaced the lead sphere inside the extraction site with a ceramic sphere.[43] In both studies they were unable to find statistically significant differences between the different numbers of projections tested (2, 4, 8, 12, 16). However, since in the first study the object of interest was very radiopaque and in the second relatively large, the authors recognized that the external validity of their inferences was limited.

The effect of the number of basis images in a detection task using TACT® has not been reported in the literature. Determining the minimum number of basis images that can be used carries two direct implications, related to patient protection from radiation and the practicality of TACT® imaging, respectively. Although radiation doses involved in dental radiology are low, the acquisition of fewer images would represent compliance with the ALARA (As Low As Reasonably Achievable) concept. Simultaneously, fewer images would also expedite the entire image generation process, making this imaging modality easier and more attractive for use.

Projection geometry has been long recognized as having fundamental importance in radiography.[44,45] For imaging modalities that depend on the acquisition of multiple projective data for image reconstruction, projection geometry also includes the spatial distribution of x-ray source positions from which they are derived. The latter factor is thought to influence image quality. Earlier explorers of tomosynthetic methods have recommended the use of a circular distribution of x-ray source positions to acquire basis images.[7-10] This recommendation stemmed from the fact that streaking artifacts were more obvious when linear patterns were used as compared with circular geometries. Therefore, it was suggested that source positions should not be placed on a straight line when subsequent image reconstruction was sought. More recently, however, with the development of TACT®,[11] such constraints have been de-emphasized and circular, square, and linear distributions of x-ray source positions have been employed.[17,18,24,42] Being able to select which imaging geometry to use assumes that, for different diagnostic tasks, it is possible to orient projections in such a way that diagnostically important information is optimally acquired.[32]

Studies making direct comparisons between circular and linear projection geometries for TACT® reconstructions have been performed. Limrachtamorn *et al*, assessing the position of implants relative to a simulated mandibular canal, found that TACT® slices generated from a circular distribution of source positions were superior to those generated from both linear horizontal and linear vertical geometries.[46] A similar finding was shared by Yamamoto *et al*.[47] Assessing accuracy in depth discrimination using test objects represented by a metallic wire mesh and a dry human mandible, they concluded that only circular beam projections produced adequate TACT® tomographic image slices with depth discrimination for objects both in vertical and horizontal orientations. Information regarding the performance of TACT® slices generated from different sampling geometries in a detection task rather than in a task requiring depth discrimination had not been reported in the literature. As of the writing of this manuscript, Webber and Hendrickson presented the results of a study[48] that explored one of the TACT® variables being evaluated in the present investigation. Although they did not use a linear horizontal array in their comparison, they found no statistically significant difference in *induced* proximal caries detection between TACT® slices generated using circular and linear vertical arrays of projections.

In tomosynthesis, for the registration process to be performed with success, it is necessary that the projection geometry used for the different basis projections be completely known prior to the exposures.[11] The latter is attained by distributing the x-ray source positions in a fixed plane relative to the object/image receptor assembly. This distribution of x-ray source positions is usually, but not necessarily, circular in nature.[7,8] TACT®, on the other hand, does not suffer from such a restraint. It allows projection geometry to be calculated after exposures have been taken by analyzing the shift pattern experienced by anatomical details or purposefully placed reference objects in the field of view.[19] In TACT®, the positions of the x-ray source can lie in a flat plane, as in tomosynthesis, or they can be situated in multiple and random planes. If the latter is chosen, the only condition that needs to be respected is that the positions of the x-ray point sources should be far enough away from the object/image receptor to avoid significant discrepancies in magnification between basis images.[18] Theoretically, using images of different magnifications in the registration and reconstruction procedures can result in slices of reduced quality for diagnostic purposes.

To date, constraining the x-ray source positions to a single flat plane (i.e., stringent projection geometry) continues to be the most commonly used methodology in the generation of TACT® slices.[17-19,24,27,32,42] Although at least two investigations have utilized unconstrained projection geometry to acquire the necessary basis images, they had conflicting outcomes.[20,33] Therefore, studies are needed to either confirm it as a potential alternative to stringent projection geometry or to definitely oppose its use in common applications of TACT®. Only one very recent study appears to have carried out a direct comparison between these two types of projection geometry.[26] In the latter study, Ramesh *et al* demonstrated that TACT® slices generated using basis images acquired through a random aiming of the x-ray source (i.e., unconstrained array of projections) provided improved, though not statistically significant, performance in detection of simulated periodontal defects over a stringent circular array of projections. For other tasks, such as caries detection, further insight is needed regarding the flexibility of TACT® to produce slices by using and registering basis images having different degrees of magnification. The latter may apply when manual aiming of the x-ray source is used in a clinical application of TACT® or when the patient inadvertently moves between exposures.

As described above, the first step in the reconstruction process of a TACT® image is the registration of the "basis" or "component" images. For this task to be accomplished, the proprietary reconstruction algorithm (TACT® Workbench, Verity Software Systems, Winston-Salem, NC, USA) measures the offset of the projected shadows of a reference object (usually a small lead sphere) located in each of the images. This offset determines the shift required to align each of the projections so that a given plane in the object of interest is brought into registration.[19] It is necessary to emphasize that the projection of points located outside the reconstruction plane will not coincide exactly because successive images are slightly displaced.[16] The process results in a relatively sharp image of the structures in the desired plane on which blurred images of object details lying outside the plane of interest are superimposed.[13] Hence, the information contained in the matrix of two-dimensional projective data of each basis image is added. In the standard method of reconstruction, known as the *average* method, each pixel of the reconstructed slice has a brightness value that is an average of the values of corresponding shifted pixels in the basis images.[49] In view of this characteristic, the latter method generates slices in which out-of-focus structures are seen as multiple laterally displaced duplicates at lower, but still visually obvious, contrast levels, i.e., causing "ringing" artifacts.[49] These artifacts may be the major problem associated with TACT® reconstructions. They are disturbing to the viewer, detrimental to image quality and may therefore lead to an inaccurate interpretation of the reconstructed slices. Iterative restoration is used to mitigate the effects of these artifacts.[14,15,17,34,35]

A reconstruction method made available only in the latest versions of the proprietary software is known as the *minimum* (or minimization) method. This method uses the minimum value of the shifted pixels instead of the average value, so that only those projected pixels characterized by minimum pixel brightness are retained.[49,50] Because each element (pixel) of the reconstructed image is generated from only one of the projections, and not from the average of them, slices generated using the minimum method are free of ringing artifacts. However, due to this same characteristic, loss of diagnostically important information may also occur.[49] An advantage of the minimum method is that it eliminates the need for deblurring techniques such as iterative restoration, which helps to expedite obtaining the final reconstructed slices. It can be theorized that TACT® slices reconstructed using the minimum method, being devoid of ringing artifacts, would possibly be advantageous in the task of caries detection as compared to TACT® slices reconstructed using the average method.

To date no well-controlled studies have been performed to thoroughly explore the multiple factors involved in TACT® image generation. Extrapolations from tomosynthesis have been suggested and taken for granted, but no scientifically proven empirical results have been reported. The present dissertation was designed to explore many of these factors in an attempt to optimize TACT® imaging for the particular task of primary dental caries detection. This study is composed of seven consecutive phases that seek to answer specific research questions. Inasmuch as the ultimate users of radiographic images are human observers, on whom the diagnoses depends, the study design is tailored to evaluate human performance in caries detection while exploring different variables involved in TACT® imaging.

The first phase of the project seeks to determine the optimal number of iterative restorations for caries detection with TACT®. This phase utilizes images from a study previously reported in the literature.[33]

The second phase of the project, utilizing new teeth, investigates the variable "angular disparity of basis projections" required for TACT® image reconstruction.

The third phase deals with the number of basis images used for TACT® slice generation.

The fourth phase tests different distributions of x-ray source positions in space to acquire the basis projections for the subsequent generation of slices.

The fifth phase of the project compares the ability of TACT® to utilize basis images taken from both unconstrained and stringent projection geometries.

The sixth phase assesses a different method of reconstruction of slices available in the proprietary TACT® Workbench software. This method is compared to the standard method used for a general-purpose TACT® reconstruction.

Finally, in the seventh phase of the project, and taking into account all the information gathered in the previous phases, TACT® slices are again compared with a conventional imaging modality represented by directly acquired digital images in the task of primary caries detection. The final goal was to find out whether the supposedly best combination of factors indeed helps to significantly raise the diagnostic yield of TACT® in primary dental caries detection over that provided by two-dimensional imaging modalities.

CHAPTER II

NULL HYPOTHESES TESTED

The following null hypotheses were tested for the task of natural primary dental caries detection:

Phase I - *Effect of the number of iterative restorations on TACT® slices*

– there is no statistically significant difference in the diagnostic value *(for proximal caries detection)* of TACT® slices submitted to one, two, or three iterative restorations.

Phase II - *Effect of the angular disparity of basis images on TACT® slices*

– there is no statistically significant difference in the performance provided by a range of angular disparities between basis images that are likely to be used in a clinical application of TACT®.

Phase III - *Effect of the number of basis images on TACT® slices*

– there is no statistically significant difference in the performance provided by TACT® slices generated from different numbers of basis images.

Phase IV - *Generation of TACT® slices using linear and circular arrays of basis projections*

– there is no statistically significant difference in the diagnostic performance provided by circular, linear horizontal, or linear vertical arrays of basis projections.

Phase V - *Image acquisition for TACT® slice generation using unconstrained and stringent projection geometries*

– there is no statistically significant difference in the diagnostic performance provided by TACT® slices generated using unconstrained and stringent arrays of projections.

Phase VI - *The effect of the method of reconstruction of TACT® slices – minimum vs. average*

– there is no statistically significant difference between the diagnostic performances provided by the minimum and average methods of TACT® reconstruction.

Phase VII - *Comparison of solid state digital radiography and tuned aperture computed tomography (TACT®)*

– there is no statistically significant difference between the diagnostic performances provided by TACT® and conventional digital radiography.

CHAPTER III

MATERIAL AND METHODS

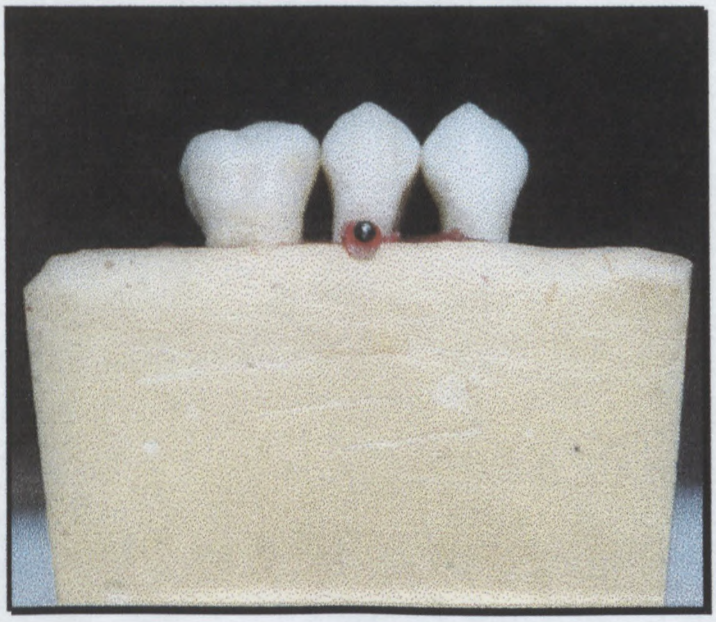
This study was carried out in seven consecutive phases. For *Phase I* of the study, a set of solid state digital images (basis images) acquired for a previously published study[33] of caries detection efficacy was used. The latter images consisted of eight different digital images of each of forty extracted human molars and premolars, acquired with a CCD digital sensor (Schick Technologies Inc., Long Island City, NY, USA) and a dental x-ray unit, from different projection angles. The use of existing images in *Phase I* was deemed necessary because the batch of teeth actually selected for the rest of this project could not be destroyed (i.e., sectioned for histology) until the images required for all phases of the investigation were acquired and because there was a need to know the ground truth for *Phase I* before proceeding with the remaining six phases of the project. For *Phases II* through *VII* a new sample of teeth was selected and imaged according to the purposes of each of the phases. Differences in methods between *Phase I* and the other phases are indicated where they apply.

Sample preparation and image acquisition for Phases II-VII

Extracted human posterior teeth were assessed for the presence of caries visually using a 2X magnifying lens and conventional film radiographs. Teeth with restorations, gross cavitations, or any defects on the proximal surface that could radiographically mimic carious lesions were excluded. Forty teeth were selected (twenty premolars and twenty molars). This selection process was carried out to choose an approximately equal proportion of carious and non-carious proximal surfaces as well as to supply lesions of varying depths to be used in the study. The clinical appearance of the tooth surfaces after cleaning included sound tooth structure, white/brown stains, small cavitations, and any combination of these.

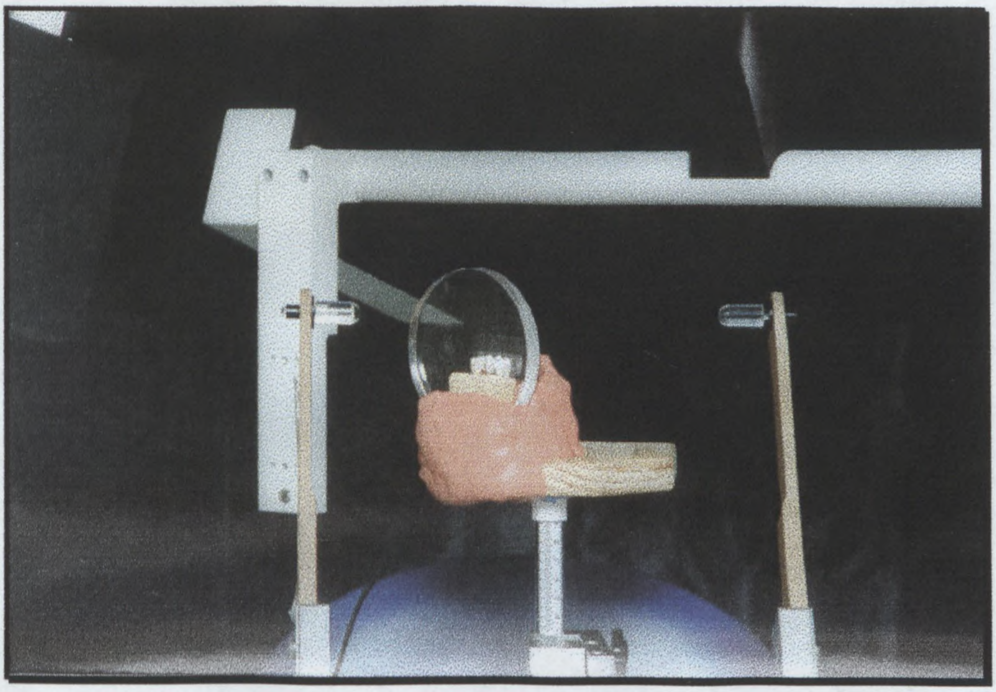
Each tooth individually had its root or roots embedded in sticky wax and mounted in dental stone to form a model. To simulate proximal contacts, two additional teeth, not part of the sample, were also included in the model, one on each side of the study tooth. In total, eighty *interproximal* and forty *occlusal* surfaces were available for use. To allow later reconstruction of TACT® images, a 1-millimeter lead sphere (X-Spot, Beekley Corporation, Bristol, CT, USA) was fixed at a distance of approximately 3 mm from the facial surface of the central tooth of the model at its cervical level (Fig. 1).

Figure 1. Teeth embedded in wax and mounted in dental stone. Only the central tooth of each model constituted the tooth of interest (sample used in *Phases II* through *VII* of the investigation). Notice the 1-mm lead sphere attached to the facial aspect of the tooth of interest.

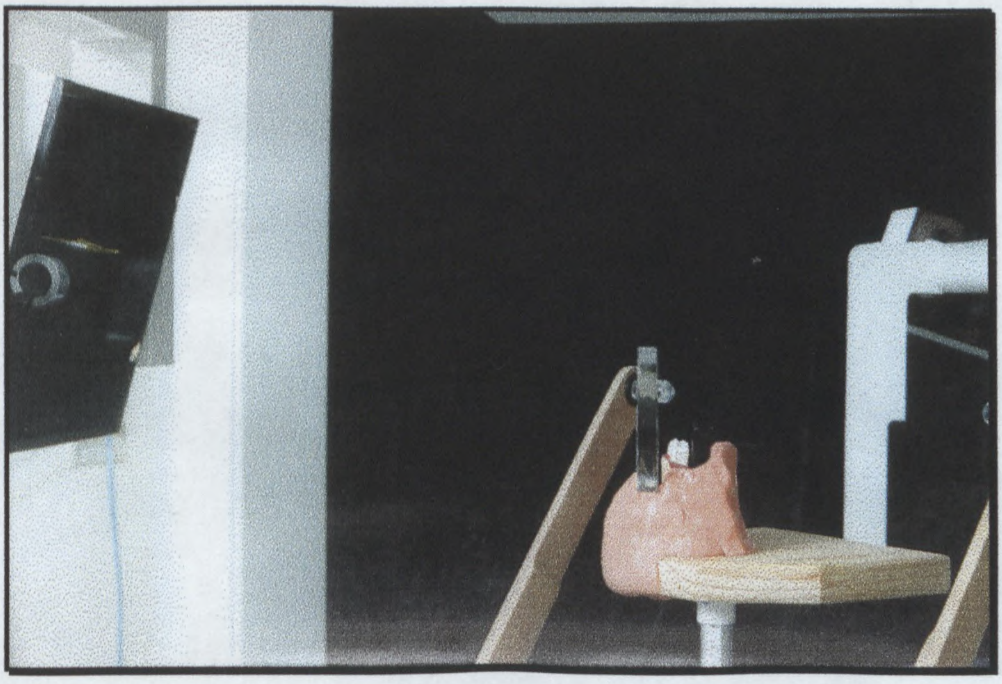


A computer-controlled multidirectional tomography unit was used as the x-ray source in *Phases II-VII* of this investigation (CommCAT, Imaging Sciences International, Roebling, NJ, USA; nominal focal spot size: 0.5 mm, total aluminum filtration equivalence: 3 mm). This unit allows positioning the x-ray tube head at finite *loci* in space relative to the object imaged. This is achieved with the use of a coordinate system available in the controlling computer software. The x-ray tube head positions are therefore programmable and provide strict projection geometry while still allowing accurate determination of the distances and angles used during exposures. The x-ray source was adjusted to operate at 70 kilovolts, 5 milliamperes, and 310 milliseconds. These exposure settings were selected because they provided the best image density in the opinion of two board certified oral and maxillofacial radiologists in a pilot project carried out prior to the actual investigation. Models with teeth were positioned on a custom-made wooden platform that adapted to the chin support of the tomography unit. To simulate beam attenuation and scatter from soft tissues, a one-centimeter thick slab of tissue equivalent material (Radiation Measurements Inc., Middleton, WI, USA) was interposed between the x-ray source and the dental stone models during imaging. A No. 2 complementary metal-oxide semiconductor (CMOS) intra-oral digital sensor (Schick Technologies Inc., Long Island City, NY, USA) was used as the image receptor. Polyvinyl impression material was used as a mold to keep the set-up in place on the wooden frame, and also to maintain the relationship between image receptor, object, TEM, and x-ray source constant (figures 2a and 2b). The object-to-image receptor distance was 53 cm for all experimental conditions in *Phases II*, *III*, *IV*, *VI* and *VII*, and for one of the experimental conditions tested in *Phase V* of the investigation. Each individual image was acquired using an exposure of 360 μGy at the position of the receptor. This was measured using a ion chamber (Model 1015, MDH Industries Inc., Monrovia, CA, USA) dosimeter.

Figure 2. The experimental set-up used to acquire images for all modalities in *Phases II*, *III*, *IV*, *VI* and *VII*, and for one of the experimental conditions tested in *Phase V* of the investigation.



a)

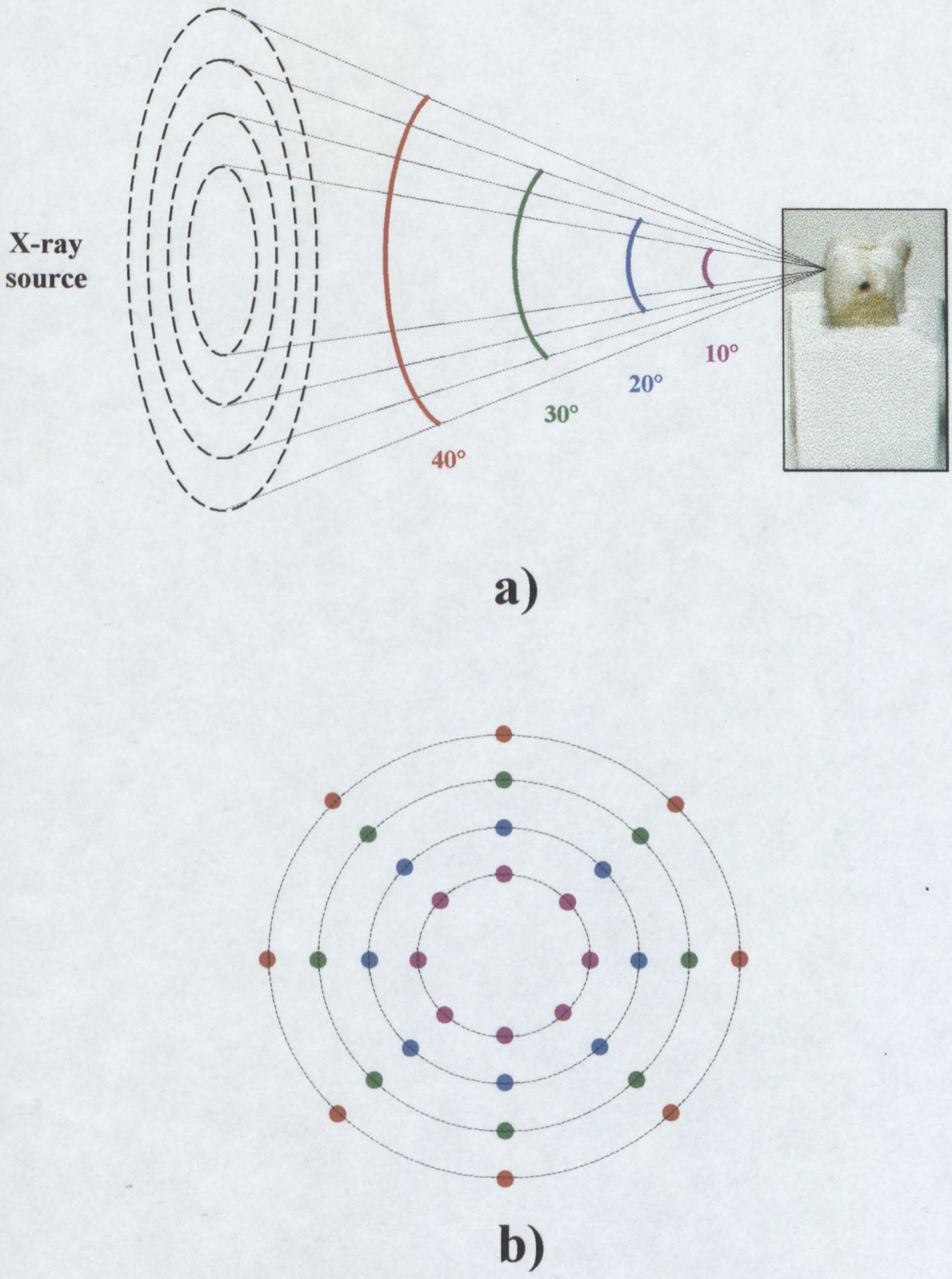


b)

For *Phase I* of the project, the set of images acquired for a previous report was used.[33] Three different experimental conditions were derived from this set of images by submitting the stack to different numbers of iterative restorations.

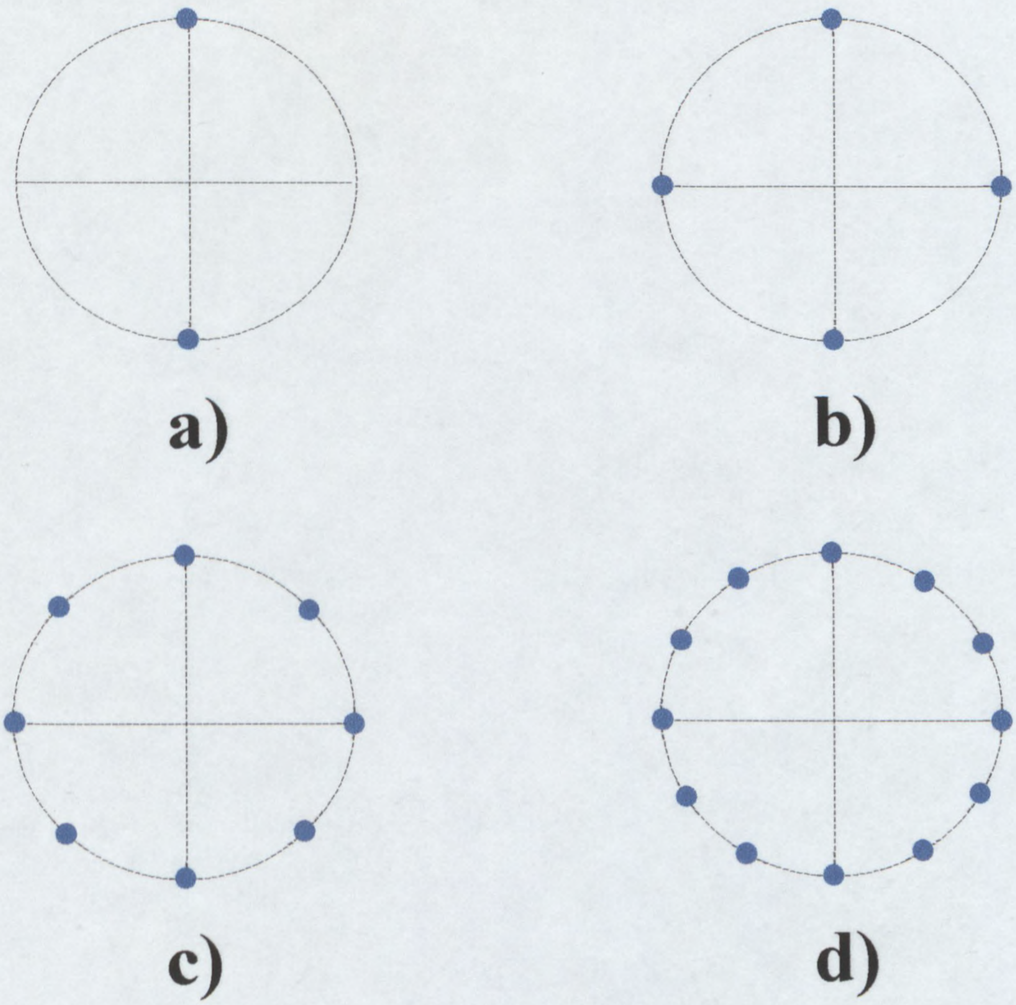
For *Phase II*, four sets of eight different images (*basis images*) of each tooth were acquired. For each set of images, the CommCAT was programmed to move its tube head sequentially to eight different *loci* around an imaginary and symmetrical circle in space, from which the projections were executed. Four concentric circles, oriented approximately parallel to the long axis of the teeth (and to the sensor surface), were defined in this fashion (Fig. 3a and 3b). The angular disparity, i.e., the angle subtended between the most extreme and opposite source positions relative to the teeth was 10°, 20°, 30°, and 40°, respectively, for each set of projections (Fig. 3a). The entry radiation dose was 2,880 μGy for the eight images combined.

Figure 3. Schematic representation of the (**a**) angular disparities and (**b**) positions of the x-ray source in space used to acquire images in *Phase II* of the investigation.



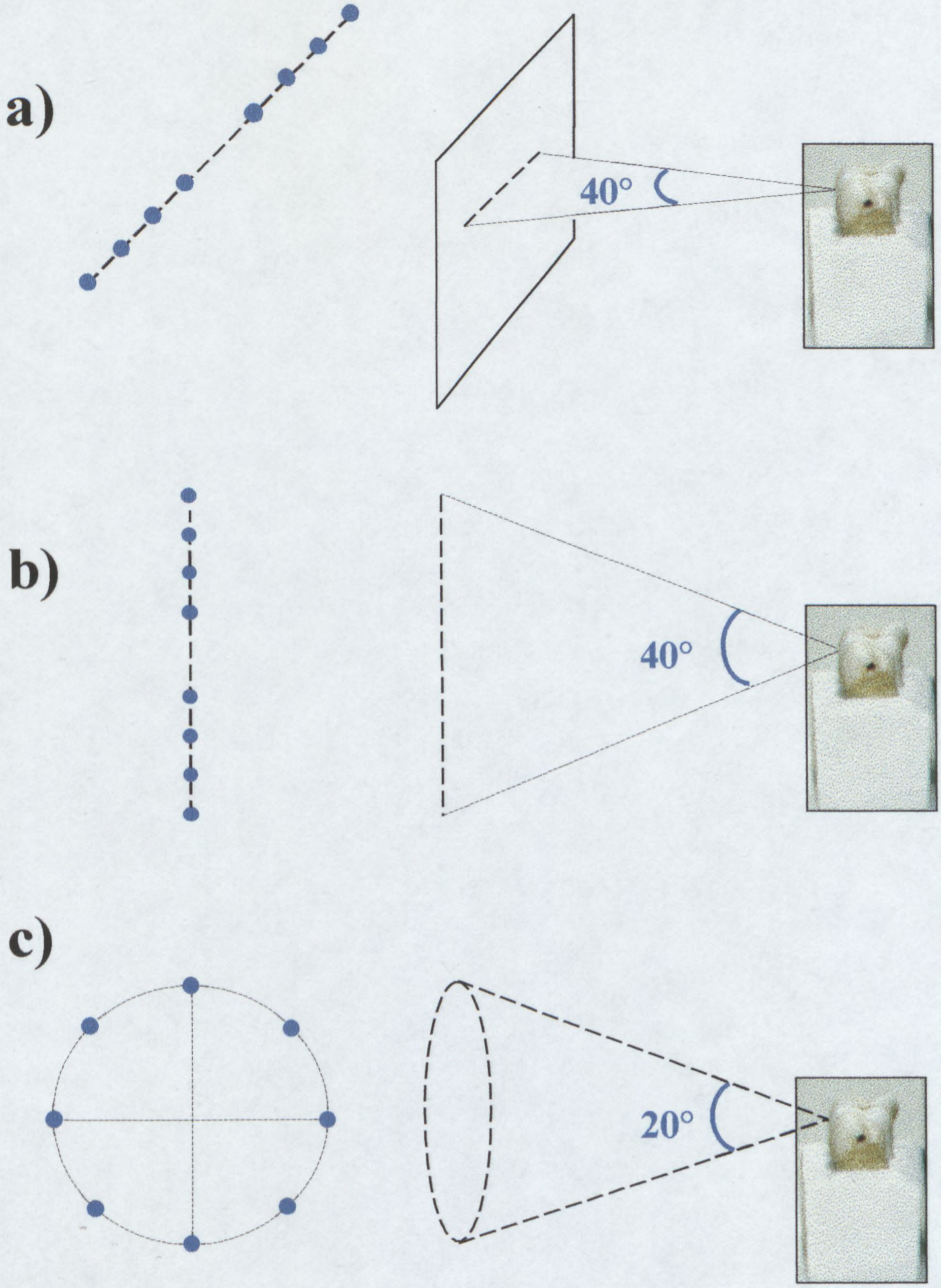
For *Phase III*, four sets of images of each tooth were acquired, each containing a different number of images (Fig. 4): a group consisting of two basis images (Fig. 4a - positions 90° and 180°); a group of four basis images (Fig. 4b - positions 0°, 90°, 180°, and 270°); a group with eight basis images (Fig. 4c – positions 0°, 45°, 90°, 135°, 180°, 225°, 270°, and 315°); and a group with twelve basis images (Fig. 4d – positions 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330°). The positions of the x-ray source from which projections were made formed an imaginary circle in space. The angular disparity, i.e., the angle subtended between opposite source positions relative to the teeth was also 20°. The combined entry radiation dose was 720 μGy for two basis images, 1,440 μGy for four basis images, 2,880 μGy for eight basis images, and 4,320 μGy for twelve basis images.

Figure 4. The four sets of x-ray projections (images) acquired in *Phase III* of the investigation: a) 2 basis images, b) 4 basis images, c) 8 basis images, and d) 12 basis images.



For *Phase IV*, three sets of eight basis images of each tooth were acquired. For two of these sets, the CommCAT was programmed to move sequentially to eight positions distributed along an imaginary line in space, one in the horizontal (linear-HZ) and the other in the vertical direction (linear-VT). Extreme positions of the linear arrays formed an angular disparity of 40° relative to the central tooth of the models (Fig. 5a and 5b). The third set of images used was the circular array of eight images and 20° angular disparity acquired for *Phase II* of this investigation (Fig. 5c). The combined entry radiation exposure was 2,880 μGy for each set of eight images.

Figure 5. Schematic representation of the angular disparities and number and spatial distribution of the x-ray source positions used to acquire images in *Phase IV* of the investigation: **a)** linear-horizontal array; **b)** linear-vertical array; **c)** circular array.



For *Phase V*, two sets of eight different images of each tooth were acquired. One set of images was acquired using a dental x-ray unit (Gendex Oralix, Monza, Italy) with nominal focal spot size of 0.7mm and 2 mm total aluminum filtration equivalence, operated at 70 kilovolts, 7 milliamperes, and 0.08 seconds. The x-ray tube head was manually moved to eight different positions from where the projections were made. Inasmuch as a common dental x-ray unit was being used, no exact determination of the distances and projection angles used for each projection was attempted. The source-to-image receptor distance actually varied to a limited degree from one exposure to the next and approximated 30cm plus or minus a few centimeters, which corresponds well to a clinical simulation of the method. The positions of the x-ray focal spot in this *unconstrained* array of projection geometries were not, therefore, located perfectly in the same plane. The object-to-image receptor relationship, however, was kept constant during the acquisition of images, so that a single lead sphere could be used as a fiducial reference marker when later reconstructing TACT® images.[7] The other set of images used was the circular array of eight basis images and 20° angular disparity acquired for *Phase II* of this investigation. In the context of this phase of the project (*Phase V*), the latter array of projections was considered to have been acquired with *stringent* projection geometry, in contrast to the manual and unconstrained fashion through which images were acquired using the conventional dental x-ray unit.

For *Phase VI*, the same circular array of eight basis images and 20° angular disparity acquired for *Phase II* of the project was used. Two different conditions were derived from this set of images by reconstructing them into TACT® slices using different reconstruction methods described later in this section.

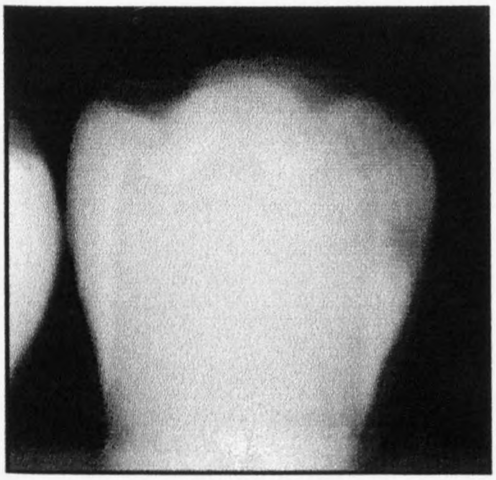
For the last phase of the investigation (*Phase VII*), again two sets of images were used. One set of images consisted of the circular array of eight images and 20° angular disparity acquired for *Phase II* of the project. The other set consisted of a single image that was acquired with the CommCAT moving to a position orthogonal to the object-receptor assembly (i.e. the projection geometry of a typical bitewing radiograph).

Image reconstruction and viewing sessions

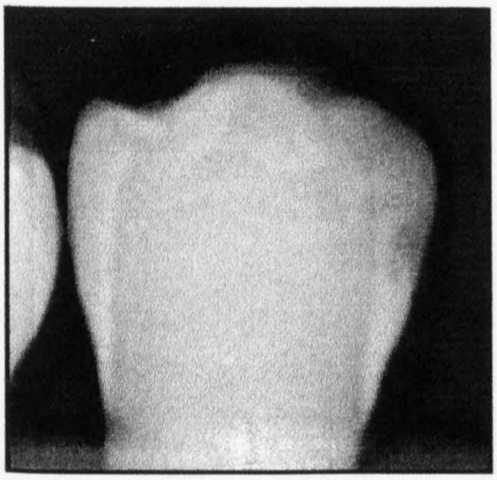
Images used in *Phase I* of the investigation and all images acquired for *Phases II-VII* were saved in tagged-interchange file format (TIFF) and transferred to a Windows-based personal computer. TACT® Workbench software (Verity Software Systems, Winston-Salem, NC, USA), version 1.09, was used to generate TACT® images. For *Phases II, III, IV, V*, and for the TACT® modality tested in *Phase VII*, each set of basis images was used to create a set of sixteen to twenty-two mesio-distal TACT® slices of the teeth. These slices were prepared for viewing as a sequential stack of static images, from buccal to lingual. The exact number of slices in each stack depended on the particular facial-lingual dimension of the tooth imaged, e.g., difference in size between molars versus premolars. Image stacks of the same tooth, however, had the same number of slices.

For *Phase I*, the single set of images was used three times to generate three different TACT® slice stacks, and subsequently submitted to one, two or three iterative restorations using the default gain setting of the software with a lambda factor of 0.2222. The three stacks represented the image modalities to be compared in that phase of the study (Fig. 6).

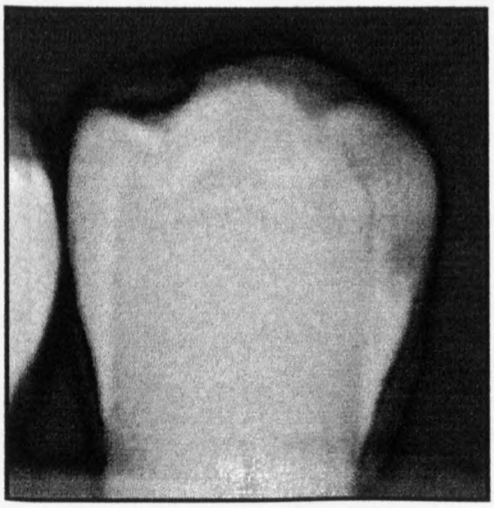
Figure 6. Representative images used in *Phase I* of this investigation. The same TACT® slice submitted to one, two, and three iterative restorations, respectively, clearly demonstrates caries on the "right" proximal surface of this mandibular premolar. Notice the apparent increase in image noise as the number of iterative restorations is increased.



TACT® slice - 1 iterative restoration



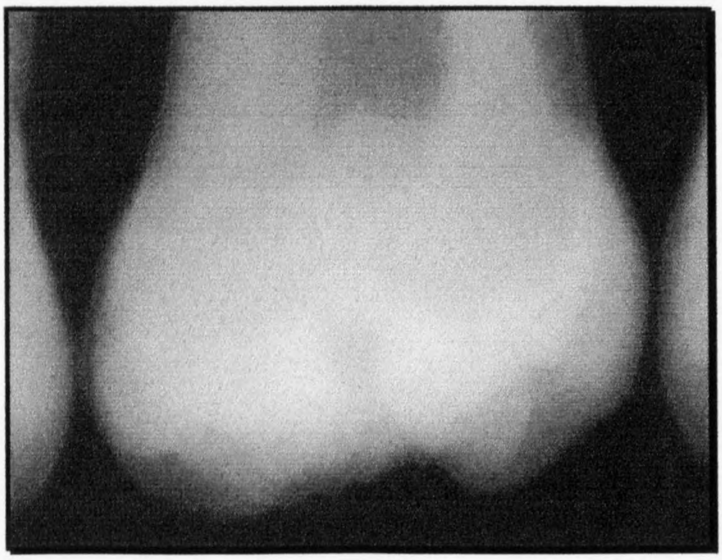
TACT® slice - 2 iterative restorations



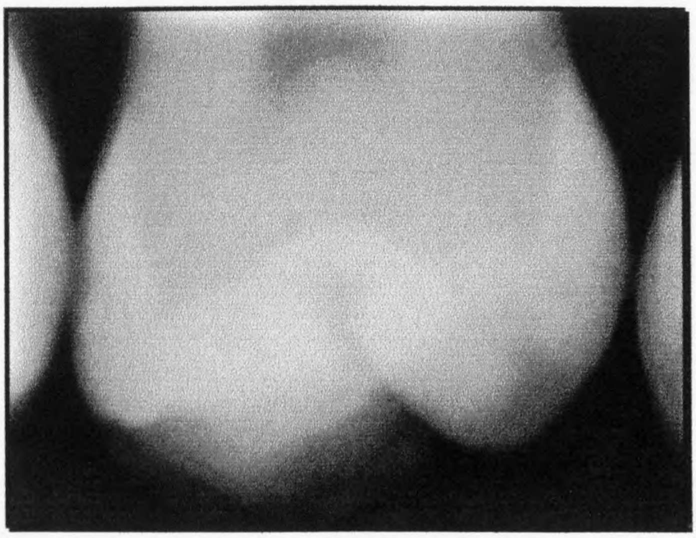
TACT® slice - 3 iterative restorations

For Phase VI, a single set of images was used twice, to generate TACT® slices by means of two different reconstruction methods, minimum and average, respectively. These methods are selectable from the proprietary software and represented the modalities to be compared in that phase of the study (Fig. 7a and 7b). While from sixteen to twenty-two slices of each tooth were generated for the average method, the number of slices varied from twenty to thirty-five for the minimum method. The difference in the number of slices between the two methods occurred because the minimum method provides a greater number of slices of the same facial-lingual dimension of the object imaged.

Figure 7. Representative images of a single TACT® slice generated using (**a**) the ***minimum*** and (**b**) the *average* reconstruction methods.



a)



b)

TACT® slice stacks used in the different phases of the study were submitted to one iterative restoration with the exception of two of the experimental conditions tested in *Phase I* (that were submitted to two and three iterations, respectively), and one of the experimental conditions tested in *Phase VI* (generated using the minimum reconstruction method, that dispenses with the use of iterative restorations). For those image sets that were indeed submitted to iterative restoration, this procedure resulted in 32-bit images, which are relatively large in terms of the computer memory they require. To save hard disk space, images were converted back to 8-bit images, without any apparent loss in their quality. TACT® slice generation and iterative restoration have also been described previously.[7,10,11,14-16] Since slices submitted to iterative restoration exhibit non-ideal contrast due to concurrent loss of plane-relevant detail,[21] contrast and brightness of the images needed to be improved prior to the viewing sessions of all phases of the investigation. This was accomplished in an objective fashion with the aid of the histogram feature of TACT® Workbench proprietary software (version 1.09). For each tooth, a "histogram stretch" of the various image stacks was performed, which optimized the use of the displayed gray scale and provided improved image contrast. Care was taken not to saturate, i.e., make exceedingly bright, the image of the enamel since this could obscure the presence of potential carious lesions, especially in occlusal surfaces. To ensure that all TACT® modalities of the same phase of the investigation would provide images with comparable contrast and brightness settings, the corresponding stacks of slices of the same tooth were displayed simultaneously on the computer monitor by the project coordinator and their histograms matched. All images were coded with computer-generated random numbers and the numerical sequence was different for each experimental condition tested.

The number of observation sessions in the different phases of the investigation was determined by the number of conditions to be compared, with one experimental phase been viewed in each single session. A period of at least one week was allowed to elapse between consecutive viewing sessions and between the end of a phase and the beginning of the next phase of the investigation. The observation sessions for this project took approximately one year to be completed.

Six observers (oral and maxillofacial radiologists) with experience in interpreting TACT® images were recruited for *Phase I* of the study and eight for the remaining phases (six oral and maxillofacial radiologists and two general dentists). They were asked to score the presence or absence of caries in the *proximal* surfaces of the teeth, for *Phase I*, and in the *occlusal* and *proximal* surfaces, for the remaining phases. The scoring system selected took into consideration observer confidence in the assessments. This was accomplished by using a 5-point Likert rating scale, in which 1= caries definitely absent, 2= caries probably absent, 3= unsure if caries absent or present, 4= caries probably present, and 5= caries definitely present. Observers were told to consider a likelihood of caries occurrence of 50% for any surface under examination, and to consider caries as any decalcification of the tooth surface without any implications regarding its treatment.

For each phase of the study, the sequence of experiments presented to observers was systematically arranged in a way that, on average, no image condition was seen earlier than any other. For that matter, each image condition was viewed first by two of the observers, second by two of the observers, third by two of the observers, and fourth by two of the observers (Note: *Phase I* used six observers and *Phases II-VII* used eight observers). Sequence orders were assigned randomly to each observer. All viewing sessions took place in a quiet room with subdued ambient lighting. To ensure observer calibration, a training exercise was completed before the beginning of each phase of the study, where instructions were provided and observers became familiar with the experimental condition or image modality to be evaluated. Observers were blinded in relation to the experimental phase they were viewing except in *Phase VII* of the study, when they were able to distinguish between TACT® and conventional digital images.

All images were viewed on a 21-inch high-resolution color monitor (Hitachi SuperScan Supreme 803, Hitachi America, Ltd., USA) using TACT® Workbench software, version 1.09, as the interface. The monitor resolution was set at 1024 x 768 pixels with a 24-bit color depth (True Color). These settings, as well as monitor contrast and brightness, were kept constant during the entire investigation. Observers were also instructed to use the "page-up/page-down" keys of the keyboard to evaluate all available TACT® slices in the stack before giving their final score to the tooth surfaces. However, one of the modalities tested in *Phase VII* of the investigation was conventional digital radiography (Fig. 8). Therefore, only one image was available for viewing. Observers were not allowed to adjust contrast and brightness of images or change the image presentation in any other way during the observation sessions of *Phase I*. For all other phases, observers were allowed to adjust those image characteristics if the preset settings did not please them.

Figure 8. Conventional digital radiography image – one of the two modalities tested in *Phase VII* of the investigation.

Histological information

Subsequent to imaging, teeth used in Phases II-VII were embedded in clear acrylic and sectioned mesiodistally in sections between 300-400 μm-thick using a low speed saw equipped with a diamond blade (Buehler Ltd., Lake Bluff, IL, USA). (Teeth used in *Phase I* had been sectioned in 300 μm-thick sections[33]). Sections were examined under a dissecting microscope for the presence or absence of caries (Fig. 9). In the presence of a lesion, the maximum depth of the carious process was recorded as the caries status for that surface. Figures 10 and 11 show the distribution of surfaces by caries status of the teeth used in *Phases I* and *II-VII* of the investigation, respectively, determined by histologic examination of tooth sections.

Figure 9. A 300 μm-thick mesio-distal section of a molar tooth viewed under a dissecting microscope showing caries in its occlusal and "right" proximal surface. The same methodology of sectioning and evaluating teeth through histology was used in the seven phases of the investigation.

Figure 10. Distribution of eighty proximal surfaces by caries status determined by histologic examination of tooth sections - sample used in *Phase I* of the investigation.

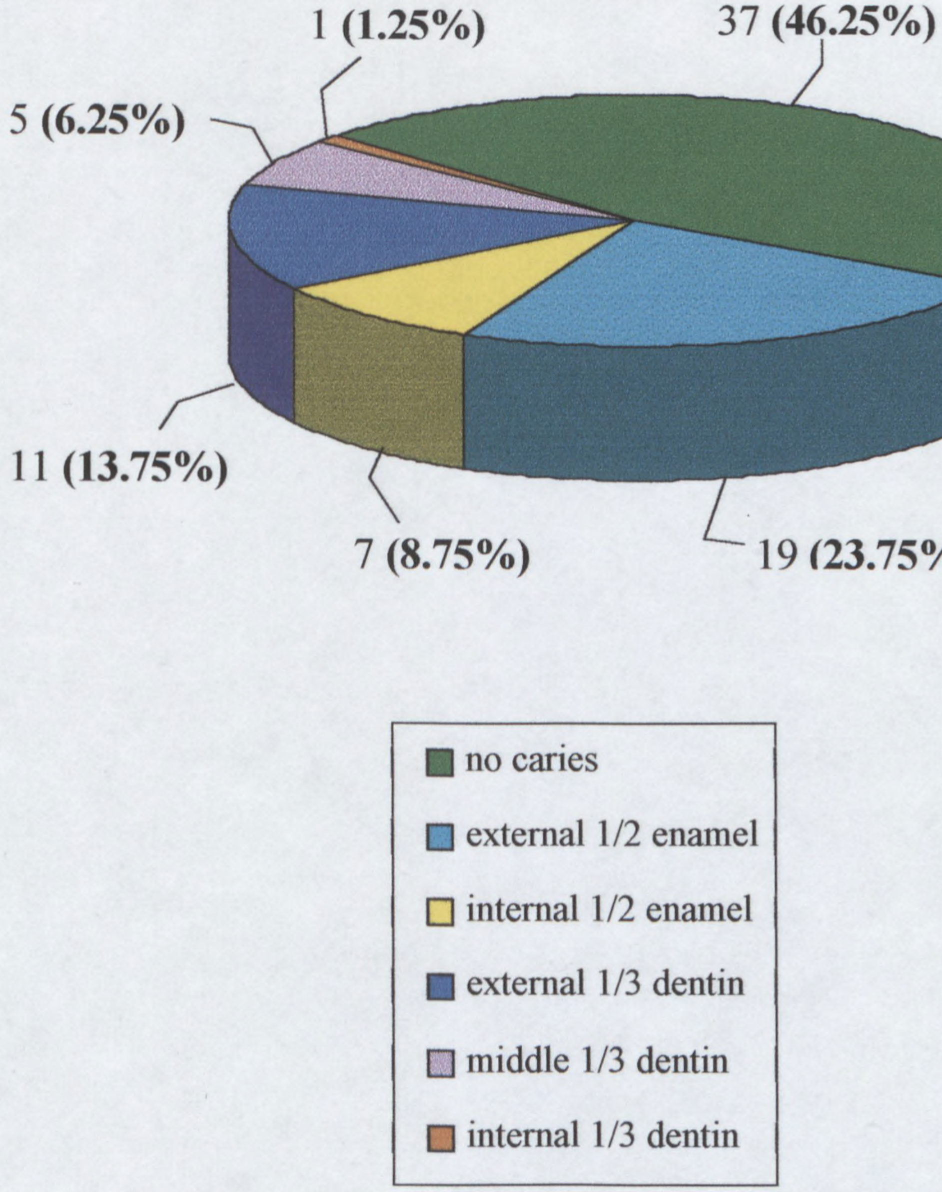
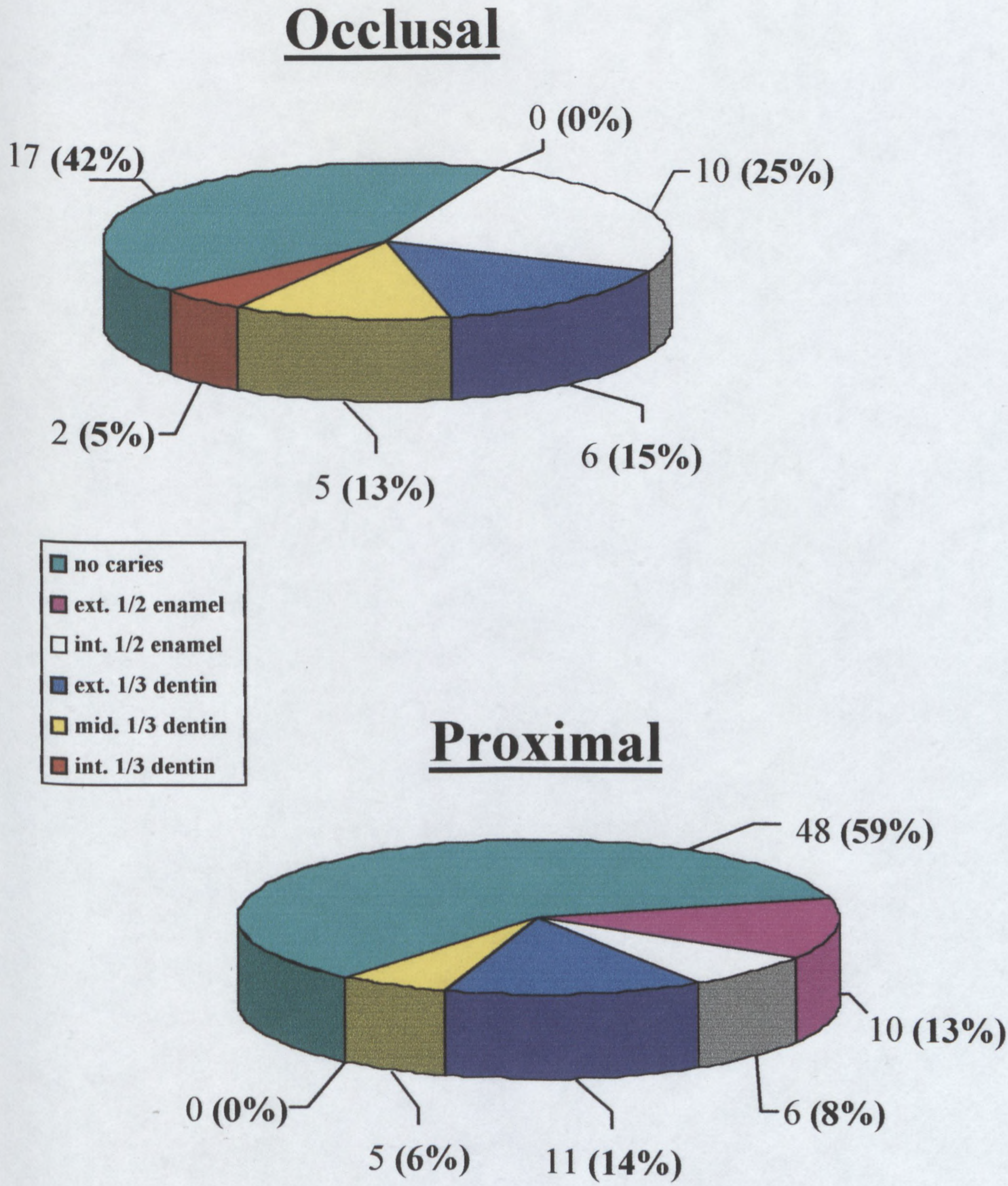


Figure 11. Distribution of 120 tooth surfaces (40 teeth) by caries status determined by histologic examination of ground sections (sample used in *Phases II* through *VII* of the investigation).



Statistical analyses

For each phase of the study, observers' assessments for each image experimental condition were recorded and compared to the ground truth provided by histology. Diagnostic performance was determined in terms of areas (A_z) under Receiver Operating Characteristic (ROC) curves. This technique provides a description of observers' decision performance as well as a description of disease detection ability that is independent from disease prevalence and decision level effects.[51] ROC curves were generated for each combination of experimental condition, observer, and surface using the maximum likelihood technique provided by ROCKIT software (Apple Macintosh version, Charles E. Metz, The University of Chicago, Chicago, IL). A_z values were analyzed using analysis of variance (ANOVA) to test the main effects of the independent variables, experimental condition, observer, and surface on the dependent variable, A_z. The level of significance was set *a priori* at $\alpha = 0.05$. In case a significant or nearly significant difference was found, Tukey's post hoc test was used to further clarify the comparisons. Sensitivity, specificity, and accuracy values were calculated since they are also commonly used to report diagnostic performance, and because they provide a clear tabulation of true-positive, true-negative, and overall correct assessments obtained with different test modalities. For that purpose, observers' scores were collapsed into two categories: scores 1, 2, and 3 were considered as representing perceived absence of caries, while scores 4 and 5 were regarded as representing perceived presence of caries. Intra-class correlation (ICC) was used to assess inter-observer reliability for each experimental condition or modality compared.

CHAPTER IV

RESULTS

Phase I (Effect of the number of iterative restorations on TACT® slices for caries detection)

Table 1 and figure 12 show individual and mean areas under the ROC curves (A_z) for TACT® slices submitted to one, two, or three iterative restoration in the detection of proximal caries. Three observers performed best with slices submitted to one iteration while the other three performed best with slices submitted to two iterations. Mean differences between modalities were small, with two iterations providing slightly better mean diagnostic performance (A_z= 0.810) than either one (A_z= 0.791) or three (A_z= 0.778) iterations. ANOVA (Table 2) did not demonstrate a statistically significant difference between the different numbers of iterative restorations tested (p= 0.250). However, a significant difference between observers was detected (p= 0.031), reflecting the variability in observer diagnostic performance. This can be noticed from the range of A_z values found for each of the numbers of restorations used during this phase of the study.

Table 1. Individual and mean areas under the ROC curves (A_z) for six observers in the detection of **proximal** caries using TACT® slices submitted to 1, 2, and 3 iterative restorations.

TACT® Experimental Condition

	1 It. Restoration		**2 It. Restorations**		**3 It. Restorations**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.699	(0.084)	0.796	(0.060)	0.783	(0.072)
2	0.765	(0.093)	0.773	(0.085)	0.699	(0.089)
3	0.771	(0.065)	0.826	(0.059)	0.783	(0.062)
4	0.823	(0.061)	0.801	(0.070)	0.800	(0.068)
5	0.857	(0.060)	0.854	(0.047)	0.824	(0.051)
6	0.832	(0.066)	0.811	(0.055)	0.779	(0.062)
Mean	**0.791**	(0.071)	**0.810**	(0.062)	**0.778**	(0.067)

Figure 12. Mean ROC curves for TACT® image set slices submitted to 1, 2, and 3 iterative restorations.

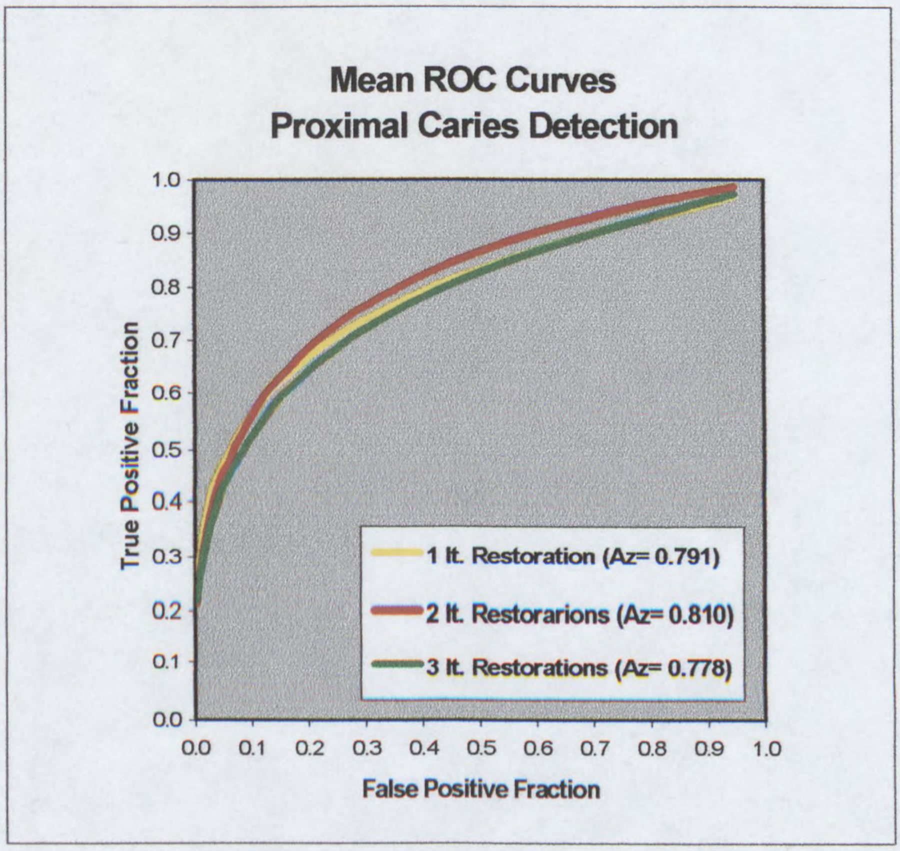


Table 2. Analysis of variance (ANOVA) – *Phase I.*

Source	sum of squares	df	Mean square	f-ratio	p
Observer	0.019	5	0.004	3.946	0.031
Exp. Cond.	0.003	2	0.002	1.596	0.250
Error	0.010	10	<0.001		

Dependent Variable: Proximal A_z; N: 18; Multiple R: 0.834; Squared multiple R: 0.696.

Sensitivity, specificity, and accuracy values for the six observers are shown in table 3. As a general rule, slices submitted to two iterations provided the highest sensitivities while slices submitted to a single iteration provided the highest specificities. The overall number of correct assessments, however, was quite similar for the three modalities, as shown by the mean accuracy values.

Table 3. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by six observers in the detection of proximal caries using TACT® slices submitted to 1, 2, and 3 iterative (It.) restorations.

TACT® Experimental Condition

	1 It. Restoration			**2 It. Restorations**			**3 It. Restorations**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.583	0.750	0.700	0.792	0.679	0.713	0.708	0.804	0.775
2	0.410	0.929	0.775	0.500	0.911	0.788	0.458	0.857	0.738
3	0.540	0.911	0.800	0.708	0.857	0.813	0.667	0.821	0.775
4	0.708	0.786	0.763	0.750	0.768	0.763	0.667	0.786	0.750
5	0.750	0.839	0.813	0.708	0.786	0.763	0.708	0.768	0.750
6	0.583	0.893	0.800	0.667	0.875	0.813	0.583	0.785	0.725
Mean	**0.596**	**0.851**	**0.775**	**0.688**	**0.813**	**0.776**	**0.632**	**0.804**	**0.752**

Inter-observer intra-class correlation demonstrated a fair agreement between observers, independently of the number of iterative reconstructions performed. Agreement was higher among observers when they viewed TACT® slices submitted to either one or two iterative restorations as compared to slices submitted to three iterative restorations. This difference, however, was small (Table 4).

Table 4. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® image slices submitted to 1, 2, and 3 iterative (It.) restorations.

TACT® Experimental Condition

	1 It. Restoration	**2 It. Restorations**	**3 It. Restorations**
mean square surface	9.64976	9.98605	9.10841
mean square error	0.92792	0.96625	1.02042
Inter-observer ICC*	**0.61**	**0.61**	**0.57**

* ICC coefficients derived from analysis of variance of the scores given by the six observers to the same surfaces.

Phase II (Effect of the angular disparity of basis images on caries detection using tuned aperture computed tomography [TACT®])

For the detection of occlusal caries (Table 5, Fig. 13), the mean areas under the ROC curves (A_z values) for the four TACT® conditions generated from different angular disparities were, respectively, 0.794 (10°), 0.821 (20°), 0.759 (30°), and 0.812 (40°). Individually, one observer performed best with the 10° angular disparity, three with the 20°, one with the 30°, and three with the 40° angular disparity. No clear trend of superior or inferior diagnostic performance could be noticed as the angular disparity increased. ANOVA (Table 6) did not prove statistically significant differences between the different angular disparities tested (p= 0.105); however, a significant difference between observers was present (p= 0.015).

Table 5. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using TACT® slices generated from different angular disparities (Ang. Disp.) of basis images.

TACT® Experimental Condition

	10° Ang. Disp.		**20° Ang. Disp.**		**30° Ang. Disp.**		**40° Ang. Disp.**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.765	0.079	0.826	0.074	0.732	0.084	0.793	0.077
2	0.730	0.084	0.763	0.084	0.825	0.069	0.880	0.060
3	0.815	0.072	0.806	0.105	0.752	0.085	0.730	0.083
4	0.843	0.053	0.836	0.052	0.891	0.038	0.849	0.047
5	0.798	0.093	0.868	0.101	0.735	0.103	0.851	0.063
6	0.773	0.130	0.841	0.070	0.675	0.168	0.694	0.116
7	0.884	0.057	0.864	0.060	0.827	0.076	0.889	0.059
8	0.748	0.083	0.762	0.077	0.634	0.094	0.808	0.070
Mean	**0.794**	0.081	**0.821**	0.078	**0.759**	0.090	**0.812**	0.072

Figure 13. Mean ROC curves for the TACT® experimental conditions using different angular disparities in the detection of **OCCLUSAL** caries.

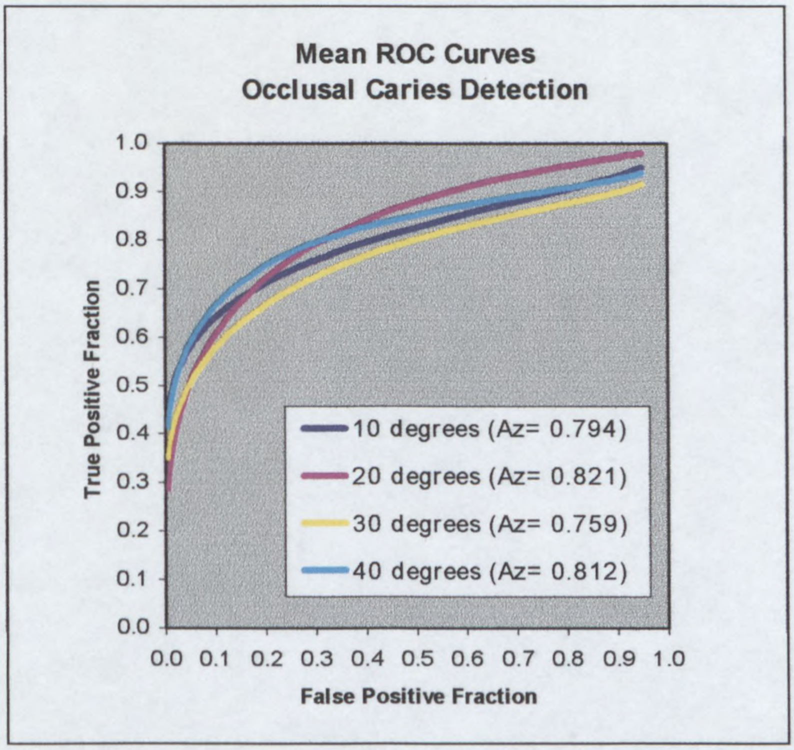


Table 6. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase II*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.061	7	0.009	3.348	0.015
Exp. Cond.	0.018	3	0.006	2.319	0.105
Error	0.054	21	0.003		

Dependent variable: Occlusal A_z; N: 32; Multiple R: 0.769; Squared multiple R: 0.591.

For the detection of proximal caries (Table 7, Fig. 14), the mean areas under the ROC curves (A_z values) for the four TACT® experimental conditions were, respectively, 0.823 (10°), 0.822 (20°), 0.755 (30°), and 0.797 (40°). Four observers obtained their highest A_z value with the 10° angular disparity, three with the 20°, and one with the 40° angular disparity. ANOVA (Table 8a) indicated that differences between the angular disparities tested were not statistically significant (p= 0.052); however, a trend of superior performance provided by both the 10° and 20° angular disparities in comparison to the 30° disparity was suggested by a *post hoc* test (Table 8b). No significant differences between observers were found (p= 0.356).

Table 7. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using TACT® slices generated from different angular disparities (Ang. Disp.) of basis images.

	TACT® Experimental Condition							
	10° Ang. Disp.		**20° Ang. Disp.**		**30° Ang. Disp.**		**40° Ang. Disp.**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.779	0.058	0.830	0.050	0.725	0.066	0.801	0.057
2	0.795	0.055	0.857	0.048	0.719	0.063	0.823	0.051
3	0.835	0.049	0.796	0.057	0.792	0.056	0.703	0.064
4	0.872	0.048	0.831	0.054	0.807	0.055	0.820	0.054
5	0.834	0.060	0.791	0.068	0.719	0.076	0.802	0.067
6	0.745	0.067	0.759	0.087	0.650	0.191	0.875	0.050
7	0.799	0.058	0.894	0.041	0.803	0.052	0.750	0.064
8	0.922	0.057	0.816	0.063	0.824	0.053	0.804	0.055
Mean	**0.823**	0.056	**0.822**	0.058	**0.755**	0.076	**0.797**	0.058

Figure 14. Mean ROC curves for the TACT® experimental conditions using different angular disparities in the detection of **PROXIMAL** caries.

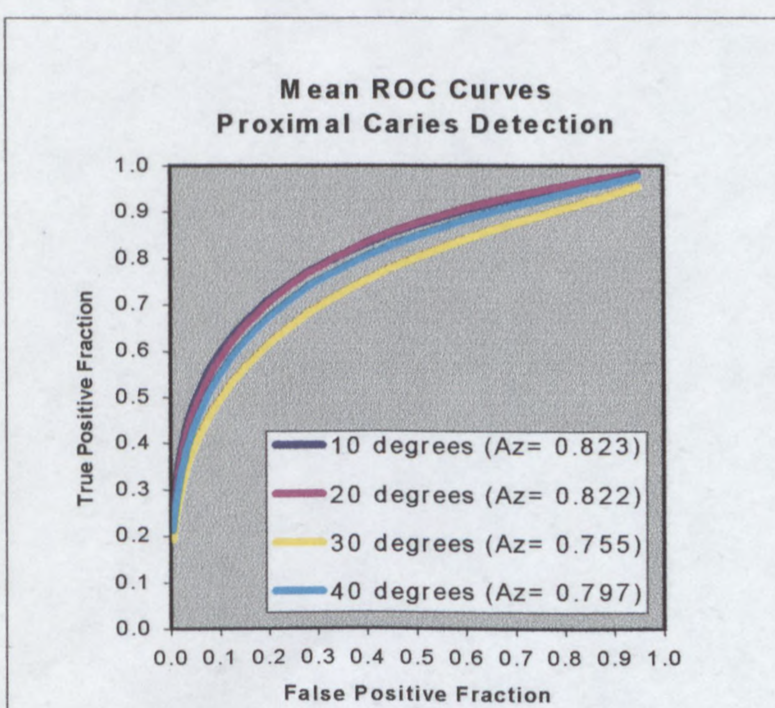


Table 8a. Analysis of variance (ANOVA): **proximal** caries detection – *Phase II*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.022	7	0.003	1.179	0.356
Exp. Cond.	0.024	3	0.008	3.029	0.052
Error	0.056	21	0.003		

Dependent variable: Proximal A_z; N: 32; Multiple R: 0.673; Squared multiple R: 0.452.

Table 8b. Tukey's Post-Hoc test: **proximal** caries detection – *Phase II*.

Matrix of pairwise mean differences*/comparison probabilities**				
	10° Ang. Disp.	**20° Ang. Disp.**	**30° Ang. Disp.**	**40° Ang. Disp.**
10° Ang. Disp.	0.000/1.000			
20° Ang. Disp.	-0.001/1.000	0.000/1.000		
30° Ang. Disp.	-0.068/0.070	-0.067/0.074	0.000/1.000	
40° Ang. Disp.	-0.025/0.759	-0.025/0.777	0.042/0.380	0.000/1.000

* Post-Hoc test of Proximal A_z using model MSE of 0.003 with 21 DF; effect: experimental condition.

** Post-Hoc test of Proximal A_z; Tukey HSD multiple comparisons; effect: experimental condition.

Sensitivity, specificity, and accuracy values for all combinations of observer and angular disparities are shown in Table 9, for occlusal, and Table 10 for proximal caries detection. In general, sensitivities were lower than specificities for all angular disparities tested. For the detection of occlusal caries, sensitivities tended to increase and specificities to decrease with greater angular disparity. For proximal caries detection, sensitivities were generally greater for smaller angular disparities while specificities were comparable between the different angles. Differences in mean accuracy between angular disparities were also relatively small for both tasks.

Table 9. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using TACT® slices generated from different angular disparities (Ang. Disp.) of basis images.

	TACT® Experimental Condition											
	10° Ang. Disp.			**20° Ang. Disp.**			**30° Ang. Disp.**			**40° Ang. Disp.**		
Obs	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.783	0.529	0.675	0.783	0.941	0.850	0.696	0.647	0.675	0.739	0.706	0.725
2	0.348	1.000	0.625	0.435	0.941	0.650	0.609	0.824	0.700	0.478	0.882	0.650
3	0.391	1.000	0.650	0.435	1.000	0.675	0.348	0.941	0.600	0.609	0.824	0.700
4	0.766	0.822	0.790	0.723	0.764	0.740	0.810	0.881	0.840	0.766	0.822	0.790
5	0.521	1.000	0.725	0.522	1.000	0.725	0.565	1.000	0.750	0.652	0.941	0.775
6	0.478	1.000	0.700	0.565	0.941	0.725	0.522	1.000	0.725	0.609	1.000	0.775
7	0.826	0.705	0.775	0.739	0.882	0.800	0.913	0.706	0.825	0.870	0.647	0.775
8	0.304	1.000	0.600	0.522	0.882	0.675	0.522	0.765	0.625	0.565	0.882	0.700
Mean	**0.552**	**0.882**	**0.693**	**0.591**	**0.919**	**0.730**	**0.623**	**0.846**	**0.718**	**0.661**	**0.838**	**0.736**

Table 10. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using TACT® slices generated from different angular disparities (Ang. Disp.) of basis images.

	TACT® Experimental Condition											
	10° Ang. Disp.			**20° Ang. Disp.**			**30° Ang. Disp.**			**40° Ang. Disp.**		
Obs	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.719	0.708	0.713	0.844	0.583	0.688	0.656	0.708	0.688	0.625	0.813	0.738
2	0.375	0.958	0.725	0.594	0.958	0.813	0.469	0.854	0.700	0.469	0.938	0.750
3	0.625	0.792	0.725	0.563	0.896	0.763	0.469	0.875	0.713	0.531	0.729	0.650
4	0.750	0.813	0.786	0.625	0.938	0.813	0.656	0.854	0.775	0.563	0.875	0.750
5	0.500	0.958	0.775	0.656	0.896	0.800	0.500	0.896	0.738	0.625	0.917	0.800
6	0.594	0.896	0.775	0.438	0.917	0.725	0.344	1.000	0.738	0.594	0.896	0.775
7	0.750	0.708	0.725	0.656	0.875	0.788	0.656	0.729	0.700	0.594	0.750	0.688
8	0.531	0.958	0.788	0.531	0.938	0.775	0.625	0.896	0.788	0.500	0.875	0.725
Mean	**0.606**	**0.849**	**0.752**	**0.613**	**0.875**	**0.771**	**0.547**	**0.852**	**0.730**	**0.563**	**0.849**	**0.735**

Table 11 shows inter-observer intra-class correlation coefficients for each angular disparity tested. Angular disparities of 10° and 20° tied for highest agreement between observers, while the 30° disparity provided the lowest.

Table 11. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® modalities reconstructed from different angular disparities (Ang. Disp.) of basis images.

	TACT® Experimental Condition			
	10° Ang. Disp.	**20° Ang. Disp.**	**30° Ang. Disp.**	**40° Ang. Disp.**
mean square surface	10.2539	10.1789	9.3825	9.4849
mean square error	1.0147	0.9813	1.1310	1.0409
Inter-observer ICC*	**0.57**	**0.57**	**0.51**	**0.54**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

Phase III (Effect of the number of basis images on caries detection using tuned aperture computed tomography [TACT®] slices)

In the detection of occlusal caries (Table 12, Fig. 15), the mean areas under the ROC curves (A_z values) for the four TACT® conditions generated from different numbers of basis images (bi) were 0.730 (2 bi), 0.787 (4 bi), 0.807 (8 bi), and 0.869 (12 bi). Six observers achieved their best performance when using TACT® slices reconstructed from twelve basis images. Slices reconstructed from four and eight basis images were responsible for the best performance of one observer each. ANOVA (Table 13a) proved statistically significant differences both between modalities (p= 0.006) and between observers (p= 0.011). Tukey's post hoc test revealed that TACT® slices reconstructed from twelve basis images provided a significantly better performance than slices reconstructed from two basis images (Table 13b).

Table 12. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from 2, 4, 8, and 12 basis images (bi), respectively.

TACT® Experimental Condition

	2 bi		4 bi		8 bi		12 bi	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.541	0.099	0.675	0.092	0.826	0.074	0.947	0.036
2	0.745	0.087	0.831	0.070	0.763	0.084	0.757	0.081
3	0.777	0.075	0.860	0.066	0.806	0.105	0.864	0.060
4	0.596	0.093	0.671	0.117	0.729	0.087	0.669	0.087
5	0.798	0.085	0.796	0.090	0.868	0.101	0.921	0.050
6	0.885	0.079	0.804	0.090	0.841	0.070	0.919	0.058
7	0.690	0.087	0.854	0.062	0.864	0.060	0.952	0.033
8	0.806	0.074	0.805	0.071	0.762	0.077	0.921	0.049
Mean	**0.730**	0.085	**0.787**	0.082	**0.807**	0.082	**0.869**	0.057

Figure 15. Mean ROC curves for the TACT® image slices reconstructed from different number of basis images in the detection of **OCCLUSAL** caries.

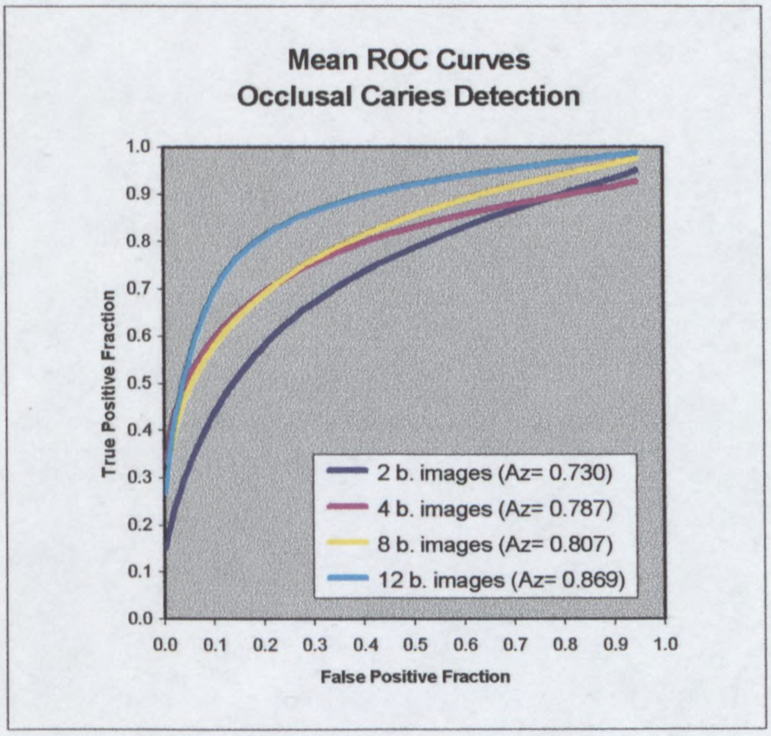


Table 13a. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase III.*

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.121	7	0.017	3.559	0.011
Exp. Cond.	0.079	3	0.026	5.443	0.006
Error	0.102	21	0.005		

Dependent variable: Occlusal A_z; N: 32; Multiple R: 0.814; Squared multiple R: 0.663.

Tables 13b. Tukey's Post-Hoc test: **occlusal** caries detection – *Phase III.*

Matrix of pairwise mean differences*/comparison probabilities**

	2 bi	4 bi	8 bi	12 bi
2 bi	0.000/1.000			
4 bi	0.057/0.377	0.000/1.000		
8 bi	0.078/0.148	0.020/0.935	0.000/1.000	
12 bi	0.139/0.003	0.082/0.118	0.061/0.316	0.000/1.000

* Post-Hoc test of Occlusal A_z using model MSE of 0.005 with 21 DF; effect: experimental condition.
** Post-Hoc test of Occlusal A_z; Tukey HSD multiple comparisons; effect: experimental condition.

In the detection of proximal caries (Table 14, Fig. 16), the mean areas under the ROC curves (A_z values) for the four modalities were 0.766 (2 bi), 0.764 (4 bi), 0.806 (8 bi), and 0.834 (12 bi), respectively. Slices generated from twelve basis images provided the best performance to five observers. Two observers performed best with slices generated from eight basis images, and one with two basis images. ANOVA (Table 15a) showed a statistically significant difference both between experimental conditions varying the number of basis images ($p = 0.005$) and between observers ($p < 0.001$). Tukey's post hoc test showed that TACT® slices reconstructed from twelve basis images provided performance significantly better than slices reconstructed from both two and four basis images (Table 15b).

Table 14. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using TACT® slices reconstructed from 2, 4, 8, and 12 basis images (bi), respectively.

TACT® Experimental Condition

	2 bi		4 bi		8 bi		12 bi	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.774	0.069	0.792	0.059	0.830	0.050	0.876	0.043
2	0.788	0.057	0.833	0.049	0.857	0.048	0.868	0.050
3	0.726	0.067	0.678	0.066	0.796	0.057	0.774	0.073
4	0.661	0.066	0.708	0.076	0.706	0.072	0.770	0.064
5	0.785	0.063	0.871	0.044	0.791	0.068	0.894	0.044
6	0.792	0.092	0.710	0.081	0.759	0.087	0.770	0.066
7	0.852	0.050	0.798	0.054	0.894	0.041	0.821	0.052
8	0.749	0.080	0.723	0.086	0.816	0.063	0.898	0.040
Mean	**0.766**	0.068	**0.764**	0.064	**0.806**	0.061	**0.834**	0.054

Figure 16. Mean ROC curves for the TACT® image slices reconstructed from different number of basis images in the detection of **PROXIMAL** caries.

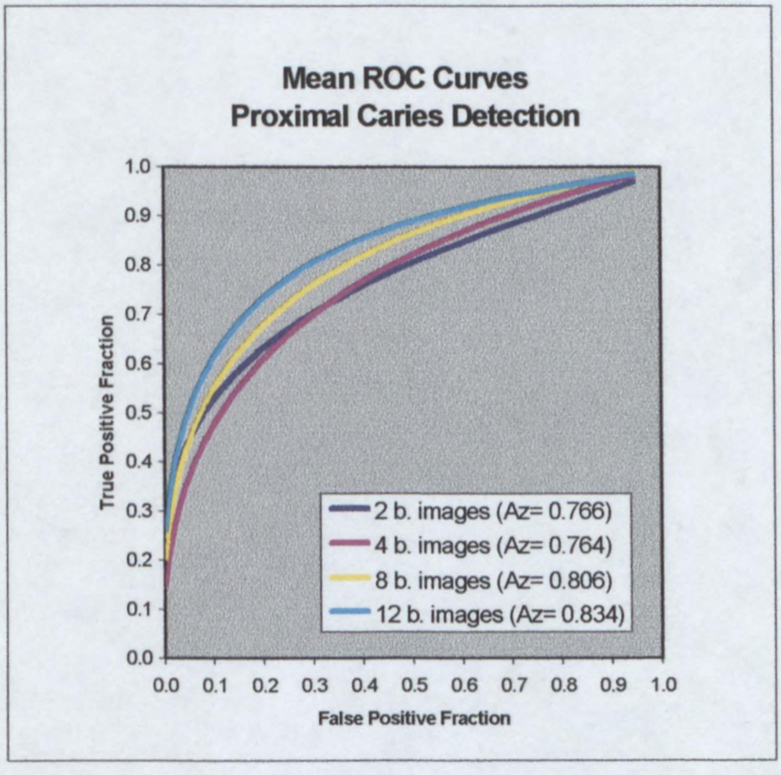


Table 15a. Analysis of variance (ANOVA): **proximal** caries detection – *Phase III.*

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.068	7	0.010	6.126	<0.001
Exp. Cond.	0.027	3	0.009	5.749	0.005
Error	0.033	21	0.002		

Dependent variable: Proximal A_z; N: 32; Multiple R: 0.861; Squared multiple R: 0.741

Table 15b. Tukey's Post-Hoc test: **proximal** caries detection – *Phase III.*

Matrix of pairwise mean differences*/comparison probabilities**				
	2 bi	**4 bi**	**8 bi**	**12 bi**
2 bi	0.000/1.000			
4 bi	-0.002/1.000	0.000/1.000		
8 bi	0.040/0.209	0.042/0.181	0.000/1.000	
12 bi	0.068/0.013	0.070/0.011	0.028/0.519	0.000/1.000

* Post-Hoc test of Proximal A_z using model MSE of 0.002 with 21 DF; effect: experimental condition.

** Post-Hoc test of Proximal A_z; Tukey HSD multiple comparisons; effect: experimental condition.

Sensitivity, specificity, and accuracy values for all combinations of observer and different numbers of basis images are shown in Table 16 (occlusal caries detection) and Table 17 (proximal caries detection). Mean indicators of performance again suggested improved diagnostic performance with increasing numbers of basis images. For the most part observers, irrespective of the experimental conditions applied to TACT®, were better in recognizing a sound surface than in detecting one that was decayed.

Table 16. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from 2, 4, 8, and 12 basis images (bi).

	TACT® Experimental Condition											
	2 bi			**4 bi**			**8 bi**			**12 bi**		
Obs	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.478	0.588	0.525	0.625	0.471	0.575	0.783	0.941	0.850	0.913	0.882	0.900
2	0.304	0.941	0.575	0.435	0.941	0.650	0.435	0.941	0.650	0.435	0.941	0.650
3	0.565	0.882	0.700	0.739	1.000	0.850	0.435	1.000	0.675	0.609	0.941	0.750
4	0.391	0.824	0.575	0.348	1.000	0.625	0.478	0.882	0.650	0.478	0.882	0.650
5	0.565	1.000	0.750	0.565	0.941	0.725	0.522	1.000	0.725	0.522	1.000	0.725
6	0.435	0.941	0.650	0.522	0.882	0.675	0.565	0.941	0.725	0.565	0.941	0.725
7	0.609	0.706	0.650	0.652	0.882	0.750	0.739	0.882	0.800	0.870	0.765	0.825
8	0.391	0.882	0.600	0.435	0.941	0.650	0.522	0.882	0.675	0.565	0.941	0.725
Mean	**0.467**	**0.846**	**0.628**	**0.540**	**0.882**	**0.688**	**0.560**	**0.934**	**0.719**	**0.620**	**0.912**	**0.744**

Table 17. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using TACT® slices reconstructed from 2, 4, 8, and 12 basis images (bi).

	TACT® Experimental Condition											
	2 bi			**4 bi**			**8 bi**			**12 bi**		
Obs	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.625	0.792	0.725	0.656	0.854	0.775	0.844	0.583	0.688	0.688	0.854	0.788
2	0.469	0.958	0.763	0.313	0.917	0.675	0.594	0.958	0.813	0.719	0.938	0.850
3	0.531	0.834	0.713	0.531	0.834	0.713	0.563	0.896	0.763	0.438	0.979	0.763
4	0.469	0.813	0.675	0.375	0.854	0.663	0.469	0.854	0.700	0.625	0.813	0.738
5	0.656	0.938	0.825	0.625	0.896	0.788	0.656	0.896	0.800	0.719	0.875	0.813
6	0.594	0.938	0.800	0.500	0.875	0.725	0.438	0.917	0.725	0.531	0.854	0.725
7	0.781	0.604	0.675	0.781	0.625	0.688	0.656	0.875	0.788	0.750	0.667	0.700
8	0.500	0.917	0.750	0.375	0.979	0.738	0.531	0.938	0.775	0.656	0.917	0.813
Mean	**0.578**	**0.849**	**0.741**	**0.520**	**0.854**	**0.721**	**0.594**	**0.865**	**0.757**	**0.641**	**0.862**	**0.774**

Inter-observer reliability assessed by intra-class correlation showed that the greater the number of basis images used for TACT® slice generation, the higher the agreement between observers when assessing the corresponding images (Table 18).

Table 18. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® image slices reconstructed from 2, 4, 8, and 12 basis images (bi).

	TACT® Experimental Condition			
	2 bi	**4 bi**	**8 bi**	**12 bi**
Mean square surface	10.3253	11.0651	11.4189	14.0815
Mean square error	1.2295	1.1180	1.0186	0.9266
Inter-observer ICC*	**0.48**	**0.53**	**0.56**	**0.64**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

Phase IV (Generation of tuned aperture computed tomography [TACT®] slices using linear and circular arrays of projections: effects on caries detection)

For the task of occlusal caries detection (Table 19, Fig. 17), mean areas under the ROC curves (A_z values) for the TACT® image slices generated from different x-ray beam arrays for basis projections were, respectively, 0.769 (linear-HZ), 0.820 (linear-VT), and 0.807 (circular). Six observers achieved their best performance when using slices generated from the linear array of x-ray beam projections in the vertical direction. One observer each performed better when using slices generated from the linear array of x-ray beam projections in the horizontal direction and the circular x-ray beam array, respectively. ANOVA (Table 20a) indicated that differences between the x-ray beam projection arrays tested were not statistically significant ($p = 0.065$); however, Tukey's post hoc test revealed a trend for the linear array in the vertical direction to be better than the linear array in the horizontal direction (Table 20b) for the task of primary dental caries detection. A statistically significant difference between observers was also proven ($p = 0.009$).

Table 19. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from two linear x-ray beam arrays of basis projections, one horizontal (HZ) and one vertical (VT), and from one circular x-ray beam array.

	TACT® Experimental Condition					
	Linear – HZ		**Linear - VT**		**Circular**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.773	0.078	0.844	0.073	0.826	0.074
2	0.712	0.085	0.835	0.074	0.763	0.084
3	0.820	0.069	0.838	0.068	0.806	0.105
4	0.714	0.087	0.751	0.079	0.729	0.087
5	0.784	0.084	0.897	0.063	0.868	0.101
6	0.693	0.113	0.706	0.107	0.841	0.070
7	0.889	0.056	0.863	0.063	0.864	0.060
8	0.767	0.078	0.823	0.068	0.762	0.077
Mean	**0.769**	0.081	**0.820**	0.074	**0.807**	0.082

Figure 17. Mean ROC curves for the TACT® image slices reconstructed from different x-ray beam projection arrays in the detection of **OCCLUSAL** caries.

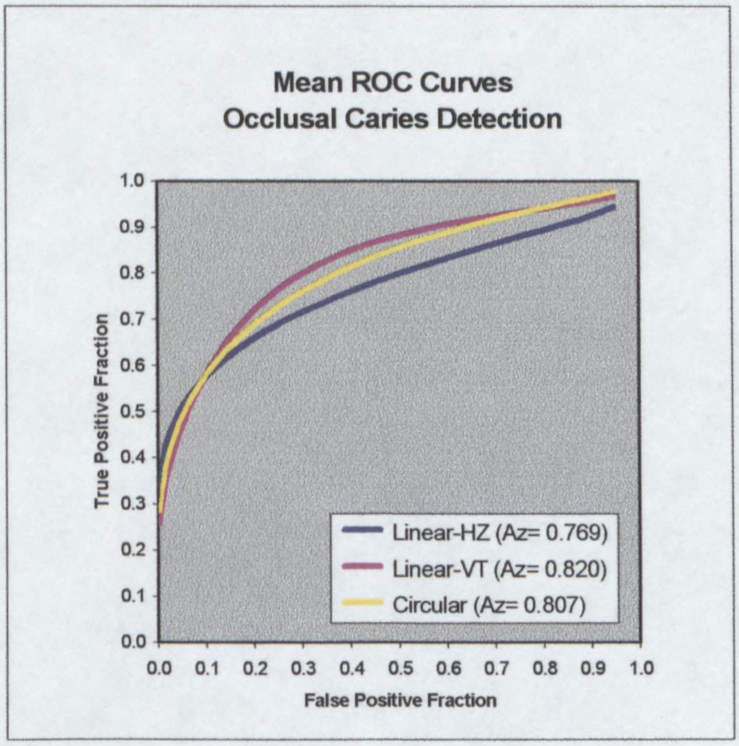


Table 20a. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase IV.*

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.051	7	0.007	4.376	0.009
Exp. Cond.	0.011	2	0.006	3.350	0.065
Error	0.023	14	0.002		

Dependent variable: Occlusal A_z; N: 24; Multiple R: 0.853; Squared multiple R: 0.727.

Tables 20b. Tukey's Post-Hoc test: **occlusal** caries detection – *Phase IV.*

Matrix of pairwise mean differences*/comparison probabilities**

	Linear - HZ	Linear – VT	Circular
Linear – HZ	0.000/1.000		
Linear – VT	0.051/0.064	0.000/1.000	
Circular	0.038/0.180	-0.012/0.824	0.000/1.000

* Post-Hoc test of Occlusal A_z using model MSE of 0.002 with 14 DF; effect: experimental condition.
** Post-Hoc test of Occlusal A_z; Tukey HSD multiple comparisons; effect: experimental condition.

For proximal caries detection (Table 21, Fig. 18), mean areas under the ROC curves (A_z values), for the various TACT® x-ray beam arrays were 0.789 (linear-HZ), 0.828 (linear-VT), and 0.806 (circular) respectively. Three observers achieved their best performance when using slices generated from the linear x-ray beam projection array in the horizontal direction and two in the vertical direction. The remaining three observers performed better when using slices generated from the circular array. ANOVA (Table 22) proved no statistically significant differences either between the x-ray beam arrays used to generate the sets of TACT® images (p= 0.515) or between observers (p= 0.577).

Table 21. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using TACT® slices reconstructed from two linear arrays of basis projections, one horizontal (HZ) and one vertical (VT), and from one circular array.

	TACT® Experimental Condition					
	Linear – HZ		**Linear – VT**		**Circular**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.855	0.053	0.846	0.057	0.830	0.050
2	0.807	0.053	0.856	0.045	0.857	0.048
3	0.648	0.078	0.785	0.062	0.796	0.057
4	0.821	0.053	0.832	0.053	0.706	0.072
5	0.857	0.044	0.838	0.062	0.791	0.068
6	0.713	0.083	0.889	0.042	0.759	0.087
7	0.745	0.069	0.862	0.048	0.894	0.041
8	0.865	0.047	0.716	0.076	0.816	0.063
Mean	**0.789**	0.060	**0.828**	0.056	**0.806**	0.061

Figure 18. Mean ROC curves for the TACT® image slices reconstructed from different arrays of projections in the detection of **PROXIMAL** caries.

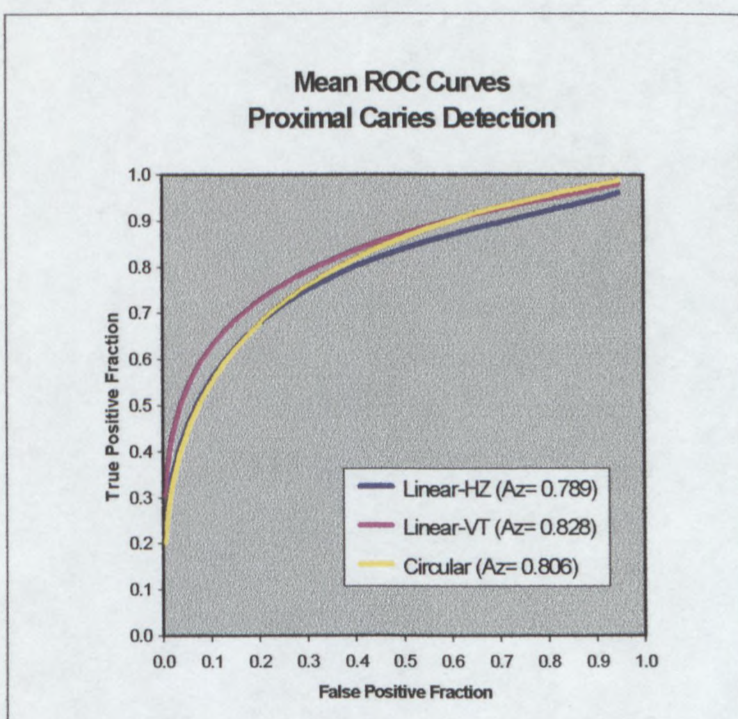


Table 22. Analysis of variance (ANOVA): **proximal** caries detection – *Phase IV*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.026	7	0.004	0.834	0.577
Exp. Cond.	0.006	2	0.003	0.697	0.515
Error	0.062	14	0.004		

Dependent variable: Proximal A_z; N: 24; Multiple R: 0.584; Squared multiple R: 0.341.

Sensitivity, specificity, and accuracy values for all combinations of observer and x-ray beam projection geometry are seen in Tables 23 and 24, for occlusal and proximal caries detection, respectively. TACT® slices generated from the vertical array usually provided the highest sensitivity but the lowest specificity in the detection of occlusal caries. In this task, mean overall accuracy was quite similar for the three modalities. For the detection of proximal lesions, all three indicators of mean performance were higher for the vertical array.

Table 23. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from two linear arrays of basis projections, one horizontal (HZ) and one vertical (VT), and from one circular array.

	TACT® Experimental Condition								
	Linear - HZ			**Linear - VT**			**Circular**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.739	0.647	0.700	0.913	0.529	0.750	0.783	0.941	0.850
2	0.391	0.824	0.575	0.435	0.882	0.625	0.435	0.941	0.650
3	0.565	0.941	0.725	0.696	1.000	0.825	0.435	1.000	0.675
4	0.391	1.000	0.650	0.522	0.882	0.675	0.478	0.882	0.650
5	0.696	0.941	0.800	0.609	0.941	0.750	0.522	1.000	0.725
6	0.478	0.882	0.650	0.609	0.882	0.725	0.565	0.941	0.725
7	0.783	0.882	0.825	0.609	0.824	0.700	0.739	0.882	0.800
8	0.478	0.941	0.675	0.609	0.824	0.700	0.522	0.882	0.675
Mean	**0.565**	**0.882**	**0.700**	**0.625**	**0.846**	**0.719**	**0.560**	**0.934**	**0.719**

Table 24. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using TACT® slices reconstructed from two linear arrays of basis projections, one horizontal (HZ) and one vertical (VT), and from one circular array.

	TACT® Experimental Condition								
	Linear - HZ			**Linear - VT**			**Circular**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.719	0.917	0.838	0.656	0.875	0.788	0.844	0.583	0.688
2	0.531	0.917	0.763	0.625	0.938	0.813	0.594	0.958	0.813
3	0.406	0.917	0.713	0.563	0.896	0.763	0.563	0.896	0.763
4	0.500	0.958	0.775	0.563	0.938	0.788	0.469	0.854	0.700
5	0.656	0.813	0.750	0.719	0.917	0.838	0.656	0.896	0.800
6	0.563	0.854	0.738	0.719	0.875	0.813	0.438	0.917	0.725
7	0.594	0.688	0.650	0.688	0.875	0.800	0.656	0.875	0.788
8	0.500	0.938	0.763	0.531	0.875	0.738	0.531	0.938	0.775
Mean	**0.559**	**0.875**	**0.749**	**0.633**	**0.899**	**0.793**	**0.594**	**0.865**	**0.757**

Agreement between observers was higher when they used TACT® slices generated from the vertical array to judge the tooth surfaces for the presence/absence of caries as compared to slices generated from the other two arrays (Table 25).

Table 25. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® image slices reconstructed from two linear arrays of basis projections, one horizontal (HZ) and one vertical (VT), and from one circular array.

	TACT® Experimental Condition		
	Linear - HZ	**Linear – VT**	**Circular**
Mean square surface	12.5440	15.0210	11.4189
Mean square error	1.0326	0.8304	1.0186
Inter-observer ICC*	**0.58**	**0.68**	**0.56**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

Phase V (Image acquisition for TACT® slice generation using unconstrained and stringent projection geometries: effects on caries detection)

Table 26 and figure 19 show the performance of observers in the detection of occlusal caries using TACT® slices reconstructed from an unconstrained and a stringent array of projection geometries. Mean ROC A_z values were nearly identical for TACT® slices reconstructed from unconstrained (0.809) and stringent (0.807) arrays of projection geometries. ANOVA (Table 27) did not show a statistically significant difference between modalities (p= 0.876), but did so between observers (p= 0.005).

Table 26. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from an unconstrained and a stringent array of projection geometries.

	TACT® Experimental Condition			
	Unconstrained TACT®		Stringent TACT®	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.816	0.085	0.826	0.074
2	0.843	0.066	0.763	0.084
3	0.805	0.071	0.806	0.105
4	0.684	0.089	0.729	0.087
5	0.850	0.073	0.868	0.101
6	0.848	0.071	0.841	0.070
7	0.859	0.060	0.864	0.060
8	0.770	0.079	0.762	0.077
Mean	**0.809**	0.074	**0.807**	0.082

Figure 19. Mean ROC curves for the TACT® image slices generated using unconstrained and stringent projection geometries in the detection of **OCCLUSAL** caries.

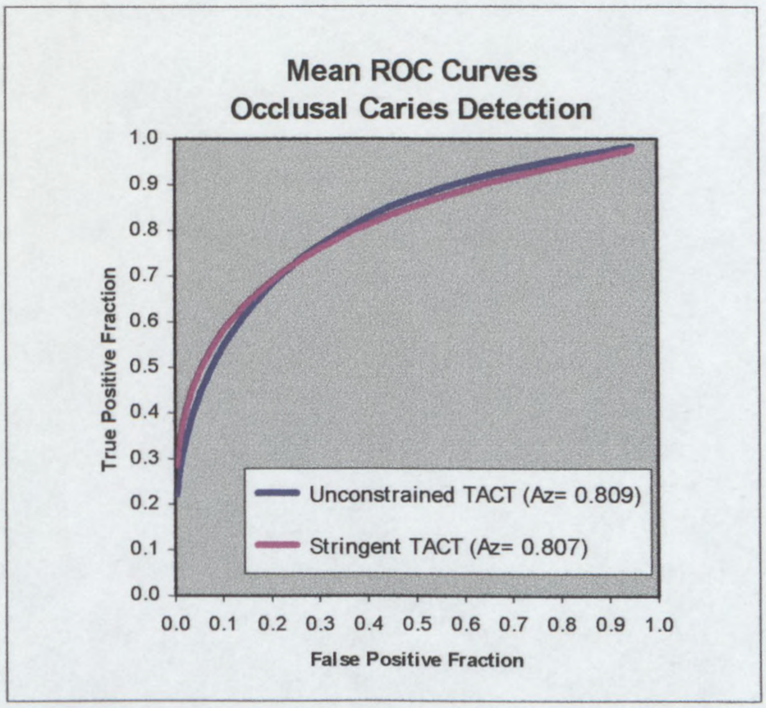


Table 27. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase V*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.038	7	0.005	8.651	0.005
Exp. Cond.	<0.001	1	<0.001	0.026	0.876
Error	0.004	7	<0.001		

Dependent variable: Occlusal A_z; N: 16; Multiple R: 0.947; Squared multiple R: 0.896.

Performance of observers in the detection of proximal caries can be seen in Table 28 and figure 20. Mean ROC A_z values were 0.755 for unconstrained TACT® and 0.806 for stringent TACT®. ANOVA (Table 29) did not detect significant differences either between modalities (p= 0.130) or between observers (p= 0.421).

Table 28. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using TACT® slices reconstructed from an unconstrained and a stringent array of projection geometries.

	TACT® Experimental Condition			
	Unconstrained TACT®		Stringent TACT®	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.746	0.070	0.830	0.050
2	0.756	0.060	0.857	0.048
3	0.759	0.059	0.796	0.057
4	0.720	0.071	0.706	0.072
5	0.628	0.085	0.791	0.068
6	0.841	0.050	0.759	0.087
7	0.758	0.058	0.894	0.041
8	0.832	0.053	0.816	0.063
Mean	**0.755**	0.063	**0.806**	0.061

Figure 20. Mean ROC curves for the TACT® image slices generated using unconstrained and stringent projection geometries in the detection of **PROXIMAL** caries.

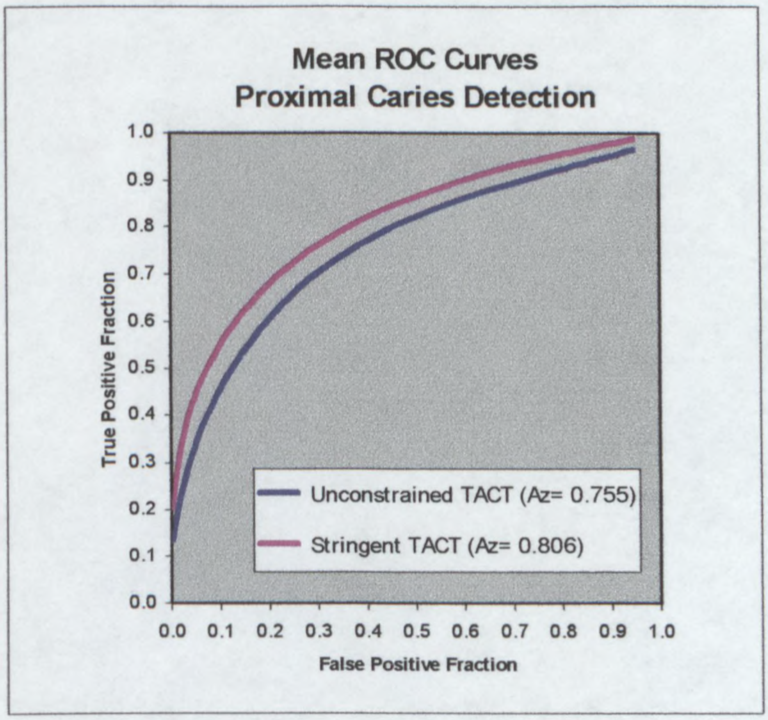


Table 29. Analysis of variance (ANOVA): **proximal** caries detection – *Phase V*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.029	7	0.004	1.170	0.421
Exp. Cond.	0.011	1	0.011	2.945	0.130
Error	0.025	7	0.004		

Dependent variable: Proximal A_z; N: 16; Multiple R: 0.784; Squared multiple R: 0.614.

Sensitivity, specificity, and accuracy values are shown in Table 30 for occlusal, and Table 31 for proximal caries detection. In general, the unconstrained method was better at detecting an occlusal lesion while the stringent method was better at recognizing a sound occlusal surface. In the assessment of proximal surfaces, however, this trend was reversed. Mean overall accuracy values were highest for unconstrained TACT® in occlusal caries detection, but highest for stringent TACT® in proximal caries detection.

Table 30. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using TACT® slices reconstructed from two arrays of projection geometries, one unconstrained and the other stringent.

	TACT® Experimental Condition					
	Unconstrained TACT®			**Stringent TACT®**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.826	0.706	0.775	0.783	0.941	0.850
2	0.478	0.882	0.650	0.435	0.941	0.650
3	0.739	0.765	0.750	0.435	1.000	0.675
4	0.348	1.000	0.625	0.478	0.882	0.650
5	0.652	0.941	0.775	0.522	1.000	0.725
6	0.522	1.000	0.725	0.565	0.941	0.725
7	0.826	0.765	0.800	0.739	0.882	0.800
8	0.739	0.824	0.775	0.522	0.882	0.675
Mean	**0.641**	**0.860**	**0.734**	**0.560**	**0.934**	**0.719**

Table 31. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using TACT® slices reconstructed from two arrays of projection geometries, one unconstrained and the other stringent.

	TACT® Experimental Condition					
	Unconstrained TACT®			**Stringent TACT®**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.563	0.833	0.725	0.844	0.583	0.688
2	0.375	0.938	0.713	0.594	0.958	0.813
3	0.438	0.875	0.700	0.563	0.896	0.763
4	0.438	0.958	0.750	0.469	0.854	0.700
5	0.406	0.875	0.688	0.656	0.896	0.800
6	0.469	0.917	0.738	0.438	0.917	0.725
7	0.594	0.750	0.688	0.656	0.875	0.788
8	0.438	0.917	0.725	0.531	0.938	0.775
Mean	**0.465**	**0.883**	**0.716**	**0.594**	**0.865**	**0.757**

Intra-class correlation indicated that unconstrained and stringent TACT® yielded comparable agreement when assessments of the same tooth surface by multiple observers were compared (table 32).

Table 32. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® image slices reconstructed from two arrays of projection geometries, one unconstrained and the other stringent.

	TACT® Experimental Condition	
	Unconstrained TACT®	**Stringent TACT®**
mean square surface	11.9008	11.4189
mean square error	0.9737	1.0186
Inter-observer ICC*	**0.58**	**0.56**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

Phase VI (The effect of the method of reconstruction of TACT® slices – minimum vs. average – on caries detection)

For the detection of occlusal lesions, individual and mean performances of observers using TACT® slices reconstructed using the minimum and average reconstruction methods are shown in Table 33 and figure 21. Six observers performed best when they used TACT® slices reconstructed via the minimum method while the remaining two observers obtained their best performance with slices reconstructed via the average method. Mean A_z values were 0.849 for the minimum method and 0.807 for the average method. ANOVA (Table 34), however, failed to prove statistical significance (p= 0.070). Similarly, no statistically significant difference between observers was detected (p= 0.057).

Table 33. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using TACT® slices generated by the minimum and average reconstruction methods.

	TACT® Experimental Condition			
	TACT® – Minimum method		TACT® – Average method	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.878	0.064	0.826	0.074
2	0.895	0.071	0.763	0.084
3	0.799	0.072	0.806	0.105
4	0.747	0.084	0.729	0.087
5	0.819	0.088	0.868	0.101
6	0.920	0.060	0.841	0.070
7	0.934	0.040	0.864	0.060
8	0.803	0.083	0.762	0.077
Mean	**0.849**	0.070	**0.807**	0.082

Figure 21 Mean ROC curves for the TACT® image slices generated using the *minimum* and *average* reconstruction methods in the detection of **OCCLUSAL** caries.

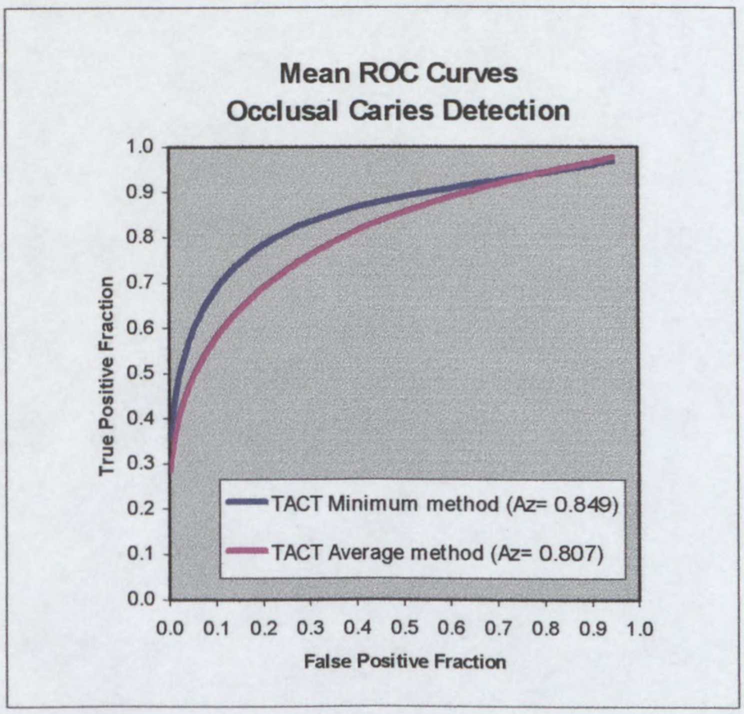


Table 34. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase VI*.

Source	sum of squares	df	mean square	f-ratio	P
Observer	0.039	7	0.006	3.588	0.057
Exp. Cond.	0.007	1	0.007	4.578	0.070
Error	0.011	7	0.002		

Dependent variable: Occlusal A_z; N: 16; Multiple R: 0.900; Squared multiple R: 0.809.

Individual and mean performances of observers using minimum and average TACT® reconstruction methods for the detection of proximal lesions are shown in Table 35 and figure 22. Three observers performed best with the minimum method, four with the average method, and one observer had identical performances with the two methods. Mean A_z values were 0.790 for the minimum method and 0.806 for the average method. ANOVA (Table 36) showed that this difference was not statistically significant (p= 0.518). No statistically significant difference between observers was detected as well (p= 0.559).

Table 35. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using TACT® slices generated by the minimum and average reconstruction methods.

	TACT® Experimental Condition			
	TACT® – Minimum method		**TACT® – Average method**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.784	0.056	0.830	0.050
2	0.802	0.055	0.857	0.048
3	0.736	0.067	0.796	0.057
4	0.777	0.056	0.706	0.072
5	0.793	0.062	0.791	0.068
6	0.836	0.054	0.759	0.087
7	0.776	0.058	0.894	0.041
8	0.816	0.054	0.816	0.063
Mean	**0.790**	0.058	**0.806**	0.061

Figure 22. Mean ROC curves for the TACT® image slices generated using the *minimum* and *average* reconstruction methods in the detection of **PROXIMAL** caries.

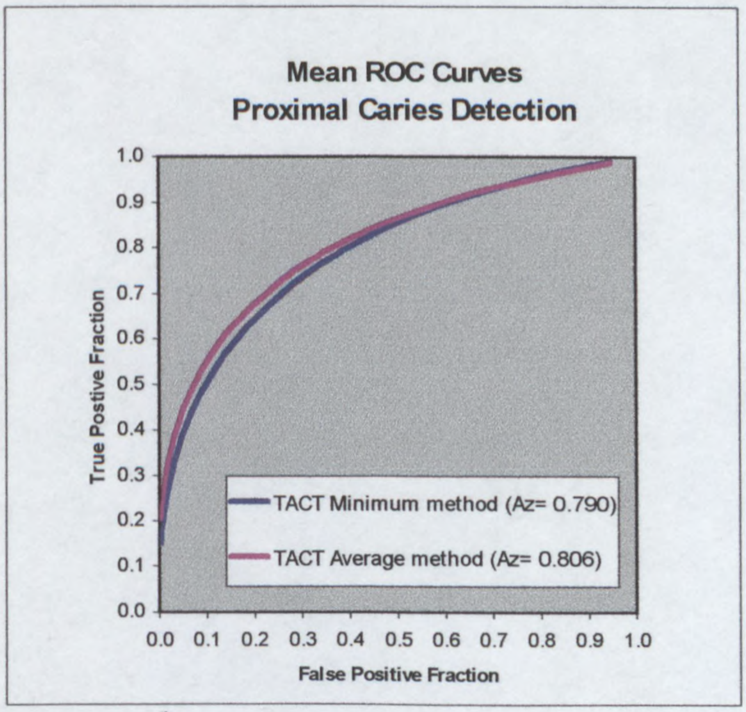


Table 36. Analysis of variance (ANOVA): **proximal** caries detection – *Phase VI*.

Source	sum of squares	df	mean square	f-ratio	P
Observer	0.014	7	0.002	0.889	0.559
Exp. Cond.	0.001	1	0.001	0.464	0.518
Error	0.016	7	0.002		

Dependent variable: Proximal A_z; N: 16; Multiple R: 0.699; Squared multiple R: 0.489.

Sensitivity, specificity, and accuracy values calculated for all combinations of observer and reconstruction methods are shown in Table 37 (occlusal caries detection) and Table 38 (proximal caries detection). Observers were generally better at recognizing a sound surface than at detecting a carious one. Mean sensitivities were higher for the average method in both detection tasks. Mean specificity was higher for the average method in the detection of proximal lesions, but lower in the detection of occlusal lesions. Differences in overall accuracy values were, however, small between the two modalities.

Table 37. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using TACT® slices generated by the minimum and average reconstruction methods.

	TACT® Experimental Condition					
	TACT® – Minimum method			TACT® – Average method		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.696	0.941	0.800	0.783	0.941	0.850
2	0.391	0.941	0.625	0.435	0.941	0.650
3	0.652	0.882	0.750	0.435	1.000	0.675
4	0.304	1.000	0.600	0.478	0.882	0.650
5	0.652	1.000	0.800	0.522	1.000	0.725
6	0.348	1.000	0.625	0.565	0.941	0.725
7	0.783	0.941	0.850	0.739	0.882	0.800
8	0.478	1.000	0.700	0.522	0.882	0.675
Mean	**0.538**	**0.963**	**0.719**	**0.560**	**0.934**	**0.719**

Table 38. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using TACT® slices generated by the minimum and average reconstruction methods.

	TACT® Experimental Condition					
	TACT® – Minimum method			**TACT® – Average method**		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.656	0.813	0.750	0.844	0.583	0.688
2	0.438	0.896	0.713	0.594	0.958	0.813
3	0.375	0.875	0.675	0.563	0.896	0.763
4	0.375	0.958	0.725	0.469	0.854	0.700
5	0.688	0.875	0.800	0.656	0.896	0.800
6	0.438	0.938	0.738	0.438	0.917	0.725
7	0.688	0.583	0.625	0.656	0.875	0.788
8	0.594	0.854	0.750	0.531	0.938	0.775
Mean	**0.532**	**0.849**	**0.722**	**0.594**	**0.865**	**0.757**

Intra-class correlation (Table 39) demonstrated that the minimum and the average methods produced a similar agreement between observers when their assessments of the same tooth surfaces were compared.

Table 39. Intra-class correlation (ICC) used to assess inter-observer reliability for TACT® slices generated by the minimum and average reconstruction methods.

	TACT® Experimental Condition	
	TACT® – Minimum method	**TACT® – Average method**
Mean square surface	10.7647	11.4189
Mean square error	0.9060	1.0186
Inter-observer ICC*	**0.58**	**0.56**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

Phase VII (Comparison of single frame digital radiography and tuned aperture computed tomography [TACT®] in caries detection)

For the detection of occlusal caries, individual and mean performances of observers using conventional digital images and TACT® slices are shown in Table 40 and figure 23. Two observers performed best when viewing conventional digital images while six observers performed best with TACT® slices. Mean A_z values were 0.754 for digital images and 0.807 for TACT® slices. ANOVA (Table 41), however, failed to prove statistical significance (p= 0.067). Similarly, no statistically significant difference between observers was detected (p= 0.491).

Table 40. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **occlusal** caries using conventional digital images and TACT® slices.

	Image Modality			
	Digital Image		**TACT® Slices**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.701	0.086	0.826	0.074
2	0.745	0.083	0.763	0.084
3	0.841	0.068	0.806	0.105
4	0.703	0.090	0.729	0.087
5	0.732	0.103	0.868	0.101
6	0.754	0.221	0.841	0.070
7	0.759	0.095	0.864	0.060
8	0.799	0.091	0.762	0.077
Mean	**0.754**	0.104	**0.807**	0.082

Figure 23. Mean ROC curves for conventional digital image and TACT® slices in the detection of **OCCLUSAL** caries.

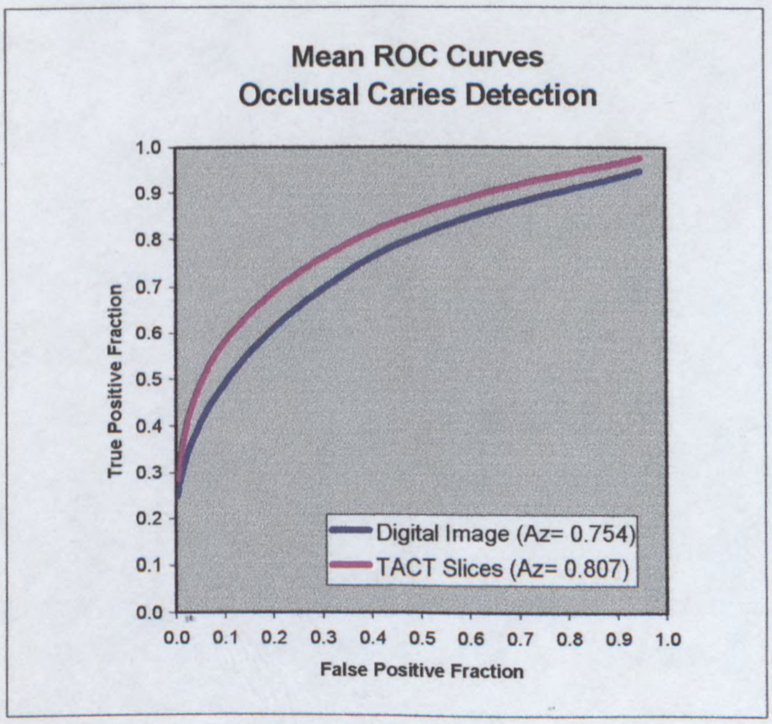


Table 41. Analysis of variance (ANOVA): **occlusal** caries detection – *Phase VII.*

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.017	7	0.002	1.018	0.491
Modality	0.011	1	0.011	4.694	0.067
Error	0.017	7	0.002		

Dependent variable: Occlusal A_z; N: 16; Multiple R: 0.793; Squared multiple R: 0.628.

Individual and mean performances of observers using the two modalities, TACT® and conventional "single frame" digital imaging, for the detection of proximal caries are shown in Table 42 and figure 24. Three observers performed best with TACT® slices, three with "single frame" digital images, and one observer had identical performances with the two methods. One observer failed to follow instructions regarding the assessment of proximal surfaces. Scores provided by this observer produced degenerate data during ROC analysis and were therefore excluded from consideration. Mean A_z values were 0.766 for "single frame" digital images and 0.806 for TACT® slices. ANOVA (table 43) showed no statistically significant difference between the two modalities (p= 0.306). No statistically significant difference between observers was proven (p= 0.632).

Table 42. Individual and mean areas under the ROC curves (A_z) for eight observers in the detection of **proximal** caries using conventional digital images and TACT® slices.

	Image Modality			
	Digital Image		**TACT® Slices**	
Observer	**ROC_Az**	(sd)	**ROC_Az**	(sd)
1	0.700	0.102	0.830	0.050
2	0.856	0.045	0.857	0.048
3	0.648	0.094	0.796	0.057
4	0.782	0.056	0.706	0.072
5	0.807	0.054	0.791	0.068
6	*	*	0.759	0.087
7	0.695	0.089	0.894	0.041
8	0.877	0.090	0.816	0.063
Mean	**0.766**	0.076	**0.806**	0.061

* Observer 6 failed to follow instructions regarding assessment of proximal surfaces and her scores were discarded.

Figure 24. Mean ROC curves for conventional digital image and TACT® slices in the detection of **PROXIMAL** caries.

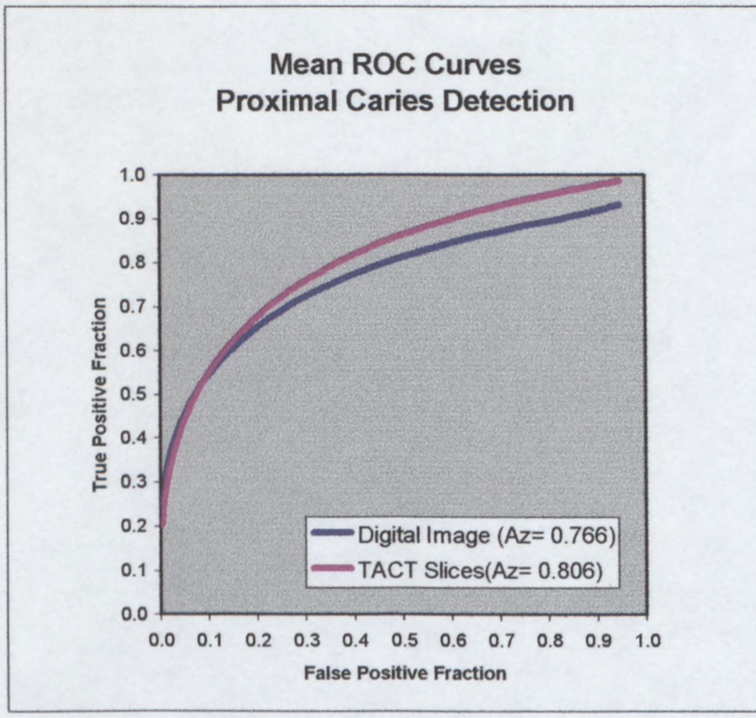


Table 43. Analysis of variance (ANOVA): **proximal** caries detection – *Phase VII*.

Source	sum of squares	df	mean square	f-ratio	p
Observer	0.033	7	0.005	0.772	0.632
Modality	0.008	1	0.008	1.251	0.306
Error	0.037	6	0.006		

Dependent variable: Proximal A_z; N: 16; Multiple R: 0.718; Squared multiple R: 0.515.

Sensitivity, specificity, and accuracy values calculated for all combinations of observer and TACT® versus conventional "single frame" digital imaging are shown in Tables 44 (occlusal caries detection) and Table 45 (proximal caries detection). Observers were generally better at recognizing a sound surface than at detecting one that was decayed. Mean sensitivities were higher for TACT® slices in both detection tasks. Mean specificity was slightly higher for TACT®

slices in the detection of occlusal lesions, but lower in the detection of proximal lesions. Overall accuracy was also higher for TACT® in the detection of both occlusal and proximal lesions.

Table 44. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **occlusal** caries using conventional digital images and TACT® slices.

	Image Modality					
	Digital Image			TACT® Slices		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.696	0.647	0.675	0.783	0.941	0.850
2	0.304	1.000	0.600	0.435	0.941	0.650
3	0.696	0.882	0.775	0.435	1.000	0.675
4	0.304	0.941	0.575	0.478	0.882	0.650
5	0.391	1.000	0.650	0.522	1.000	0.725
6	0.217	1.000	0.550	0.565	0.941	0.725
7	0.696	0.941	0.800	0.739	0.882	0.800
8	0.261	1.000	0.575	0.522	0.882	0.675
Mean	**0.446**	**0.926**	**0.650**	**0.560**	**0.934**	**0.719**

Table 45. Sensitivity (SS), specificity (SP), and accuracy (A) values obtained by eight observers in the detection of **proximal** caries using conventional digital images and TACT® slices.

	Image Modality					
	Digital Image			TACT® Slices		
Observer	**SS**	**SP**	**A**	**SS**	**SP**	**A**
1	0.500	0.938	0.763	0.844	0.583	0.688
2	0.438	0.938	0.738	0.594	0.958	0.813
3	0.652	0.979	0.775	0.563	0.896	0.763
4	0.344	0.938	0.700	0.469	0.854	0.700
5	0.531	0.896	0.700	0.656	0.896	0.800
6	0.156	1.000	0.663	0.438	0.917	0.725
7	0.469	0.854	0.663	0.656	0.875	0.788
8	0.313	1.000	0.700	0.531	0.938	0.775
Mean	**0.425**	**0.943**	**0.713**	**0.594**	**0.865**	**0.757**

Intra-class correlation (Table 46) demonstrated that conventional digital images yielded higher agreement between observers than TACT® slices.

Table 46. Intra-class correlation (ICC) used to assess inter-observer reliability for conventional digital image and TACT® modalities.

	Image Modality	
	Digital Image	**TACT® Slices**
mean square surface	10.2900	11.4189
mean square error	0.8290	1.0186
Inter-observer ICC*	**0.62**	**0.56**

* ICC coefficients derived from analysis of variance of the scores given by the eight observers to the same surfaces.

CHAPTER V

DISCUSSION

Effect of the number of iterative restorations on TACT® slices

One of the major limitations of imaging modalities such as tomosynthesis (including TACT®) and conventional tomography is the loss of detail and contrast from superimposition of multiple radiographic projection data.[11,39] However, in tomosynthetic and TACT® reconstructions the blurring of structures is not the smooth blurring typical of the continuous image acquisition used in tomography.[21] In *Phase I* of the present investigation, TACT® slices were reconstructed from eight basis or component images acquired using a hand-held x-ray source positioned at different projection angles. In this scenario, objects above or below the in-focus plane are displayed as eight separate objects on the reconstructed image. Each object has approximately one-eighth the contrast of the original object,[21] and will contribute to the blur observed in the in-focus plane. The main drawback inherent in the tomosynthetic method is the poor suppression of large object details, characterized by low frequency, located outside the plane of interest.[37] The larger the object detail, the more it tends to spill over into adjacent slices.[15] Radiographically, enamel and dentin are considered to be anatomic details of low frequency. To further aggravate the problem, shadows cast by these dental tissues are of high contrast, therefore exaggerating the influence of adjacent planes on the plane of interest. This is especially true if the projection angles of the basis images are not able to displace a detail to a distance greater than its own diameter - overlapping two thicknesses of enamel, for example.

Complete elimination of the undesired information from other tomosynthetic slices on the slice of interest, i.e., complete independence between slices, can only exist when thick structures are excluded from the image, such as with high-pass filtered images.[15,16] However, high-pass filters result in images of fewer gray levels and are perhaps more difficult to orientate for interpretation.[14] Iterative restoration, another method to alleviate the problem, preserves the original contrast of images and is the method available in the most current version of TACT® proprietary software. Therefore it was used in *Phase I*, and largely in the entire investigation.

Iterative restoration partially removes distracting blur associated with tomosynthetic slices producing images that have a better edge contrast.[13] This may make them better suited for applications such as detection of small lesions in calcified tissues.[16] The optimal number of iterations to be performed in each case depends on the task at hand and is routinely determined in an empirical manner. Slices submitted to increasing numbers of iterative restorations may be viewed as apparently sharper, because of cancellation of out-of-plane artifacts. However, a simultaneous increase in image noise is readily noticed. This high-frequency noise is a result of the amplification of the random noise and quantization artifacts present in the basis images.[15,37] In *Phase I*, three iterations were selected as the maximum number of repetitions because it has been suggested that for images of dental interest no further improvements of image quality could be attained after three or four iterations.[16]

One might expect that the use of slices submitted to increasing numbers of iterative restorations would yield a greater number of correct assessments of both disease presence and disease absence, and in consequence, a better overall diagnostic performance. The results of the present investigation, however, were not able to reject the null hypothesis that there is no statistically significant difference in observer performance in proximal caries detection between TACT® slices submitted to one, two, or three iterative restorations. Furthermore, mean sensitivity was highest when two iterations were used, mean specificity was highest when a single iteration was utilized, and all mean performance indexes were lowest when the maximum number of iterations tested in *Phase I* – three – was used. As suggested, it can be inferred that the simultaneous and antagonistic effects of removal of blur and build-up of noise are already felt after a single iteration procedure.

Because of the lack of a statistically significant difference, the small differences generally observed, which are not likely to be clinically meaningful, and the slightly higher inter-observer agreement provided by TACT® slices submitted to one and two iterations, it is logical to recommend that iterative deconvolution steps should not be repeated more than twice when caries detection is the task in question. This would be justified inasmuch as TACT® slice reconstruction procedures presently require relatively long periods of time. If time is a major constraint, even a single iteration could be used without anticipated loss of image quality. The extrapolation of these results to other common dental diagnostic tasks such as detection of periodontal defects or periapical lesions is not warranted. Each task should be tested separately.

Effect of the angular disparity of basis images on TACT® slices

The quality of TACT® slices depends on both the number and angular disparity of basis projections used in their generation. The major limitation of *Phase II* of this investigation was our inability to use a factorial design to test the interactions between these two factors on the detection of primary caries. With an average of 19 slices generated per tooth, the total number of slices viewed by an observer during the observation sessions was already high: 3040 (19 slices x 40 teeth x 4 modalities). If, for example, a factorial design testing four different numbers of basis images had been used, the corresponding figure would have been 12160 slices. This was considered impractical. Therefore, number of basis images was not included as a variable in *Phase II* of the investigation. Eight images were chosen because this is the number of images commonly used for general-purpose TACT® reconstructions, inasmuch as it seems to provide reasonable blur patterns when projections have reasonably small angular disparities.[9,11] In that respect, Groenhuis *et al* have suggested that a simultaneous increase in angular disparity and number of projections does not appear to add significantly to the diagnostic value of tomosynthesis.[36]

Angular disparities used in *Phase II* spanned a range from 10 to 40 degrees. The former angle was chosen as the lower limit because angles narrower than that would lead to the loss of the plane concept, and the slice would resemble an ordinary film with high contrast and resolution.[52] Forty degrees was used as the upper limit because it was the widest angle to allow the region of interest to be cast within the area of the receptor without cut-offs in any of the basis images. This was supported by the fact that there is no significant decrease in slice thickness for tomographic arcs in excess of 40 degrees.[53] Furthermore, projections used for tomosynthetic reconstruction must be rich in plane-related information, which is satisfied for projection data taken at angles around the normal to the plane of interest.[53] For the above reasons, it is legitimate to consider that the range of angles selected was appropriate, and that that range spans the angular disparities that are likely to be used in a clinical application of TACT®.

The theory underlying TACT® and tomosynthesis suggests that depth-discrimination accuracy is improved with wider angular disparities between basis projections because "thinner" slices are produced. Although *Phase II* of this investigation made use of a detection task as opposed to a localization task to compare different angular disparities, the better definition of depth expected by the use of wider angles did not improve the detection of primary caries. A possible explanation for the absence of improved diagnostic performance with increasing angular disparities is that contrast-dependent tasks such as caries detection do not benefit from "thinner" image slices. Caries morphology in posterior teeth is ellipso-conical. Individual slices sample only a portion of the long axis of the ellipse of demineralization. Like tomograms, the thinner the slice thickness the lower the contrast of the structures that will be displayed. Therefore, narrower slices may have actually discarded some of the signal present in the images that would be helpful for the task of caries detection.

The most important fact that should be kept in mind when considering the results of *Phase II* of the study may be that TACT® theory also supports that greater angular disparities should be accompanied by more basis projections to reduce quantization artifacts to an acceptable level.[7,11,16] Increasing the angular disparity progressively while keeping the number of basis images constant has probably produced images with corresponding increase in quantization artifacts. This, along with the potentially inferior contrast of thinner slices discussed earlier, may have counteracted the benefit of using wider angular disparities in the detection task assessed in this phase of the investigation.

Another possible explanation for the results obtained in *Phase II* is that TACT® is experienced as a dynamic viewing process: continuous tracking through the volume of interest (stack of slices) allows for a first degree differentiation of the focused structures, as these gradually come into and out of the focus.[54] As a result, contrast differences anywhere within the stack might be detected as a lesion. Small lesions might be better localized by a wide angular disparity but ultimately the lesion will be present in one or more central slices and absent in peripheral slices. This pattern of lesion appearance and disappearance as the observer paged through the stack was present in the entire range of angular disparities tested in *Phase II* of this study.

The results of *Phase II* show that varying the maximum angular disparity of eight basis projections from 10 to 40 degrees does not significantly affect observers' performance in primary caries detection using tuned aperture computed tomography. By the same token, it can be inferred that, when the latter number of images is used, TACT® offers the operator flexibility to select from such a range of angular disparities without running the risk of ending up with images of inferior quality. The results of the present study, those of Chai-U-Dom *et al*,[41] and several others,[7,24,36,53] suggest that small angular disparities may be used when caries is being assessed with TACT®.

Effect of the number of basis images on TACT® slices

As described earlier, to reconstruct a particular TACT® slice, basis or component images are translated with respect to each other and superimposed in a way that there is complete coincidence of the projection of structures lying in the desired tomosynthetic plane.[13] Basis images of structures lying in all planes other than the desired plane do not coincide exactly because successive images are slightly displaced due to the different amounts of translation they experience. This results in a depth-dependent blurring of those features in the summation image.[16] If the number of component images is N, for example, the amplitude of each in the summation image will be 1/Nth of that for a detail in the tomographic plane.[52] The higher the number of basis images the better the blurring effect.[55] This need for "diluting" the blur is well known to earlier explorers of tomosynthetic methods such as Richards,[8] who used conventional film images rather than digital images to generate image slices of an object. Accordingly, he felt that when the procedure was used with more than two films, each film bore a smaller fraction of the total image so that when the films were superimposed for viewing the out-of-focus images became less apparent to the eye.

Phase III shows that increasing numbers of basis images appear to lead to improved diagnostic performances in caries detection. This may be attributed to a few factors, one of them discussed above: with more basis images to distribute the blur more evenly, TACT® slices generated from eight or twelve images probably produce sharper depictions of each successive plane in focus and experience less influence from out-of-plane object details. A closely related phenomenon is that proportionally fewer quantization artifacts are present in those slices as compared to slices generated using fewer basis images.

One might argue that results of *Phase III* were purely caused by differences in the signal-to-noise ratio (SNR) provided by the different number of basis images. Legitimately, the SNR of the reconstruction is enhanced, for small angular disparities, by the square root of the number of exposures.[32] As a consequence, slices generated from twelve basis images had approximately 2.45, 1.73, and 1.23 times more signal than those generated using two, four and eight basis images, respectively. However, not only SNR but also the contrast of objects involved in the diagnostic task needs to be considered as an influential factor. This may help explain the discrepancy between the results of our study, which used a detection task, and those of Yamamoto *et al*,[40,43] which used a task requiring depth discrimination. Since they used objects of a known shape (spherical) that were either very radiopaque or relatively large, making their identification easier, their task probably required low signal-to-noise ratios. They recognized the latter as being the reason why it was possible to discriminate depth using TACT® slices generated from as few as two basis images.

In caries detection tasks, although the location of both occlusal and proximal lesions can be easily predicted, their specific size and shape cannot. More importantly, carious lesions, especially small ones, usually represent low contrast areas relative to their enamel or dentin surroundings. Perhaps the differential attenuation between the structure of interest and its surroundings is the most important physical factor that determines the ability to visualize structures in a conventional radiograph.[10] This is likely to be the case with TACT® slices as well. Correspondingly, it has been suggested that in laminagraphy the quality of the laminagram also depends on the contrasts in the subjects radiographed.[9] Furthermore, the more radiopaque that a feature is, the greater the number of radiographs and the greater the slice separation required to reduce this feature to inconspicuousness. Although angular disparity was not altered in *Phase III* (which would produce "thinner" or "thicker" slices), it can be said that the task of assessing caries (radiolucencies in radiopaque dental structures) appears to have required enhanced signal-to-noise ratios and that it has benefited from increasing numbers of basis images according to theory.

One of the main attractions of tomosynthetic imaging is the possibility of acquiring multiple samples of the object of interest from different angles. By so doing, TACT® reconstructions contain data derived from a much broader distribution of diagnostic alternatives than conventional transmission radiographs. It is likely that some of the projections are better oriented for acquisition of diagnostically important information than others.[32] In this respect, increasing numbers of basis images provided a greater chance for tooth surfaces, either carious or sound, to be depicted accurately.

In *Phase III*, TACT® slices were generated using a range from two to twelve basis images. By definition, the minimum number of basis images that can be used to produce TACT® slices is two. A decision had to be made regarding the spatial distribution of this pair of images. In a pilot study prior to this investigation, images reconstructed from two basis images varying in horizontal angulation by 20 degrees (i.e., the angular disparity used in that phase of the study) produced slices of evident low image quality. Therefore this option was discarded and the vertical distribution of the two basis images was adopted. Furthermore, vertical sampling of an open contact is likely to provide more information about proximal surfaces than is horizontal sampling where none of the basis images open the interproximal contact. Twelve images were chosen as the upper limit because it was assumed that this figure is close to the limits of practicality for a relatively simple task such as caries detection. At least one study has explicitly recognized that the work required to take a large number of images (sixteen in that particular case) and reconstruct them is very intensive.[24]

The results of *Phase III* suggest that increasing numbers of basis or component images provide improved diagnostic performance in caries detection using TACT®. At least eight basis images should be used for this task. Even greater numbers of images may be used, but issues regarding radiation dosages and the practicality of the procedure also need to be considered, at least until an automated device has become available in the market.

Linear and circular arrays of projections for TACT® slice generation

When contemplating TACT® image slice generation, it can be assumed that the registration process of basis images works properly irrespective of the array of projections used. However, images produced from different geometric arrays are obviously not identical because they cast the shadow of the object of interest in slightly different ways. Accordingly, the quality of the reconstructed slices depends, among other factors, on the quality of the acquired projections, not only in terms of their image characteristics,[9,53] but also in terms of the amount of diagnostically important information they contain.[32]

The different sampling geometries tested in *Phase IV* of the present investigation yielded images for registration containing anatomical superimposition in different amounts and orientations. The amount of overlap between proximal surfaces was greatest with the linear horizontal array, intermediate with the circular array, and least or nonexistent with the linear vertical array. In conventional bitewing radiographs the visibility of proximal surface carious lesions is maximized when the contacts between neighboring teeth are open.[48] Also, conspicuity of the lesion is optimized when the x-ray geometry parallels the long axis of the demineralized region. In the case of TACT® slices, although the reconstruction procedure permits visualization of an open contact, by no means is it able to retrospectively improve the quality of previously acquired basis images. In this context, the output information provided by the reconstructed slices is proportional to the input information provided by the acquired basis projections. For occlusal surfaces, a similar decrease in the amount of overlap from horizontal to circular to vertical arrays may be envisioned if it is considered that the bulk of the crown structure was superimposed in all projections acquired horizontally. In the latter situation, the overlap of sound dense enamel over potentially carious tissue may have typically prevented an optimal depiction of the occlusal surfaces. Conversely, projections distributed vertically or circularly may have "viewed" occlusal surfaces from different and more useful perspectives.

Different sampling geometries produce images with differences in absorption unsharpness. Absorption unsharpness is a type of unsharpness that arises from the gradual change in x-ray absorption across the boundary or edge of an object,[56] especially if this object has rounded contours like a dental crown. For proximal surfaces, for example, the linear vertical x-ray beam array provided, in the horizontal direction, a single pattern of absorption unsharpness. In contrast, the linear horizontal x-ray beam array produced images all of which contained different amounts of absorption unsharpness in the horizontal direction. In the registration and final generation of TACT® slices this may have represented a smearing of the image of the proximal surfaces, with concurrent loss of contrast. In this regard, it is known that the diagnostic potential (of bitewing radiographs) is maximized when contrast registered within the image of the enamel is maximized.[57] However, it can be argued that the net effect of differences in absorption unsharpness was similar for all three arrays of projections used in *Phase IV* of this study. The above-mentioned smearing of the image of tooth edges may have been present, likewise, in slices reconstructed from all these arrays, varying only in their direction and in their relative amount.

In *Phase IV*, total angular disparities used in association with the linear and circular x-ray beam arrays were not identical (i.e., 20° for the circular array and 40° for both linear horizontal and linear vertical arrays). This was not considered to be a problem since in *Phase II* of this investigation it was found that differences in the angular disparity of basis images between 10° and 40° were not statistically significant for caries detection using TACT®. Moreover, only the most extreme projections of the linear arrays bore an angular disparity of 40°. Angular disparities between any other two images were smaller. If a mean angular disparity could be derived from the angles used for each pair of corresponding projections of the linear arrays, from the outside to the inside (Fig. 5a and 5b), it would be approximately 25° for both linear arrays. This "mean" angular disparity of the linear arrays does not differ appreciably from the 20° disparity used for the circular array.

Despite the potential factors that might have contributed to the differences found in *Phase IV*, the latter were not shown to be statistically significant. The results obtained are in agreement with a recent report by Webber and Hendrickson.[48] In their study, although they did not assess linear horizontal arrays, they found no statistically significant differences between the performances in artificial proximal caries detection provided by TACT® slices generated using linear vertical and circular arrays of basis projections. The same trend of improved diagnostic performance with linear vertical arrays as found in the present study was observed. From the results of this investigation and those of Webber and Hendrickson,[48] it is recommended that, for the task of caries detection, either a linear vertical or a circular array of projections should be used when acquiring the necessary basis projections for TACT® image reconstruction. If a specific diagnostic task is not in mind, or if diagnostic tasks requiring depth discrimination are anticipated, a circular array of projections should be used inasmuch as it also seems to satisfy the needs of those diagnostic applications.[46,47]

Unconstrained and stringent projection geometries for TACT® slice generation

In a previous study of caries detection efficacy an unconstrained array of projections was used to acquire the necessary images for TACT® slice generation.[33] The results of that study yielded no statistically significant difference in caries detection between TACT® slices and conventional digital images. On that occasion it was hypothesized that a possible explanation for the absence of improved diagnostic performance with TACT® was that a more stringent projection geometry was not employed. The results of *Phase V* of the present study, which demonstrated no statistically significant difference in observer performance in caries detection between TACT® slices generated using unconstrained and stringent projection arrays, are reassuring inasmuch as they confirm the validity of the previous investigation.[33]

Ramesh and colleagues appear to be the authors responsible for the only other study in the English language literature that has performed a direct comparison between TACT® slices generated using unconstrained and stringent arrays of projections.[26] In what seemed unexpected to the authors, TACT® slices generated using images acquired with random aiming of the x-ray source provided improved, though not statistically significant, detection of simulated *proximal* periodontal lesions over TACT® slices generated using a fixed circular array of projections. The investigators, explaining their results, stated that random projection patterns may be considered to approximate a Gaussian distribution with the mean orientation directed parallel to the proximal surfaces. In this way, the random aiming they used may have yielded a favorable result by providing basis images with open contacts in the region of interest. Perhaps it is possible to explain the results of *Phase V* using a similar reasoning, albeit in a different direction. It is possible that the unconstrained array of projections used in the present investigation may have produced basis images with relatively greater amounts of overlaps of proximal surfaces than was the case with stringent geometry. Since superimpositions preclude an optimal depiction of the superimposed structures, slices reconstructed from the unconstrained projection geometry may have contained less useful information related to the proximal surfaces than those derived from the stringent array of projections. This idea is substantiated by the fact that observer performance related to the unconstrained geometry was reduced for proximal caries detection, but not for occlusal caries detection. If differences existed, however, they were not statistically significant.

Analyzing the experimental set-up of their particular study, Ramesh *et al* also considered that images produced with the random aiming of the x-ray source had relatively higher signal-to-noise ratios than those produced with a fixed geometry because the former used shorter source-to-receptor distances.[22] This hypothesis cannot be used to explain possible differences found in the present study because either shorter or longer source-to-receptor distances were probably used in equal proportions when acquiring unconstrained projections because, as the name implies, projection geometry is not strictly controlled when the above mentioned method is used.

Webber and Bettermann have recently developed a scheme to compensate for the problem of discrepancies in magnification possibly occurring in TACT® imaging.[58] The new method tries to correct for differences in magnification present in the basis images before they are registered and, therefore, allows magnification to be constant between basis images and also from one reconstructed slice to the next. It was thought that this would theoretically improve the diagnostic quality of the reconstructed slices. However, when this scheme was put in practice and directly compared to the conventional methodology that does not correct for magnification it showed limited usefulness being statistically inferior.[26]

The results of *Phase V* of the present study and those of Ramesh *et al*[26] suggest that either unconstrained or stringent arrays of projections can be used to generate TACT® slices for common dental diagnostic tasks. Furthermore, it has been demonstrated that the TACT® slice generation process is capable of dealing with images having different degrees of magnification, at least for the range likely to be encountered in actual clinical applications. A word of caution is, however, warranted. From apparent trends observed in these two studies, it is reasonable to say that when implementing unconstrained projection geometries, care should be taken not to superimpose adjacent anatomical structures excessively in the resulting images. This is to say that small angular disparities between basis projections are to be preferred. The lesson to be remembered is that the quality of the information provided to the system (i.e., basis images) will determine the quality of the information the system can give back (i.e., TACT® slices).

Minimum and average reconstruction methods of TACT® slices

The minimum method of reconstruction of TACT® slices has been suggested to be superior to the average method in terms of its perceived interpretability in *in vitro* mammography examinations.[49,50] Slices reconstructed using the minimum method have also subjectively been preferred to slices reconstructed using the average method in the interpretation of pelvic studies.[50] In the latter report, the minimum method produced slices that were judged to be more similar in appearance to conventional radiographic (two-dimensional) images, perhaps facilitating visualization and preliminary interpretation of structures by those observers less familiar with the TACT® image presentation.

In *Phase VI* the minimum method of reconstruction of TACT® slices was used in a caries detection task. Diagnostic performances represented by ROC curves demonstrated that the minimum and average methods appear to be comparable for such a task. This is to say that, although the minimum method does not use the entire projective data made available by the set of basis images (on the contrary, each pixel of the reconstructed slice carries the information from a single projection), this characteristic does not significantly lower its diagnostic yield. It may be considered, therefore, that the information presumably lost represents mostly unwanted, or at least redundant, signals. For tasks dealing with highly radiopaque structures, these signals usually represent comparable details situated outside the focal plane that are cast on the plane of reconstruction with reduced but still visible contrast levels (ringing artifacts). It was interesting to see that the minimum method outperformed the average method for occlusal caries detection, although not to a statistically significant degree ($p = 0.057$). If that indeed represented a trend, for some reason the elimination of ringing artifacts was more beneficial to the detection of occlusal rather than to proximal caries. It is possible that, with the average method, the effects of ringing artifacts concentrated around the occlusal areas may have reduced the contrast necessary to evaluate these surfaces accurately,[49] thereby reducing their yield. However, the observed difference may also be the result of the particular size of lesions used in the present investigation or an adverse effect of sampling, and it may not be detected in repeated studies. In the present study, specificity for occlusal caries detection was slightly higher with the minimum method whereas for proximal caries detection it was slightly lower. At the same time, sensitivities were generally higher with the average method for both detection tasks.

An advantage of the minimum method is that deblurring procedures are not required since slices produced with this method are devoid of ringing artifacts. Procedures such as iterative restoration used with the conventional average method lengthen the time required to obtain the final reconstructed slices. Time should be a concern when the implementation of a diagnostic modality is contemplated. Tomosynthetic artifacts are annoying to the viewers and can significantly interfere with image interpretation. Because of the absence of these "ringing" artifacts, observers used in this study subjectively preferred the slices generated using the minimum method of reconstruction to the ones generated using the average method. From the results of the present study, this method can be considered as an alternative to the average method when TACT® is to be used in diagnostic tasks in which extensive amounts of ringing artifacts are anticipated, such as in the case of caries detection.

TACT® slices as compared to single frame digital radiography

Multiple technical factors are involved in the generation of TACT® images and therefore may influence its diagnostic quality as an imaging modality. *Phase VII* followed a series of experiments that tried to optimize TACT® for primary caries detection (*Phases I* through *VI* of this investigation). From the results and inferences collected in those phases, the combination of factors that was apparently best suited for such a diagnostic application was selected. Relative to the two previous studies reported in the literature that compared TACT® with film and digital radiography for the assessment of caries,[32,33] a few changes were implemented. These changes were related to the number of iterative restorations used during the generation of slices, the number and angular disparity of the basis images required for their reconstruction, the spatial relationship between acquired projections, and the stringency of the image acquisition scheme.

The present study showed that even when the presumably most appropriate factors were used for TACT® image generation, a significant improvement of this imaging modality for caries detection over conventional digital radiography was not achieved. The results of the present investigation corroborate those of the previously published reports,[32,33] and suggest that TACT®, although valuable in a variety of other diagnostic tasks, including simulated recurrent caries detection,[17-20,24,27] does not seem to be necessary for caries diagnosis inasmuch as a single and undemanding conventional film or digital image can provide comparable diagnostic performance.

TACT® is generated by integration of several conventional two-dimensional images - so called *basis* or *component* images.[11] This integration averages out the noise contained in each basis image producing tomogram-like slices of the object of interest with supposedly improved signal-to-noise ratio when compared to conventional digital radiography.[11,32] TACT®, as a tomographic modality, also gets rid of some of the typical superimpositions seen in conventional radiography, which seems to be beneficial from a diagnostic point of view. For caries detection, however, these theoretical advantages seem to be undermined or perhaps totally eliminated by the fact that tomosynthetic techniques such as TACT® inherently produce images that are not as sharp as conventional radiographs.[7,13,15,16] The integration of images, along with blurring, is likely to cause smearing of tooth surfaces and decrease the contrast between a potential carious lesion site and its surrounding tissues, especially when the object of interest is as radiopaque as a tooth crown.[9]

Ultimately, spatial resolution and intra-tissue contrast[57] may be deemed the factors responsible for the absence of an improved primary caries diagnostic performance with TACT®. The reconstruction process used in TACT® produces a sharp image of structures in the desired plane on which blurred images of object details lying outside the plane of interest are superimposed.[13] This is exactly what happens in conventional tomography. In the latter modality, the x-ray moves during the exposure. In TACT® or tomosynthesis, the x-ray source is "flashed" in various positions along a specified trajectory. Although the source does not actually move during each exposure, the subsequent registration of images may be seen as having a motion component to it inasmuch as images are shifted and added to reconstruct slices at different depths of the anatomy. The presence of any kind of motion usually results in radiographic images of lower spatial resolution. Regarding intra-tissue contrast, it is known that thinner image slices (thinner "cuts") result in reduced differential attenuation between anatomical structures of different physical densities or atomic numbers. This may decrease the contrast between the potential site of a carious lesion and its surroundings. All the above mentioned circumstances may preclude TACT® from performing significantly better than conventional digital radiography which, although two-dimensional, does not suffer from blur and is composed of a single radiographic transmission profile, which makes it free from smearing effects.

An interesting finding of the present study was the higher inter-observer agreement provided by conventional digital images compared to that provided by TACT® slices, even though the latter yielded better (but not significantly so) diagnostic performance. A possible reason for the observed difference is that, although observers who participated in the present study had previous experience with TACT® images, they are still more used to interpreting conventional two-dimensional images. This familiarity with conventional images, common to all dentists, may have reduced the differences between their assessments of the tooth surfaces. The other potential reason for the difference in inter-observer reliability is intrinsic to the two modalities compared. While conventional digital radiography is displayed as a single image, TACT® slices are displayed as a stack of multiple sequential images (sixteen to twenty-two in the present study). More variability might be expected when a judgment (presence/absence of caries) is based on multiple alternatives rather than on a single option. The outcomes of the present study regarding inter-observer reliability and diagnostic performance are an example of the fact that precision does not always translate into accuracy and vice-versa, i.e., although conventional digital radiography was more precise (produced less inter-observer variability), it was less accurate (provided inferior diagnostic performance), though not significantly so.

The approach used to test the null hypotheses in the present investigation was based on the comparison between the diagnostic performances achieved by trained observers using TACT® images treated with each different variable. Receiver Operating Characteristic curves were used as the primary measure of this performance.[51,59-63] Although carrying a subjective component, this method has been extensively used in radiological studies.[64-71] One of its advantages is that it takes into account the influence and perceptions of the actual users of radiographic images (i.e., human beings) on the diagnostic performance attained with each test modality. This approach was selected due to the lack of practical objective methods to compare the quality of variables being evaluated. However, although an objective approach may appear to be ideal or at least more suitable because of the absence of human interference on its outcomes, significant differences potentially observed using such an approach do not necessarily mean that similar differences will also exist in a real clinical setting. Therefore, it is thought that this approach, despite any possible limitations, was appropriate for the purposes of this investigation.

CHAPTER VI

CONCLUSIONS

Tuned aperture computed tomography (TACT®) appeared to be an imaging modality with great potential to improve the current status of dental caries diagnosis. This belief was built on the basis that TACT® has been shown to improve observer performance in virtually all of the dental diagnostic tasks to which it has been applied, including the detection of *recurrent* dental caries.[17-31] Apparently the only task that had not benefited significantly from the three-dimensional attributes of TACT® imaging was the detection of primary caries. Both of the studies previously reported in the English language literature that tried to implement TACT® in the latter task found no statistically significant difference between the diagnostic performances provided by TACT® versus conventional film or digital radiography.[32,33] Since TACT® is still a relatively new imaging modality having much to be explored it was thought that the unsatisfactory results obtained in those two studies were caused by the selection of non-ideal factors or variables related to TACT® image acquisition and slice reconstruction.

From the results of the present investigation, it was possible to confirm that the presumed benefit of using additional iterative restoration steps during the reconstruction of slices is counteracted by an increase in image noise with each iteration. This noise may prevent substantial improvement of image quality. Since TACT® slice generation is still relatively time-consuming, a single iterative restoration may be used to expedite the process. In the present investigation, a direct comparison between TACT® slices submitted to iterative restoration and slices that were not treated with iteration procedures was not carried out. This comparison was not performed because a previous study had shown a better performance of the iterated slices and because of the empirical observation that iterated slices provide "sharper" images than non-iterated ones.[17] Nonetheless, this may be acknowledged as a limitation of this investigation that would be eliminated if the study were to be repeated.

Regarding the angular disparity between basis or component projections necessary for the reconstruction of TACT® slices, it can be concluded that small angles should be used when relatively small numbers of projections (e.g., eight) are acquired. Although larger angular disparities provide "thinner slices," with less superimposition of overlying anatomy, they produce greater amounts of quantization artifacts. In theory, large angles should be accompanied by increased numbers of basis projections. However, there is always a limit of exposures that should be used both in terms of patient protection from radiation and the time required by the imaging procedure. Small angular disparities for detection tasks have also been recommended by Chai-U-Dom *et al.*[41]

In contrast to two other studies previously reported in the English language literature,[40,43] the present study showed that the number of basis or component images does play a significant role in TACT® imaging for the task of primary dental caries detection. It was possible to show that at least eight projections should be used when the task of primary caries detection is being carried out. Increased numbers of basis images can be used and tend to improve diagnostic performance, although not significantly so. Nevertheless, the same considerations regarding the amount of radiation to be received by the patient and the practicality of the acquisition and reconstruction processes should be kept in mind, at least until an automated device has become available in the market. As stated previously, another, if not the most important, limitation of this investigation was the inability to implement a factorial design to assess the variables number and angular disparity of basis images simultaneously in the same experiment. Future studies may try to use such a design, but researchers have to bear in mind that the collaboration of observers is not easily achieved. Observer fatigue is another issue that must be considered.

The use of different spatial arrays of basis projections to generate TACT® slices was studied in the present investigation. The results obtained are in agreement with those of Webber and Hendrickson[48] in that a linear array of projections oriented in the vertical direction tended to provide superior diagnostic performance in caries detection than a circular array, although not significantly so. Since other diagnostic tasks, especially those that require depth determination, may benefit from circular arrays of projections,[46,47] the latter may be recommended as the array of choice to be used when basis images for TACT® are being acquired.

Prior to this investigation a concern existed regarding the ability of TACT® to deal with basis projections that were not acquired from the same plane in space. The present investigation showed that TACT® is indeed able to cope with basis images having different magnifications, at least the range of magnifications produced by the use of an intra-oral source in a simulated clinical application of the method for the task of primary dental caries detection. The diagnostic performance achieved with the unconstrained geometry was not significantly different from the one achieved when employing stringent geometry.

Phase VI of this project evaluated a different method of TACT® slice reconstruction for caries detection. This method, called the *minimum* or *minimization* method, eliminates the ringing artifacts present in slices reconstructed using the more conventional *average* method.[49] The results of the present investigation demonstrated comparable performances between the two methods in caries detection. The minimum method does not require time-consuming deblurring procedures, which shortens slice generation, and it may therefore be considered as an alternative to the average method, especially when the object under evaluation is highly radiopaque, which makes it more likely to produce extensive amounts of spurious ringing artifacts.

Finally, it was disappointing to see that even when the best combination of variables involved in the generation of TACT® slices was used, this imaging modality failed to outperform conventional digital radiography in caries detection. It is noteworthy calling attention to the fact that the projection corresponding to the conventional digital image was never used as a basis image for TACT® slice reconstruction. It would be interesting to find out whether the addition of this image, being orthogonal to the tooth imaged, therefore geometrically superior to all others, would improve observer performance in any meaningful way. Since conventional digital radiography is simple, inexpensive, less time-consuming, and well established as a radiographic modality, it should be used until improved diagnostic tools for caries detection are found.

Future studies using TACT® should consider the information gathered in the present investigation and concentrate on tasks where depth discrimination is of value, such as in assessment of depth of occlusal and proximal caries and in the relationship between those lesions and the dental pulp. Comparisons between the estimated depth provided by different imaging modalities including TACT® and histology would be in order, inasmuch as it is well known that conventional radiography methods underestimate caries depth relative to microscopy. Using the potential TACT® advantage to provide slices of anatomy with less superimposition of overlying structures, the assessment of caries through orthodontic bands and/or restorative materials can also be attempted. As an anticipation, these diagnostic tasks would probably require a considerable number of optimal quality basis images, since they would put a high demand on the modality to display dental carious lesions below those (usually radiopaque) objects. Finally, another area of potential interest would be to utilize TACT® in tasks where noise needs to be blurred out of competition with signal, such as in subtraction radiography.

Summary

In summary, the null hypotheses tested in the present investigation and the results obtained for the task of natural primary caries detection were:

Phase 1: there is no statistically significant difference in the diagnostic value (for proximal caries detection) of TACT® slices submitted to one, two, or three iterative restorations.
Results: the study failed to reject the null hypothesis; the three numbers of iterative restorations provided similar diagnostic performances.

Phase II: there is no statistically significant difference in the performance provided by a range of angular disparities that are likely to be used in a clinical application of TACT®.
Results: the study failed to reject the null hypothesis; the four angular disparities provided similar diagnostic performances, with the smaller angles being slightly superior.

Phase III: there is no statistically significant difference in the performance provided by TACT® slices generated from different numbers of basis images.
Results: the null hypothesis was rejected; twelve basis images provided significantly better diagnostic performance than both two and four basis images.

Phase IV: there is no statistically significant difference in the diagnostic performance provided by circular, linear horizontal, or linear vertical arrays of basis projections.

Results: the study failed to reject the null hypothesis; there was a trend for the linear x-ray beam array in the vertical direction to be better than the linear array in the horizontal direction.

Phase V: there is no statistically significant difference in the diagnostic performance provided by TACT® slices generated using unconstrained and stringent arrays of projections.

Results: the study failed to reject the null hypothesis; the two arrays of projections provided similar diagnostic performances, with the stringent array being superior in the detection of proximal caries.

Phase VI: there is no statistically significant difference between the diagnostic performances provided by the minimum and average methods of TACT® reconstruction.

Results: the study failed to reject the null hypothesis; the two reconstruction methods provided similar diagnostic performances, with the minimum method being superior in the detection of occlusal caries.

Phase VII: there is no statistically significant difference between the diagnostic performances provided by TACT® and conventional digital radiography.

Results: the study failed to reject the null hypothesis; there was a trend for TACT® slices to perform better than digital radiography.

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