Determining the Clinical Effects of Photostimulable Phosphor Plate Artifacts on the Interpretation of Periapical Inflammatory Disease

by

Trevor Seow-Tjong Thang

A thesis submitted in conformity with the requirements for the degree of Master of Science (Oral Radiology)
Faculty of Dentistry
University of Toronto

© Copyright by Trevor Thang 2019
Determining the Clinical Effects of Photostimulable Phosphor Plate Artifacts on the Interpretation of Periapical Inflammatory Disease

Trevor Seow-Tjong Thang

Master of Science (Oral Radiology)

Faculty of Dentistry
University of Toronto

2019

Abstract

Objectives: This thesis aims to determine the extent that photostimulable phosphor (PSP) plate artifacts hinder the radiologic interpretation of common dental diseases, such as periapical inflammatory disease.

Methods: Gold standard radiologic interpretations for periapical inflammatory disease were determined on high-quality clinical radiologic images. PSP plate artifacts were digitally superimposed over these high-quality images to virtually degrade the image. These simulated images were presented to general dentists who were asked for their radiologic interpretation, the confidence in their interpretation, and their opinion on whether to discard the plates.

Results: With increasing levels of artifacts, there was a statistically significant reduction in clinicians’ confidence and increase in the proportion of plates discarded (p < 0.05). No significant differences in diagnostic sensitivity or specificity were observed.

Conclusion: Severely-damaged PSP plates reduced clinicians’ confidence in their radiologic interpretations and increased discard proportions.
Acknowledgements

This work could not be accomplished without the support, enthusiasm, and expertise of my supervisors, Drs. Massieh Moayedi and Susanne Perschbacher. Thank you for guiding me through my academic journey and promoting a culture of curiosity and excellence.

The feedback from my committee members, Drs. Anil Kishen and Pascal Tyrrell has elevated the quality of research by encouraging collaboration and widening my horizons.

Many thanks to Drs. Edwin Chang and Jeff Chadwick for sharing their clinical expertise and their continued support. As well, I have to thank Dr. Danielle Douglas for offering her keen eyes throughout the editing process.

This research would not be possible without the generous support of the Canadian Institutes of Health Research (CIHR) and the Faculty of Dentistry SEED Grant Fund (University of Toronto).
# Table of Contents

Acknowledgements ........................................................................................................... iii

Table of Contents ................................................................................................................ iv

List of Tables ....................................................................................................................... vii

List of Figures ..................................................................................................................... viii

List of Abbreviations ......................................................................................................... ix

1 Introduction ....................................................................................................................... 1

1.1 Photostimulable Phosphor Plates ............................................................................... 1

1.1.1 Composition and Anatomy .................................................................................. 1

1.1.2 Generating a Digital Image .................................................................................. 3

1.1.3 Types of PSP Plate Artifacts ............................................................................... 4

1.1.4 Prevalence of PSP Plate Artifacts ...................................................................... 5

1.1.5 Longevity of PSP Plates ..................................................................................... 6

1.1.6 Quantification of PSP Plate Artifacts .................................................................. 7

1.1.7 Quality Assurance Standards and Protocols ....................................................... 8

1.1.8 Need for Updated Canadian Guidelines ............................................................. 9

1.2 Periapical Inflammatory Disease ............................................................................... 10

1.2.1 Prevalence ......................................................................................................... 10

1.2.2 Disease Mechanism and Treatment ................................................................... 10

1.2.3 The Role of Dental Radiography ...................................................................... 12

1.3 Statement of the Problem ......................................................................................... 13

2 Objective and Hypotheses ............................................................................................ 14

3 Materials and Methods .................................................................................................. 15

3.1 Ethical Design .......................................................................................................... 15

3.2 Acquiring Artifact Masks ....................................................................................... 15
9.1 University of Toronto Ethics Board Approval .......................................................... 43
9.2 Informed Consent Form and Receipt of Payment ...................................................... 44
9.3 PSP Artifact Masks (total: 24) ............................................................................. 49
  9.3.1 Brand New (total: 4) ...................................................................................... 49
  9.3.2 Moderate Artifacts (total: 5) .......................................................................... 49
  9.3.3 Severe Artifacts (total: 15) ............................................................................ 49
9.4 Clinical Images (total: 100) .................................................................................. 50
9.5 Testing Images ..................................................................................................... 52
9.6 E-mail Thread acquiring Permission for Image Reproduction .............................. 53
List of Tables

Table 4-1  Descriptive statistics for interpretative accuracy................................. 23
Table 4-2  Descriptive statistics for subjective metrics. ........................................ 24
Table 4-3  Odds ratios for response variables when compared to controls............... 25
# List of Figures

| Figure 1-1  | Examples of Intra-Oral PSP plates ........................................................................ 2 |
| Figure 1-2  | Photostimulable Phosphor (PSP) Plate Workflow. ...................................................... 2 |
| Figure 1-3  | Phosphorescence Phenomenon for PSP plates ............................................................. 3 |
| Figure 1-4  | Examples of Physical PSP Plate Damage ................................................................... 5 |
| Figure 1-5  | Disease Mechanism for Periapical Inflammatory Disease .............................................. 11 |
| Figure 1-6  | Periapical Images of Normal Bone and Periapical Inflammatory Disease. .... 12 |
| Figure 3-1  | Examples of PSP plates with “severe” artifact ............................................................ 16 |
| Figure 3-2  | Examples of marked high-quality CMOS images. ....................................................... 17 |
| Figure 3-3  | Comparison of computer-simulated and a real PSP image......................................... 18 |
| Figure 4-1  | Flowchart for Gold Standard Interpretation Agreement. ............................................. 21 |
| Figure 4-2  | Interpretative accuracy for periapical inflammatory disease .................................... 23 |
| Figure 4-3  | Subjective impacts when interpreting clinical images ................................................. 24 |
| Figure 4-4  | Sample Images with Intermediate Discard Proportions ............................................. 26 |
| Figure 6-1  | Simulating PSP Plate Artifacts .................................................................................. 34 |
## List of Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CCD</td>
<td>charge-coupled device</td>
</tr>
<tr>
<td>CMOS</td>
<td>complementary metal-oxide semiconductor</td>
</tr>
<tr>
<td>lap/mm</td>
<td>line pairs per millimeter</td>
</tr>
<tr>
<td>ML</td>
<td>machine-learning</td>
</tr>
<tr>
<td>PACS</td>
<td>picture archiving and communication systems</td>
</tr>
<tr>
<td>PSP</td>
<td>photostimulable phosphor</td>
</tr>
</tbody>
</table>
1 Introduction

Photostimulable phosphor (PSP) plates are popular digital receptors used in dental radiology. However, they have a finite lifespan due to the accumulation of irreversible physical damage (scratches and bends) to the delicate and photo-receptive surface of the plate. This damage manifests radiologically as white (radiopaque) artifacts that are superimposed over the desired image, reducing the overall image quality. It is recommended by both manufacturers and dental regulatory agencies that dentists quality control their radiology armamentarium; however, specifics of how this should be accomplished are not provided. This is because there is a lack of scientific evidence on the effects that these artifacts have on the clinical interpretation of common dental diseases. This thesis aims to study these effects on the interpretation of a common dental disease, periapical inflammatory disease.

1.1 Photostimulable Phosphor Plates

1.1.1 Composition and Anatomy

There are many forms of digital receptors used in dentistry including photostimulable phosphor (PSP) plates, charge-coupled devices (CCD), and complementary metal-oxide semiconductor (CMOS) sensors. PSP plates have become popular in modern dentistry due to having similar handling properties of traditional film, including their thinness, flexibility, and availability in a range of sizes. Each PSP plate consists of a polyester base with an active surface made up of a delicate lattice of europium-doped barium fluoride halide. Unlike other forms of digital radiography, PSP plates can be manufactured in numerous sizes; including the traditional intraoral film sizes (size 0, 1, 2, and 4) and larger extra oral film sizes (ex. skull films) (Figure 1-1). To take advantage of their flexibility and thinness, when used intra-orally in dentistry, PSP plates are minimally wrapped within a thin plastic sheath for infection control purposes.
**Figure 1-1  Examples of Intra-Oral PSP plates.** The left image shows various sizes of PSP plates. Sizes 0, 1, 2, and 4 are shown in the top left, middle left, bottom left, and right, respectively, as compared to a Canadian 5-cent nickel coin. The right image shows a comparison between the thicknesses of a nickel, a PSP plate, and a CMOS sensor (from left to right).

This sleeve provides minimal protection for the delicate PSP lattice of intra-oral plates and therefore, plates can be easily damaged during their manipulation in and out of their sleeves or if the patient accidentally bites on them. This is contrasted by extra-oral films, which are typically placed in bulky, rigid cassettes to protect them. This makes the minimal protection used for intra-oral imaging, a situation unique to dentistry (Figure 1-2).

**Figure 1-2  Photostimulable Phosphor (PSP) Plate Workflow.** To be used, PSP plates are first wrapped in a hygienic sleeve for infection control purposes (left image). They are subsequently placed inside the oral cavity using a positioning-indicating device (middle). The plate is then exposed to x-ray photons to create a latent image. The plate is removed from the sleeve and placed into a scanner for digitization of the image (right).
1.1.2 Generating a Digital Image

PSP plates rely on a physical phenomenon known as phosphorescence, which describes the absorption, storage, and emittance of radiation energy (Figure 1-3). The active surface is made of a barium fluoro-halide that has been doped with europium. At rest, europium electrons lie in the lowest energy state, also known as the valence band. When a europium atom is exposed to an x-ray photon, one of its valence electrons is energized to the conduction band where it can migrate to the nearest halogen vacancy (F-centers). Within these F-centers, the electrons are trapped and remain in a metastable state. The number of electrons trapped within these F-centers is proportional to the x-ray exposure. Therefore, after being exposed in the patient’s mouth, a latent image of trapped, excited electrons is formed on the PSP plate1,2.

Figure 1-3  Phosphorescence Phenomenon for PSP plates.
(1) At rest, electrons (e⁻) lie in a low energy state known as the valence band.
(2) Upon exposure to an x-ray photon (excitation), the electron is energized to the conduction band and settles in a metastable state within an F-center.
(3) During read out, a red light within the scanner provides enough energy to excite the meta-stable electron into the conduction band. It quickly falls back into the valence band emitting a green light, which is measured, recorded and digitized.
For this latent image to be transformed into a digital radiologic image, the plate is placed into a scanner where a red laser light (approximately 600 nm wavelength) scans across the surface of the plate. When stimulated by this red light, the electrons trapped within the F-centers are provided enough energy to re-enter the conducting band and then quickly drop back into the valence state, returning to the europium ion. This loss of energy is released in the form of green light (approximately 300 to 500 nm wavelength) that has an intensity proportional to the number of trapped electrons within each F-center. This green light is collected and read by a photomultiplier tube which converts this light energy into an electrical signal. When this signal is read by an analog-to-digital converter, a grey-scale value (corresponding to the intensity of the green light) is mapped to the laser’s position on the PSP plate, creating a digital image1.

1.1.3 Types of PSP Plate Artifacts

As with all imaging detectors, intra-oral PSP plates are prone to different errors and artifacts. Although several types of PSP plate artifacts are described in the literature, there is no consensus on their classifications or definitions. The most comprehensive description of these artifacts is reported by Caliskan et al., who categorize these artifacts into four major groups based on their causes: operator-and patient-induced (i.e. cone cutting, elongation), ambient light-induced (i.e. fading, noisy image), scanner-induced (i.e. skipped image part, lines paralleling the slow scan direction), and PSP-induced artifacts and errors3. PSP-induced artifacts were sub-classified into two categories: reversible and irreversible. Reversible PSP-induced artifacts include dust particles, glove powder contamination, fingerprints, and adhesive contaminations. With proper handling and regular cleaning, these types of plate artifacts can be prevented and removed. Irreversible PSP-induced artifacts manifest when excessive mechanical forces are placed on the plate, thus, damaging the delicate crystal lattice used to capture the latent image. These include scratches, cracking, peeling of the plate, bite marks, and crescent-shaped bending (Figure 1-4).
Figure 1-4   Examples of Physical PSP Plate Damage. PSP plates are susceptible to damage during their routine use in the clinical setting. Black arrows show examples of cracking, peeling of the plate, and bite marks (from left to right images).

Scratches and cracks are a result of excessive plate bending and they appear radiographically as linear radiopaque lines, which may be smooth or irregular depending on the depth of damage into the plate. Peeling of plate borders are larger and irregular defects concentrated on the edges due to excessive friction and handling at the periphery of the plate. Bite marks appear as small radiopaque dots on the radiologic image, and crescent-shaped, radiopaque bends manifest when patients bite improperly on the intraoral bite block used to help position the plate intra-orally. Chiu et al. describes similar PSP-induced artifact categories, including damage as a result of scratches or bite marks, teeth of the jaws of a “Snap-A-Ray X-Ray Holder” (Dentsply Sirona, York, USA), and from partial peeling of the intraoral sensor plate coating. The fish scale artifact, as first described by Buchanan et al., is an artifact inherent to the barium fluoro-halide lattice itself and thought to be related to improper disinfection use, handling, and/or manufacturing. This study will focus specifically on irreversible PSP artifacts that accumulate over time and progressively reduce the quality of the desired radiologic image.

1.1.4 Prevalence of PSP Plate Artifacts

The reported prevalence of PSP plate artifacts varies across the dental community. In a retrospective analysis conducted by Caliskan et al. of 2100 PSP images from a university's radiographic database, PSP-induced artifacts and errors, specifically, peeling of the plate borders, scratches, and cracks had relative frequencies of 53.4%, 41.5%, and 16.1%, respectively. This contrasts findings from Chiu et al., which found only 60 images with
sensor defects, out of a total of 15,912 (0.4%)⁴. This striking difference in the artifact prevalence is likely due to multiple factors, such as the frequency at which plates are used and the operators’ care when using this technology⁴. For example, the prevalence of these artifacts would be elevated if plates were used frequently or if they were being used in a training institution (such as a dental school). However, the most important factor that would influence the prevalence of these artifacts would be differing imaging quality control standards and practices. It is expected that PSP plate be discarded once plates become “undiagnostic”; however, the threshold for diagnosis and the frequency at which quality control is conducted is subjective and variable.

The quality assurance protocol described in the longitudinal study conducted by Chiu et al. described that within the first four weeks of the study 12 out of the 50 new intraoral PSP sensors required replacement due to physical plate damages, and by the end of the study, an additional eight plates needed to be discarded. Removal of these damaged plates explains the marked reduction in the prevalence of these artifacts reported by the study’s end. Given that it was a cross-section study, no quality assurance protocol was conducted by Caliskan et al. and no description is provided on the overall level of quality control practices conducted at the institution. This suggests that differing quality assurance practices lead to variable PSP artifact prevalence, and that strict quality control practices may reduce the prevalence of these types of artifacts.

1.1.5 Longevity of PSP Plates

Different metrics have been used in the literature to attempt to describe the longevity of PSP plates. Most studies determine a plate’s durability and longevity by assessing the generalized degradation of the crystal lattice overtime in controlled, laboratory settings⁶–⁹. This degradation is determined by assessing changes in objective image quality metrics, such as mean grey value, spatial resolution, and contrast resolution. Van Langen and Castelign conducted a cross-sectional study of 21 extra-oral PSP plates that were used for between one month and two years, being exposed between 191 and 3797 times⁶. After exposing these plates in a radiologic phantom, a user-defined box of approximately 1 cm² was used to calculate the mean pixel value (MPV) in this area. It was shown that the mean
pixel value was not dependent on the number of times the PSP plates was used, suggesting that the PSP crystal lattice did not significantly degrade with each use. Similar findings were seen by Ergün et al., who showed that after a small initial deterioration of the plate after the first exposure, no statistical changes in the mean grey values were seen after PSP plates were used clinically in a dental clinic up to 200 times\textsuperscript{7}. Matsuda et al. extended this duration by showing that Digora Optime® PSP plates had no significant change to their mean grey values after 1000 exposures\textsuperscript{8}. In addition to assessing the mean grey values, Buchanan et al. also explored changes in spatial and contrast resolution as PSP plates are used\textsuperscript{9}. Using a radiologic phantom, they showed a significant drop in the spatial resolution from 6 line-pairs per millimeter (lp/mm) to 5 lp/mm after 48 clinical uses. No statistical significant changes were observed in the mean grey values nor the contrast to noise ratios after 60 clinical uses\textsuperscript{9}. In total, it appears that when measuring PSP plate longevity using mean grey values, plates can be used for upwards of 1000 times in a dental setting. However, when considering other metrics such as spatial resolution, a statistical difference was seen after only 48 uses\textsuperscript{9}. Since many of these studies were conducted in controlled environments, these longevity results are unlikely to be generalizable to a clinical dental setting since the studies do not account for PSP-induced artifacts such as bends and scratches as described by Caliskan et al. Furthermore, the clinical significance of these changes is unknown.

1.1.6 Quantification of PSP Plate Artifacts

To challenge the idea that dental PSP plates could be used upwards of 1000 times, Bedard et al. wanted to look specifically at PSP-induced artifacts and how they accumulate over time. They subjected a total of 140 PSP plates to five different clinical handling scenarios that would be typical for radiography\textsuperscript{10}. Four of these scenarios were conducted in controlled experimental settings, while one out of the five groups was subjected to the clinical setting. Based on the subjective amount of artifacts visualized on the plates, a six-point scale was developed as a guide to categorize plates based on the number, length, and depth of the scratches. Images with the poorest rating of 5 were deemed to be undiagnostic by the expert opinion of an oral and maxillofacial radiologist. After reviewing over 800
images, they determined that 45% of PSP plates were undiagnostic after 33 uses, while 95% were undiagnostic after 50 uses. Based on the average ratings of the different control groups, most of the artifacts were created during the processing of the images in the PSP scanner.

Another attempt to quantify PSP plate artifact was conducted by Kalathingal et al., who subjectively classified a total of 280 PSP images on their own ordinal five-point scale\textsuperscript{11}. Their scale assessed the number and size of artifact lines and “blobs”. After an estimated average of nine months and 50 uses per plate, the study found that only 25% of the plates were classified in the two most severe categories. This contrasts findings by Bedard et al. which had 95% of the plates in the worst two categories after the same number of uses. This can be a result of many things, such as different handling conditions or different PSP plate systems; however, it is likely that most of the variability between these two studies are due to the utilization of two different subjective grading criteria. Since there is no current standard measure of artifact level, what one research team may have considered to be an undiagnostic plate may differ from other research teams.

1.1.7 Quality Assurance Standards and Protocols

In 2014, Metsälä et al. conducted a systematic review of the literature, looking specifically at quality assurance in digital dental imaging\textsuperscript{12}. Four core competencies were identified – management of dental imaging equipment, image quality and factors associated to it, dose optimization, and quality assurance. Regarding the quality assurance competency, many of the reviewed articles discuss the need for staff to be aware of the presence of artifacts on an image and ideally, know how to correct for them. Furthermore, they recommend that quality assurance protocols would include performing quality control tests, ensuring optimal condition of imaging equipment, and having knowledge of sources of artifact\textsuperscript{12}. Currently, these standards of quality assurance for PSP plates are not maintained due to the lack of clinically-relevant guidelines indicating how to conduct these quality control tests or how to appraise the condition of imaging plates.
For these reasons, most clinicians who use PSP plates discard plates at their own discretion. However, it is fundamentally unknown what factors motivate clinicians to discard their plates. Do clinicians’ use an objective scheme similar to those described by Bedard et al. or Kalathingal et al. who counted the number and size of various scratch and blobs or are subjective factors such as clinicians’ confidence, more motivating influences? Furthermore, are these thresholds swayed by auxiliary factors, such as the cost of replacing a PSP plate or social pressures from their patients or staff members?

1.1.8 Need for Updated Canadian Guidelines

Unfortunately, there are very few Canadian guidelines regarding the quality control of PSP plates. The Royal College of Dental Surgeons of Ontario (RCDSO) states that “dentists [who] use digital radiography must ensure that the radiographic images provided are of diagnostic quality” and recommend a “reject-repeat analysis as a daily quality control method” for digital radiographs. This sets the expectation that dentists ensure high quality images through a quality control protocol; however, no guidelines on how to achieve this standard are provided.

One of the main reasons for the lack of guidelines pertaining to quality control of PSP plates is the lack of understanding of their clinical significance. Current radiographic quality assurance guidelines are outdated because they are based on the traditional film, and thus, do not account for the type of accumulating physical artifacts seen on PSP plates. As a result, most clinicians opt to use direct visualization of the active surface of the plate – a process that is both subjective and unstandardized. As a result, clinicians may continue using damaged sensors, potentially rendering unnecessary treatment or missing serious oral diseases. For these many reasons, new guidelines need to be created that are objective, more rigorous, and less ambiguous to stay relevant with advancing technology.
1.2 Periapical Inflammatory Disease

1.2.1 Prevalence

The prevalence of periapical inflammatory disease is variable due to many factors. There are tooth-specific factors, individual factors, and geographic factors that can change the incidence of periapical inflammatory disease. A nationwide Finnish study in 2000 found the overall prevalence of periapical inflammatory disease was 27%. However, there was variability in who was more prone to this disease. For example, males were more likely to have periapical inflammatory disease than females (31% vs. 23%)\textsuperscript{15}. Population differences were seen when contrasting studies of the Greek and Jordanian populations showed the prevalence of periapical inflammatory disease to be 13.6% and 83.7%, respectively\textsuperscript{16,17}. To get the best estimate of a world-wide prevalence, a meta-analysis conducted by Pak \textit{et al.} found that 5% of teeth had periapical inflammatory disease which broadly speaking, averages one tooth with periapical inflammatory disease per person\textsuperscript{18}.

1.2.2 Disease Mechanism and Treatment

Each tooth consists primarily of the mineralized tissues of enamel, dentin, and cementum; however, within the center of the tooth is a small space that contains the soft tissues that are collectively termed the dental pulp. The dental pulp extends down each root exiting the tooth at its apex into the surrounding bone through a small opening called the apical foramen. It is this apical foramen that transmits small nerves and blood vessels into the tooth\textsuperscript{19}.

Normally, the outer casing of enamel and dentin protects the dental pulp from bacterial ingress. However, when this protective barrier is breached due to caries or fracture, bacteria can invade the tooth pulp resulting in pulpal inflammation. Pulpal inflammation can also result from physical trauma or thermal injuries from dental treatment. Unfortunately, due to its limited repair potential, pulpal inflammation typically progresses to pulpal necrosis (Figure 1-5). This isolated area within the tooth pulp acts as a bacterial reservoir, secreting bacteria and its metabolites out of the apical foramen into the surrounding bone. This elicits a cascade of inflammatory events within the periapical bone.
resulting in destruction of the normal trabecular bone and replacement with inflammatory byproducts\(^1\).

**Figure 1-5  Disease Mechanism for Periapical Inflammatory Disease.** The enamel and dentin provide a strong outer coating to protect the vital tooth pulp. However, this protective layer can be breached by caries. This results in a bacterial invasion into the tooth pulp causing inflammation and subsequently, tooth necrosis. This necrotic tissue acts as a reservoir for bacteria and their metabolites which eventually drain out of the apical foramen into the bone. This elicits more inflammation within the bone, which can be visualized radiologically. Image reproduced with the permission of the Swedish Agency for Health Technology Assessment and Assessment of Social Service, www.sbu.se/en.

If left untreated, this inflammatory response can extend well beyond the original odontogenic source. Osteomyelitis can result when this inflammatory response spreads through the marrow spaces of the bone. If instead, the inflammation spreads into the surrounding soft tissue structures, a cellulitis (inflammation of the skin) or a deep space infection can occur. When periapical inflammatory disease progresses to these more extensive diseases processes, not only is there more morbidity due to the larger area affected, but also, these conditions are much more difficult to treat conservatively\(^4\). Timely treatment should be rendered to prevent this from occurring.

The treatment for periapical inflammatory disease requires removal of the bacterial source. This is typically accomplished through either a root canal procedure or a tooth extraction. A root canal procedure involves mechanical and chemical removal of the necrotic pulp.
tissues, while preserving the outer mineralized tooth structures. Unfortunately, this procedure weakens the overall tooth structure and makes it more prone to future failures, such as endodontic failure and vertical root fractures\textsuperscript{19}. Therefore, accurate diagnosis is important to avoid rendering unnecessary overtreatment.

1.2.3 The Role of Dental Radiography

Dental radiography is a valuable diagnostic test for periapical inflammatory disease due to the characteristic changes seen on radiologic images (Figure 1-6). Once the inflammatory process exits the apical foramen, bone destruction ensues locally. This loss of bone density manifests radiologically as a rarefaction of the bone and appears as a region of relative radiolucency (black area). In response to the presence of this inflammation, the peripheral normal bone lays down more bone to “wall off” the inflammation. This sclerotic bone response appears as a diffuse radiopacity peripheral to the radiolucent center. These two imaging features are termed rarefying and sclerosing osteitis and together, they are important radiographic features for the diagnosis periapical inflammatory disease. Additional signs of inflammation include the presence of periosteal new bone formation, sequestration of bone, and periostitis\textsuperscript{1}.

![Figure 1-6 Periapical Images of Normal Bone and Periapical Inflammatory Disease.](image)

The left image shows an intra-oral periapical image of the mandibular right teeth with no evidence of periapical inflammatory disease (green arrow). The right image shows a periapical image of the mandibular left teeth with the most distal tooth (red arrow) exhibiting imaging features consistent with periapical inflammatory disease. The radiolucent (black) halo around the tooth apex is consistent with rarefying osteitis; while the overall radiopaque (white) bone seen peripherally, is consistent with sclerosing
osteitis. Indirect evidence of periapical inflammatory disease is seen in the form of a large carious lesion (cavity) on the last tooth (blue arrow).

However, radiologic interpretation requires more than just visual perceptive skills; cognitive skills also heavily influence the radiologic interpretation\textsuperscript{20}. By understanding the disease mechanisms of periapical inflammation, a skilled clinician can also predict which teeth are most prone to having inflammatory disease, even in the absence of clear visual signs. These indirect features can include teeth with a history of root canal treatment, inadequate or large restorations, deep caries, or fractured crowns. By processing all this information together, dental clinicians can make reasonable and accurate radiologic interpretation. A systematic review conducted by Leonadi Dutra \textit{et al.} found that digital periapical images had a good specificity (0.78) for periapical inflammatory disease\textsuperscript{21}.

1.3 Statement of the Problem

Irreversible PSP plate artifacts are commonly seen on dental radiologic images and their presence degrade the quality of the desired image. Eventually, these plates should be discarded due to excessive accumulation of these artifacts. Unfortunately, there are minimal guidelines for when these plates should be discarded due to the lack of scientific evidence. Currently, it is unknown to what degree, if any, these artifacts impact radiologic interpretation and patient management. By studying their effects on diagnostic accuracy in a clinical scenario, such as the radiologic interpretation of periapical inflammatory disease, the results can be used to create quality assurance protocols for users of this technology.
2 Objective and Hypotheses

This study aims to determine the clinical impact of PSP plate artifacts on the radiologic interpretation of periapical inflammatory disease.

This will be accomplished by evaluating:

1. The degree by which artifacts hinder radiologic interpretation;
2. How the presence of artifacts affects diagnostic confidence; and
3. Whether practicing dentists subjectively choose to discard PSP plates.

It is hypothesized that images with increased artifact severities will have an:

1. Increased odds ratio for an inaccurate interpretation;
2. Increased odds ratio for a reduced confidence level; and
3. Increased odds ratio for higher discard proportions.

Ultimately, these findings will help in the development of quality assurance guidelines for the dental community.
3 Materials and Methods

3.1 Ethical Design

To determine the clinical impact of PSP plate artifacts, *in vivo* periapical inflammatory lesions were investigated. Since the use of ionizing radiation while using a damaged, and thus potentially undiagnostic, PSP plate would not be ethical, the study design utilizes digital simulation to create the testing images. Testing images were created by superimposing real PSP artifact masks over artifact-free clinical images.

All procedures were approved by the University of Toronto Research Ethics Boards (Protocol Number 00035933).

3.2 Acquiring Artifact Masks

PSP plates (Carestream, CS 7600, Rochester, USA) were acquired from the oral radiology clinic at the Faculty of Dentistry, University of Toronto (Toronto, Canada). Plates were wiped (as per manufacturer's recommendations) using a 0.6% w/v sodium hypochlorite solution, and then wrapped in thin, plastic, hygiene sheathes. Plates were then exposed at a typical posterior periapical image setting (Belmont Phot-X IIs, 70 kV, 6.0 mA, 0.22 seconds, Somerset, USA) at the minimum exposure distance permitted by the long cone position indicating device. The sheathes were removed, and the plates were placed into the PSP scanner. The raw digital images were exported manually from the workstation in a lossless format (portable network graphics, *.png).

Twenty-four PSP plate images were selected for analysis and were used as artifact masks. Fifteen were deemed to have severe artifacts, five had intermediate levels, and four were brand-new PSP plates. An additional completely blank mask was added, and its data were pooled with the brand-new plates to act as negative controls. Images were characterized as having severe levels of artifact if it was deemed that no reasonable clinician would continue using these plates. Examples are shown in Figure 3-1.
3.3 Determining the radiologic interpretations of *in vivo* artifact-free images

A total of the 160 anonymized periapical images were acquired from the Faculty of Dentistry’s Medicor Imaging Picture Archiving and Communications System (MiPACS™, Medicor Imaging, Charlotte, USA) in a lossless format (tagged image file, *.tif). The inclusion criteria for these images were that they were:

1. acquired using a Size 2 CMOS sensor (Carestream, RVG 6200, Rochester, USA);
2. posterior periapical images of the maxillae or mandible;
3. adequate for visualization of the periapical region of a tooth of interest; and
4. of optimal brightness and contrast for diagnosis.

To indicate the tooth of interest, a red asterisk was manually placed digitally over its crown, ensuring that this additional marking would not interfere with the diagnostic task. Examples are shown in Figure 3-2. CMOS images were used to ensure that these images were devoid of any physical artifacts.
Figure 3-2  Examples of marked high-quality CMOS images. These images were acquired at the Oral Radiology clinic at the Faculty of Dentistry at the University of Toronto. These images were prescribed by a dentist for clinical purposes. The full set of images are provided in Appendix 9.4.

Gold standard radiologic interpretations were acquired by polling two oral and maxillofacial radiologists. They were asked to review these images in their preferred viewing conditions and indicate the presence or absence of periapical inflammatory disease (binary decision). A subset of 100 images were randomly selected that had interpretation agreement: 50 images were normal, 50 with periapical inflammatory pathology.

This was chosen based on a power analysis for diagnosis studies. In order to achieve $\alpha = 0.05$, $\beta = 0.2$, prevalence of 0.5, $H_0 = 0.5$, $H_1 = 0.7$, at least 49 cases within each group (or a total of 98) are required\textsuperscript{22}.

3.4  Superposition of Clinical and Artifact Images

To create the testing images, the selected PSP artifact masks were digitally combined with the in vivo artifact-free images through pixel addition. By summing weighted pixel intensities from each component image, a new image was formed. This was accomplished using Equations 3-1 and 3-2.
Equation 3-1
\[ c_{ij} = w_{ij} \cdot a_{ij} + w_2 \cdot b_{ij} \]

where \( w_{ij} \) and \( w_2 \) represent the artifact and CMOS image weighting factors respectively; \( a_{ij} \) and \( b_{ij} \) represent the grey scale values from the artifact and the CMOS image respectively; and \( c_{ij} \) represents the grey scale value of the combined image.

Equation 3-2
\[ w_{ij} = A \cdot B^{a_{ij}} \]

where \( w_{ij} \) is an exponential transformation of the pixel intensity of \( a_{ij} \) with constants (A and B).

Reference images were made using damaged PSP plates on a dental radiographic phantom (DXTTR III - Dental X-ray Trainer, DENTSPLY Rinn, York, USA) to calibrate the superimposition algorithm. By using these images as a reference, the weighting factors were adjusted until the simulated images were comparable to the reference images. The weighted factors were set to: \( w_2 = 0.85 \), \( A = 0.08069 \), and \( B = 1.00718 \). A side-by-side comparison between the simulated image and the real image is shown in Figure 3-3.

This algorithm was applied to combine the 25 artifact masks with the 100 CMOS images resulting in a total of 2500 images with known radiologic interpretations with superimposing simulated PSP plate artifacts of various severities.

**Figure 3-3** Comparison of computer-simulated and a real PSP image. The weighting factors used in the superimposition algorithm were selected by using a real PSP image acquired on a radiologic phantom as a guide. The left image was computer-generated, and the algorithm was adjusted until it was comparable to the real PSP image (right).
3.5 Clinical Testing

Twenty-five participants were recruited to each analyze a unique set of 100 testing images. Inclusion criteria for dentists were: (1) being registered and in good standing with the Ontario dental regulatory body as either a full member or a graduate student member and (2) having a minimum of one year of clinical dentistry experience after dental school that involves interpreting periapical pathology on radiologic images. Oral and maxillofacial radiology specialists were not eligible to be participants because their expertise in interpreting radiographs could potentially confound the results and would not be representative of the general dentist population.

All testing was done in the Faculty of Dentistry’s oral radiology clinic under standardized viewing conditions. Verbal and written instructions were given, and informed consent was obtained prior to testing. Participants reviewed 100 images in dim lighting on a light-emitting diode (LED) monitor (24” Monitor: P2417H, 1920x1080, 60 Hz, brightness: 75%, contrast: 75%, DELL, Round Rock, TX, USA) using Windows Photo Viewer (Microsoft, Redmond, WA, USA) and reported their evaluations in an Excel spreadsheet (Microsoft, Redmond, WA, USA). To prevent recall bias of the interpretation, it was ensured that the underlying CMOS image was not repeated for each participant. The brightness and contrast of the images could not be altered. Participants were asked to report: (1) their radiologic interpretation of periapical inflammatory disease for the tooth of interest (pathology vs. normal); (2) the confidence of their interpretation on a four-point Likert scale anchored between “not confident” and “very confident”; and (3) whether they would discard the PSP plate (yes vs. no). When deciding if a plate should be discarded, participants were asked to consider whether these artifacts would hinder their radiologic interpretations on a typical day in their private practices.

3.6 Statistical Analysis

Inter-rater agreement was determined for the gold standard interpretations through the Cohen’s kappa co-efficient statistic (κ).
The responses from the 25 participants were collected and the pooled diagnostic accuracy (sensitivity/specificity), average clinicians’ confidence, and discard proportions of each plate severity category were calculated. Descriptive statistics were performed for each response variable, including means with standard errors and medians with inter-quartile ranges.

Random intercept mixed models were used to assess interpretative accuracy, clinicians’ confidence levels, and discard proportions by considering participants as clusters and artifact severity as the explanatory variable (with “Brand New/Blank” as the reference group). Specifically, an ordered logit model was used to analyze the clinicians’ confidence levels.

Chi-square tests were conducted to test for association between sensitivity and specificity proportions between the three artifact severities. Additionally, chi-square tests were used to assess for associations between the three response variables. Bonferroni corrections were conducted to account for multiple tests. Statistical significance was set at \( p < 0.05 \).

Commercially available software (Prism v. 7.05 for Windows; GraphPad Software, San Diego, CA and SAS Ver 9.4 for Windows, Cary, NC, USA) was used for statistical testing.
4 Results

4.1 Gold Standard Interpretations of Artifact-free Images

When determining the gold standard radiologic interpretations, the intra-observer agreement between the two oral and maxillofacial radiologists was “substantial” for the radiologic interpretation ($\kappa = 0.80, 95\% \text{ CI} [0.71, 0.89]$). Of the 160 images reviewed, there was 90% (144/160) agreement of interpretation. This is shown diagrammatically in Figure 4-1.

**Figure 4-1  Flowchart for Gold Standard Interpretation Agreement.** The flow chart shows the level of agreement between the two oral and maxillofacial radiologists for the 160 images. The kappa-score for diagnosis was 0.80.

4.2 Clinical Testing

The pooled sensitivities, specificities, clinicians’ confidence, and discard proportions when using brand new/blank plates (negative control), intermediate artifacts, and severe artifact plates (mean ± standard error of the mean) are reported in Table 4-1 and 4-2.

Frequency distributions for sensitivities, specificities, clinicians’ confidence, and discard proportions are shown in Figure 4-2 and 4-3. Clinicians’ confidence is reported as the average confidence level percentage (mean confidence score divided by the maximum possible confidence score) for each plate. Odds ratios from the random intercept mixed analyses are shown in Table 4-3.
A decreased clinician confidence is associated with an increased discard proportion ($\chi^2 = 41.79, p < 0.0001$). The odds ratio for discard proportions was 1.73 (95% CI: 1.46, 2.04) when clinicians had above average confidence compared to below average confidence. An association between interpretative accuracy and clinicians' confidence was also found ($\chi^2 = 174.9, p < 0.0001$). There was an odds ratio for an accurate interpretation of 4.12 (95%: 3.307, 5.773) when clinician confidence was above average, compared to below average.

Sample images of those with intermediate discard rates are presented in Figure 4-4. These images illustrate the tipping point for when the artifacts influence most clinicians to start discarding damaged plates.
Table 4-1  Descriptive statistics for interpretative accuracy.

<table>
<thead>
<tr>
<th></th>
<th>Sensitivity</th>
<th>Specificity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand New / Blank</td>
<td>84.4 ± 2.29%</td>
<td>77.2 ± 2.65%</td>
</tr>
<tr>
<td>Intermediate</td>
<td>89.2 ± 1.96%</td>
<td>76.4 ± 2.69%</td>
</tr>
<tr>
<td>Severe</td>
<td>86.9 ± 1.23%</td>
<td>76.7 ± 1.54%</td>
</tr>
</tbody>
</table>

Means ± standard errors of the mean are presented for the diagnostic sensitivity and specificity for periapical inflammatory disease when using plates with various degrees of artifact.

Figure 4-2  Interpretative accuracy for periapical inflammatory disease. Box-and-whisker plots show the distributions for the sensitivities and specificities for each artifact plate, categorized by their artifact severities. No statistically significant differences between artifact severity categories were seen in the interpretative accuracy of periapical inflammatory disease. (n.s. – no significance)
Table 4-2  Descriptive statistics for subjective metrics.

<table>
<thead>
<tr>
<th></th>
<th>Clinicians’ Confidence</th>
<th>Discard Proportions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brand New / Blank</td>
<td>86.0 ± 1.05%</td>
<td>5.0 ± 1.0%</td>
</tr>
<tr>
<td>Intermediate</td>
<td>86.1 ± 0.71%</td>
<td>35.2 ± 10.2%</td>
</tr>
<tr>
<td>Severe</td>
<td>80.1 ± 1.08%</td>
<td>88.2 ± 3.17%</td>
</tr>
</tbody>
</table>

Means ± standard errors of the mean are presented for the subjective metrics of clinicians’ confidence and discard proportions when using plates with various degrees of artifact.

Figure 4-3  Subjective impacts when interpreting clinical images. Box-and-whisker plots shows the distributions for the confidence levels and discard proportions for artifact plates within each artifact severity. A statistical difference was seen in the clinicians’ confidence level when interpreting an image on a severely-damaged PSP plate compared to either intermediate levels or brand new/blank PSP plates. Furthermore, the discard proportions for PSP plates between severe levels of artifact, intermediate levels of artifact, and brand new/blank PSP plates were statistically different.
Table 4-3  Odds ratios for response variables when compared to controls.

<table>
<thead>
<tr>
<th>Response Variable</th>
<th>Brand New/Blank</th>
<th>Intermediate</th>
<th>Severe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diagnostic Accuracy</td>
<td>1.0 (reference)</td>
<td>1.15</td>
<td>1.07</td>
</tr>
<tr>
<td>(reference)</td>
<td>95% CI: [0.83, 1.60], p = 0.41</td>
<td>95% CI: [0.82, 1.34], p = 0.61</td>
<td></td>
</tr>
<tr>
<td>Clinicians’ Confidence</td>
<td>1.0 (reference)</td>
<td>0.97</td>
<td>1.71*</td>
</tr>
<tr>
<td>(reference)</td>
<td>95% CI: [0.75, 1.24], p = 0.80</td>
<td>95% CI: [1.40, 2.10], p &lt; 0.01</td>
<td></td>
</tr>
<tr>
<td>Discard Proportions</td>
<td>1.0 (reference)</td>
<td>14.8*</td>
<td>393.0*</td>
</tr>
<tr>
<td>(reference)</td>
<td>95% CI: [9.12, 24.01], p &lt; 0.01</td>
<td>95% CI: [236.01, 654.45], p &lt; 0.01</td>
<td></td>
</tr>
</tbody>
</table>

The odds ratios generated by the random intercept mixed models are presented. No statistical significances were seen in diagnostic accuracy. Differences in clinicians’ confidence and discard proportions were seen between brand new/blank vs. severe artifacts. (* statistically significant results (p < 0.05))
Figure 4-4  **Sample Images with Intermediate Discard Proportions.** The top row of images shows the artifacts as they would appear if the PSP plates were blank exposures, while the bottom row represents the corresponding artifacts digitally superimposed over a dental radiograph. The discard proportions for the following artifacts (from left to right) are: 30%, 51%, 56%, and 66%, respectively.
5 Discussion

5.1 Study Design

The objective of the study was to investigate the effects of PSP plate artifacts on the radiologic interpretation of dental diseases. Several study designs could potentially have been used to assess these effects. Regardless of the chosen design, a diagnosis study will require images with PSP plate artifacts to act as the testing images and a gold standard against which to compare these testing images. Three potential study designs were explored:

1. Anthropomorphic radiologic phantom,
2. Clinical study, and

An anthropomorphic radiologic phantom containing cadaveric jaws and teeth could be used to acquire these radiologic images. Using this phantom, an unlimited number of images could be acquired using various damaged PSP plates and CMOS sensors, allowing for the creation and analysis of real radiologic artifacts and images. However, this approach would not allow for the assessment of real clinical diseases, such as caries or periapical inflammatory disease. Even though both caries and periapical inflammatory disease have been simulated in vitro, real diseases have more subtle radiologic features that may not be reproduced accurately. As well, participants will have trained their eyes and minds, after many years of clinical experience, to be in tune with real diseases. To present participants with simulated diseases could potentially confuse and interrupt their natural interpretation process; therefore, biasing the results.

A clinical study could be conducted where two images are acquired of the same tooth on a patient - one using a damaged PSP plate and the other using the gold standard imaging modality. This would allow the study of real diseases in a true clinical setting. However, due to ethical considerations, acquiring additional clinical images on patients using potentially undiagnostic PSP plates would not be possible and thus, this study could not be performed.
The final approach, and the approach that was selected is computer superimposition. This approach overcomes the limitations of the previous two study designs – real diseases could be studied with no additional patient exposure. Although every attempt was made to optimize the superimposition algorithm to have the testing images be indistinguishable from “real” images, there remains subjectivity in the process. Therefore, an assumption is made that the computer-simulated images are realistic and thus, can act as a proxy for real PSP images. Additionally, by extension, an assumption is also made that the results from the simulated images in this study are comparable to the results expected from real PSP plate images. However, the significant results found with respect to participant confidence and discard rates replicates the clinical scenario expected with damaged PSP plates and thus support these assumptions.

5.2 Deciding on the Radiologic Task

The interpretation of intra-oral radiologic images is required for many diagnostic tasks, including the diagnosis of dental diseases - any of which could be potential candidates for this study. These diseases include caries, periodontal bone loss, foreign bodies, and intra-osseous pathology (i.e. cysts and tumors). Many factors were taken into consideration when deciding the radiologic diagnostic task and which disease to study. From a clinical perspective, the diagnostic question should be clinically-relevant and have significant impact on the patient’s treatment. As well, the task should be conducted routinely by general dentists and thus, the disease studied should be fairly common. From a research perspective, the diagnostic question should ideally be dichotomous to simplify data gathering and the analysis of the results.

One potential diagnostic task would be to differentiate PSP plate artifacts from intra-osseous foreign body materials, such as root sealer material. This is a task that novice clinicians may have difficulty with due to their similar radiologic appearance. However, differentiating between the two is rarely clinically relevant since the presence of foreign body material infrequently impacts treatment and is not associated with disease.
Another potential task would be diagnosing intra-osseous pathologies, such as cysts and tumors. This would be a challenging diagnostic task even for the most skilled general dentists because these diseases are rarely seen in a typical general practice dental office. Therefore, participants would be less familiar with these diseases and their variable experience levels would likely influence the results more than the artifacts themselves. As well, given the low prevalence of these pathoses, the societal significance of studying the impact of PSP plate artifact on the diagnosis of intra-osseous pathologies would be minimal.

Caries and periodontal bone loss are common dental diseases, and radiology plays an important diagnostic role for both. However, both diseases would be difficult to study from a research design perspective because they are typically graded on ordinal scales. Caries is reported based on its depth of invasion (enamel, dentinal, gross) and periodontal bone loss is reported based on its severity (normal, mild, moderate, and severe) for clinical reasons. This complicates the data collection for participants since the participants would need to be calibrated for each disease severity, and there is subjectivity on the divisions of these groups. As well, a new classification for periodontal bone loss was recently introduced in 2017 that changed the criteria by which bone loss should be assessed radiologically. Given its recent introduction, it was unlikely that general dentists would have familiarized themselves with this new classification scheme and thus, would introduce confusion amongst the participants.

The diagnosis of periapical inflammatory disease meets the clinical and research criteria. Its diagnosis is a common clinically-significant task that can greatly impact a patient’s care. As well, the diagnosis of periapical inflammatory is a dichotomous variable – normal or pathologic. There are no clinically-significant grading criteria because, regardless of the severity of periapical inflammatory disease, treatment is usually the same.

5.3 Deciding on Participant Inclusion Criteria

Careful attention was put on the inclusion and exclusion criteria for study participants to ensure that the study results would be generalizable to the dental community. The
inclusion criteria were that: (1) participants be registered and in good standing with the Ontario dental legislative body as either a full member or a graduate student member, and (2) a minimum of one year of clinical dentistry experience after dental school that involves interpreting periapical pathology on radiologic images. These baseline criteria ensure that all participants have shown sufficient competency to practice clinical dentistry in Ontario and could be tasked with not just the interpretation of images acquired using PSP plates, but also be responsible for their quality assurance as well. New graduates have less clinical experience and thus, may be more likely to make diagnostic errors (even in the absence of PSP plate artifacts). However, even new graduates will have frequently encountered periapical disease during their training and practice. Stricter inclusion criteria (such as requiring 10+ years of experience) would reduce the generalizability of the results, as their elevated experience levels would not be representative of the entire dental community. This is also the reason why oral and maxillofacial radiology specialists were not eligible to be participants, as their expertise in interpreting radiographs could potentially confound the results.

5.4 The Impact of PSP Plate Artifacts

Understanding the impact of PSP plate artifacts on diagnosis is a necessary step in determining their significance and to ensure adequate maintenance of these plates. This study shows a significant relationship between the severity of PSP plate artifacts and clinicians’ confidence levels and discard proportions. As these plate artifacts increase, clinicians lose confidence in their radiologic interpretation and thus, are more likely to discard their plates. This aligns with the progressive nature of how plate artifacts accumulate and thus, the progressive degradation of image quality.

The clinical manifestation of a lack of clinician confidence may have an adverse effect on the patient-dentist relationship or cause a delay in treatment. Loss of confidence due to poor quality radiographs may also lead to repeated image acquisition, resulting in increased patient exposure to ionizing radiation. Although subjective, these factors can hinder the delivery of dental care and thus, limit the effectiveness of a dental practice. In addition, this study found that this lack of confidence was associated with inaccurate
radiologic interpretations. Inaccurate interpretation can lead to missed diagnosis or unnecessary treatment. In the case of periapical inflammatory disease, untreated periapical inflammation can spread into the surrounding structures, resulting in osteomyelitis or cellulitis\(^1\). The treatment for these conditions is significantly more difficult once the infection has spread outside of the tooth bearing regions; therefore, timely treatment of localized periapical inflammation can reduce patient morbidity. On the other hand, overtreatment of periapical inflammatory disease involves a root canal procedure that results in unnecessary damage to the tooth, making it more susceptible to future failure. This is in addition to the time and financial cost of performing the root canal procedure, along with the necessary auxiliary treatment required to maintain the tooth, such as a full coverage crown\(^{19}\).

The striking differences seen in the collective discard proportions between the different severities of PSP plate artifacts show that as PSP plate artifacts increase, dentists are more likely to discard PSP plates. The results of this study are more compelling than those of similar studies which utilize only one expert opinion - this study presents the collective opinion of 25 dentists.

Unfortunately, despite every effort to reproduce a realistic clinical setting, potential bias may arise because unlike in this study, there is a monetary cost to discarding (and then subsequently replacing) a damaged PSP plate in private practice. This was not replicated through this study’s design and may have artificially skewed participants to discarding more plates than they normally would. However, this may be beneficial because each participant’s decision to discard is solely influenced by the extent that the PSP plate artifacts affected their perceived ability to diagnose. By absolving participants of an associated financial burden when deciding to discard plates, their decision will be based solely on the clinical effects.

5.5 No Effects on Diagnosis

Despite the lack of scientific evidence, it is easy to assume that artifacts hinder the accuracy of diagnosis. This study did not support this notion. There was no significant difference in
sensitivity or specificity of interpretation between artifact-free and damaged PSP plates. Accurate interpretations require the visualization of a sufficient number of radiologic features to lead a clinician to an interpretation. Therefore, if a sufficient area of the region of interest is unobscured by artifacts, an accurate interpretation can still be made. For instance, in periapical inflammatory disease, the clinician presumably looks for osseous rarefaction and sclerosis, as well as features supporting a pulpal etiology, such as widening of the periodontal ligament space, loss of the lamina dura, or a large coronal restoration. Thus, one inference from the data is that periapical inflammatory diseases can elicit changes across a sufficiently large area of the image, and therefore, PSP artifacts do not significantly hinder the clinician’s visualization. A future study testing the effect of artifact on diagnosis of more diseases with more subtle radiographic presentation, such as enamel interproximal caries, would likely find that these artifacts adversely affect interpretation. Another possibility is that the artifacts selected for this study were simply insufficiently large enough to obscure the region of interest to hinder the interpretation. However, the results of this study suggest that most clinicians would not continue using plates beyond the severity of artifacts presented.

To ensure that the sampled participants are representative of the community, we compared their results to those reported in the literature. A meta-analysis conducted by Dutra et al. found that the specificity for periapical inflammatory disease on digital periapical images had a pooled specificity of 78% (range: [42%, 100%]) using gold standards of either a clinical diagnosis or known simulated defects\(^\text{21}\). The pooled specificity of this study’s participants was 76.2% (range: [38%, 96%]), which falls within the reported range. Unfortunately, there is no scientific literature assessing the diagnostic accuracy of general dentists on the interpretation of periapical inflammatory disease when compared to the radiologic interpretation of oral and maxillofacial radiologists.

Due to the novelty of the research design, comparison of our results to others in the literature could not be conducted.
5.6 Creating Quality Assurance Guidelines

The results of this study can be used to guide future quality assurance protocols. As of now, this study’s results represent the collective opinion of 25 dentists and thus, give the best guidance for the community as to when plates should be discarded. Figure 4-4 provides examples of plates with intermediate discard proportions. It is recommended to utilize these plates as the threshold for discarding/keeping PSP plates. Plates that appear to have less artifact than those present in Figure 4-4 can justifiably be kept, while those that appear to have increased artifact severity should be considered for replacement.
6 Project Limitations

6.1 Superimposition Algorithm

Despite every effort to create the most realistic superimposition simulation, it would be difficult to achieve complete parity between simulated and “real” images. Even though multiple PSP plate masks were evaluated to calibrate the algorithm, ultimately, the weighting factors were selected and finalized through visual analysis (Figure 6-1). There could potentially be subtle, yet clinically-significant features of real PSP plates that were not accurately replicated through the simulation. The technique used in this study was a novel approach, required to overcome ethical limitations in potential study designs, with no other known standardized technique to accomplish this in the literature. Examples of testing images are presented in Appendix 9.5.

![Simulating PSP Plate Artifacts](image)

**Figure 6-1 Simulating PSP Plate Artifacts.** The top row of images was created using computer simulation using a superimposition algorithm. The bottom row of images represents real images acquired using damaged PSP plates. By calibrating the weighting factors in the superimposition algorithm, the best attempt was made for the top row of images to be visually indistinguishable from the bottom row of images.
6.2 Participant Variability

As with any clinical study, variability is expected in each participant’s interpretative skills and their experiences with interpreting PSP plate artifacts. In fact, inter-rater variability in diagnosis was large in this study, reducing the power of the study to detect small losses in diagnostic accuracy.

To overcome this problem, an alternative study design could entail presenting each clinician with the gold standard image and the damaged PSP plate image. This allows for each participant to act as their internal control and thus, any errors made in the interpretation of the image with simulated PSP plate artifacts would be due to the PSP artifacts. This may reduce the variability between our participants as they each have different experience levels and baseline confidence levels. However, this introduces a potential recall bias, as participants may remember the interpretation that they gave previously. Even though a wash-out period may reduce the risk of recall bias, there is a trade-off between increasing the duration of the wash-out period and increasing drop-out rates.

Another way to limit the inter-rater variability is to have stricter participant inclusion criteria to promote uniformity within the participant pool. A decision was made to have a more inclusive selection criteria, so the results were more generalizable to the dental community. It was felt that from a patient’s perspective, all licensed general dentists should be equally competent and thus, restricting a participant pool to studying the most experienced general dentists would not be representative of the overall dentist population.

6.3 Lack of Generalizability to Other Dental Diseases

This study looked at one specific diagnostic task - the interpretation of periapical inflammatory disease. Therefore, the results from this study may not be generalizable to other diagnostic tasks because it is hypothesized that each diagnostic task has a different tolerance to PSP plate artifacts. As discussed earlier, periapical inflammatory disease can elicit changes across a large area of the radiologic image, which explains why even in the presence of severe artifacts, diagnosis was not shown to be hindered. Therefore, it can be
said that the diagnosis of periapical inflammatory disease has a high tolerance for PSP plate artifacts. On the other hand, the diagnosis of caries is expected to have a lower tolerance for PSP plate artifacts. The caries disease process results in changes in a much smaller area of the radiologic image, and thus, PSP plate artifacts may be more likely to hinder caries diagnosis. Additional studies will be required to test these hypotheses to determine which diagnostic task has the lowest tolerance for PSP plates.
7 Future Directions

7.1 Study Different Dental Diseases

Even though this study found that PSP plate artifacts did not hinder the interpretation of periapical inflammatory disease, other dental diseases could potentially be more susceptible to these artifacts. These could include the interpretation of dental caries, periodontal bone loss, or intra-osseous pathology, such as cysts and tumors. Besides the diagnosis of disease, dental radiography is also used to determine the quality of restorations or for localization of anatomical structures. Hindrance to any of these radiologic tasks can be studied and determined. Ultimately, these results can be combined with this study's results to determine the most conservative threshold.

7.2 Assess PSP Plates made from Different Manufacturers

This study only looked at one brand of PSP plates, Carestream Dental's CS 7600 (Rochester, USA). However, the results of this study may not be generalizable to other PSP plate manufacturers. It is suspected that some PSP artifacts may be specific to a manufacturer, such as the “fish-scale” artifact described by Buchanan et al. that was seen in DIGORA Optime PSP plates (Soredex/Orion Corp., Helsinki, Finland). By studying different brands of PSP plates, there may be differing findings.

7.3 Improved Quality Assurance Guidelines and Protocols

There are many potential approaches to developing quality assurance guidelines. One promising avenue utilizes a trained machine-learning (ML) algorithm, also known as artificial intelligence. This technique allows for a computer to make a decision on a specific task (i.e. whether or not to discard a PSP plate) based on its previous training on gold standard or ground truth data. For example, after the algorithm has assessed the 2500 images from this study, along with whether the participant opted to discard the plate, the ML algorithm is able to generalize its training to predict whether any plate should be discarded or not.
ML algorithms have many benefits, including being objective, reproducible, and easily transferable via the internet globally. As well, ML techniques allow for evolution and improvement because they can be re-trained with new data sets to improve their capabilities. For example, if a similar study was conducted, looking at the effects of PSP plate artifacts on the diagnosis of caries or if another PSP system was studied, those results should be combined with the results of the current study to create a more robust ML algorithm. This algorithm could be implemented globally through an app or software built directly into PSP scanners or into picture archiving and communication systems (PACS). These programs could analyze a plate and determine not only whether a plate should be discarded, but also provide an objective metric for the artifact severity for monitoring purposes.
8 Conclusions

PSP plates have a finite lifespan because as they accumulate physical artifacts from use, the quality of the radiologic image is decreased. It is currently unknown how these artifacts affect the interpretation of common dental diseases. This study presents a novel technique to study the clinical impact of PSP plate artifacts on interpretation without requiring any additional patient exposure. Regardless of the severity of PSP plate artifacts, the interpretative accuracy of periapical inflammatory disease was not altered. However, as artifact severity increased, clinicians were less confident with their interpretation and were more likely to discard the damaged plate. These results can guide recommendations for quality assurance of PSP plates. Sample images have been provided as a guide for when plates should be discarded. Future study on the effects of artifacts on other dental diseases is required.
References


Appendices

9.1 University of Toronto Ethics Board Approval

Dear Trevor Thang,

Re: Your research protocol application entitled, “Developing a Quantitative Artifact Metric for Photo-Stimulable Phosphor (PSP) Plates to determine a threshold for Diagnostic Hindrance”

The Health Sciences REB has conducted a Delegated review of your application and has granted approval to the attached protocol for the period 2018-07-18 to 2019-01-09.

Please note that this approval only applies to the use of human participants. Other approvals may be needed.

Please be reminded of the following points:

- An Amendment must be submitted to the REB for any proposed changes to the approved protocol. The amended protocol must be reviewed and approved by the REB prior to implementation of the changes.
- An annual Renewal must be submitted for ongoing research. You may submit up to 6 renewals for a maximum total span of 7 years. Renewals should be submitted between 15 and 30 days prior to the current expiry date.
- A Protocol Deviation Report (PDR) should be submitted when there is any departure from the REB-approved ethics review application form that has occurred without prior approval from the REB (e.g., changes to the study procedures, consent process, data protection measures). The submission of this form does not necessarily indicate wrongdoing; however, follow-up procedures may be required.
- An Adverse Events Report (AER) must be submitted when adverse or unanticipated events occur to participants in the course of the research process.
- A Protocol Completion Report (PCR) is required when research using the protocol has been completed. For ongoing research, a PCR on the protocol will be required after 7 years (Original and 6 Renewals). A continuation of work beyond 7 years will require the creation of a new protocol.
- If your research is funded by a third party, please contact the assigned Research Funding Officer in Research Services to ensure that your funds are released.

Best wishes for the successful completion of your research.

Protocol #5869
Status: Delegated Review App
Version: 0001
Sub Version: 0001
Approved On: 18-Jul-18
Expires On: 09-Jan-19
Page 10 of 10
PSP Artifact Quality Assurance

Study Information Sheet

**Title of the Project:** Developing a Quantitative Artifact Metric for Photo-Stimulable Phosphor (PSP) Plates to determine a threshold for Diagnostic Hindrance

**Ethics Protocol Number:** 00035933

**Investigators:**
- Dr. Trevor Thang (D.D.S.), Faculty of Dentistry
- Dr. Susanne Perschbacher (D.D.S., M.Sc., Dipl. A.B.O.M.R., F.R.C.D.(C)), Faculty of Dentistry

**Goals of the Study**

Photostimulable phosphor (PSP) plates progressively lose image quality as they are being used due to the accumulation of bends and scratches, appearing as artifact on the radiologic image. It is currently unknown to what degree these artifacts affect the clinicians radiologic interpretation skills. This study aims to determine these effects and create guidelines that can be used to quality assure PSP plates in the clinical setting.

**Participation Involvement**

You can be a research participant if you are: 1) registered and in good-standing with a provincial dental legislative body as either a full member or a graduate student member AND 2) have a minimum one year of clinical dentistry experience after dental school that involves interpreting periapical pathology on radiographic images.

This study will ask for you to diagnose periapical pathology on periapical images with varying degrees of artifacts. Periapical pathology will encompass bony changes at the apices of teeth due to inflammatory disease. You will be presented with one hundred (100) images along with an answer sheet to input your answers. We anticipate that this will take approximately 60 minutes and will conducted at an agreed upon location. Approximately 35 participants will be polled.

Make sure to fill out your participant ID when given to you.
Rights as a Research Participant

1. **Confidentiality** - Your response data is strictly confidential and your data will be anonymized. You will be assigned a numeric identification code that will be used throughout the data analysis. Only your consent form will have your personal information. Including your e-mail address is optional; it will be only used to communicate the final results of the research project.

2. **Data Storage** - Data will be stored on an encrypted USB in a locked room. Only the members of the research committee will have access to this data. The data will be destroyed upon publication of the results, or up to five years after the collection data; whichever occurs first.

3. **Withdrawal from the Study** - You may withdraw from the study at any point during the testing or up to one-month after the testing date. If you choose to do this, your data will be deleted and will not be used for data analysis.

**Risks:** There are no foreseeable risks or harms in your participation in this survey besides your time and your expertise.

**Benefits:** Your participation in this study will help improve the dental community knowledge on the effects on PSP artifacts on diagnostic ability. These results will shed light on proper quality control protocol and can demonstrate to clinicians the value of replacing a damaged PSP plates. Ultimately, your patients will receive improved quality of care and improved oral health. For your time, you will be compensated $130 CAD.

**Future Direction:** Results from this study may be published in scientific journals or presented in scientific conferences. All data will be anonymized.
Objective: Evaluate the changes to the periapical region of the indicated tooth due to inflammatory disease.

Questions:

1. Do you see any changes to the periapical region of the indicated tooth due to inflammatory disease?

   indicate ‘YES’ if you see:
   - apical widening of the periodontal ligament space
   - rarefying osteitis
   - sclerosing osteitis, and/or
   - incomplete osseous healing.

   indicate ‘NO’ if you see:
   - normal periapical bone
   - complete osseous healing, and/or
   - having insufficient evidence of disease.

2. What is the confidence in your interpretation?

   4 - Excellent
   3 - Good
   2 - Fair
   1 - Poor

3. Would you discard this PSP plate?

   YES - you would discard this plate due to the level of PSP artifact
   NO - you would NOT discard this plate due to the level of PSP artifact
I, _____________________________________________ have read and understand the consent form. I have been given a copy of this form to keep. This study has been explained to me by one of the investigators. All of my questions have been answered. I voluntarily consent to participate in this study and understand that I have the right to withdraw at any time.

If I have any questions about this study, I may contact Dr. Trevor Thang at trevor.thang@mail.utoronto.ca

If I have any questions concerning my rights as a research participant, I may contact the University of Toronto Research Ethics Board at (416) 946-3273 or write to ethics.review@utoronto.ca.

____________________________________
Participant’s Signature

____________ ______________________________________
Investigator’s Signature

____________________________________
Date

____________________________________
E-mail Address (optional)

____________________________________
Personal Identification Number (PIN)
Receipt for Payment

Thank you for taking the time for providing your interpretations and insight!

I acknowledge that I have received $130.00 in cash in recognition of the time spent completing the study titled: “Developing a Quantitative Artifact Metric for Photo-Stimulable Phosphor (PSP) Plates to determine a threshold for Diagnostic Hindrance”.

Name
______________________________________________

ID Number
______________________________

Date
______________________________

Phone number
______________________________________________

Email
______________________________________________

Signature
______________________________________________

Received from: Trevor Thang, M. Sc. Candidate (Faculty of Dentistry)

Signature, Date
9.3  PSP Artifact Masks (total: 24)

9.3.1 Brand New (total: 4)

9.3.2 Moderate Artifacts (total: 5)

9.3.3 Severe Artifacts (total: 15)
9.4 Clinical Images (total: 100)
9.5 Testing Images

16 sample images from the “Testing Images” are shown. Each row contains images with the same artifact mask, while each column contains images with the same clinical image.
9.6 E-mail Thread acquiring Permission for Image Reproduction

SBU 2019/305: Reproduction of Image for Masters Thesis

Anna Björklöf Annabjorklof@abu.se vs utoronto.ca... Apr 28, 2019, 9:38 AM (6 days ago) 

to Trevor, Registrar

Dear Mr. Thang,

Thank you for your kind e-mail. It is perfectly fine to use the graphic on p 31, just make sure to mention SBU and web address www.sbu.se/en by the picture.

Best

From: Trevor Thang <trevor.thang@mail.utoronto.ca>

Skickat: den 24 april 2019 01:43

Till: Registrar <registrar@abu.se>

Anmärkning: Reproduction of Image for Masters Thesis

Dear Registrar,

My name is Dr. Trevor Thang and I am currently working on my thesis related to periapical inflammatory disease and have been using your article titled “Methods of Diagnosis and Treatment in Endodontology: A systematic review” dated June 2012, as a reference.

I also think the graphic on page 31 of this document is extremely informative and would like to include it in my thesis.

What are your guidelines for reproducing this image in my thesis, with proper referencing, of course?

Trevor

[Message clipped] View entire message

Trevor Thang <trevor.thang@mail.utoronto.ca> Apr 26, 2019, 2:27 PM (6 days ago) 

to Anna

Thank you.

Figure 1-5 Disease Mechanism for Periapical Inflammatory Disease. The enamel and dentin provide a strong outer coating to protect the vital tooth pulp. However, this protective layer can be breached by caries. This results in a bacterial incursion into the tooth pulp causing inflammation and subsequently, tooth necrosis. This necrotic tissue acts as a reservoir for bacteria and their metabolites which eventually drain out of the apical foramen into the bony. This results in an inflammation within the bony, which can be visualized radiologically. Image reproduced with the permission of the Swedish Agency for Health Technology Assessment and Assessment of Social Service. www.sbu.se/en

Is this sufficient?

Anna Björklöf via utoronto.com/microsoft.com Apr 28, 2019, 4:17 AM (4 days ago) 

to Registrar, Trevor

Thank you.

That looks fine! Good luck with your thesis!

Anna