Diagnostic Potential of Panoramic Radiography and CBCT in Detecting Implant-Related Ex Vivo Injuries of the Inferior Alveolar Canal Border

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The aim of this ex vivo study was to compare the diagnostic performances of panoramic radiography and cone beam computerized tomography (CBCT) in detecting implant-related injuries of the inferior alveolar canal. Monocortical bone windows were created in 60 fresh sheep hemimandibles, the inferior alveolar canals were revealed and 120 dental implants were inserted. Three types of injuries, described as pilot drill damage (PDRILL), collapsing of the superior border of the canal (COLL), penetration of the implant tip into the canal (PENET) and one control group, were simulated. Standard (PANO) and dentition mode panoramic (PANO-DENT) images as well as CBCT data presented as multiplanar reconstruction (MPR) and cross-sectional (CROSS) views were evaluated by 6 observers who had also expressed their level of confidence to their final diagnosis. Intra- and interobserver agreement scores were rated good. The area under the curve (AUC) values and the confidence scores for CROSS and multiplanar reformation (MPR) views were both significantly higher than those of PANO and PANO-DENT ($P < .05$ for each) in PDRILL group. In COLL group, observers showed less confidence to PANO and PANO-DENT compared to CROSS and MPR techniques ($P < .05$ for each). No other significant differences were found. Within the limits of this experimental study, it can be suggested that the standard and dentition modes of panoramic radiography can be as effective as CBCT in the detection of penetrating and collapsing injuries, but multiplanar and cross-sectional views of the CBCT are more accurate than panoramic radiography in the detection of pilot drill injuries in sheep mandible.

Key Words: inferior alveolar canal, implant, nerve injury, panoramic radiography, cone beam computerized tomography

INTRODUCTION

Iatrogenic injury of the trigeminal nerve branches is a serious cause for concern in modern dentistry. Even the dental professionals who only perform low-risk procedures such as local anesthesia, root canal filling, and restorative treatment, will have to manage an average of 2 cases of nerve injury, which lasts more than 1 month during their career.[1] The risk will be greater for those who routinely place implants, as inferior alveolar nerve is the most frequently injured branch of trigeminal nerve during this surgery. The incidence of implant-related nerve damage reported in previous studies varies between 0% and 13%,[2,3] mostly due to the mechanical, chemical, or thermal factors. The implant drills, implant tip, and bone debris are common causes of direct mechanical trauma, which may result in the pressure, entrapment, transection, or laceration of the nerve.[4] Such structural damages may lead to the clinical complaints described as anesthesia, mild hypoesthesia, dysesthesia, or pain. If the neurosensory disturbances become permanent, they interfere with every aspect of daily routines, adversely affect the quality of life and can result in medicolegal claims.[5] As nerve degeneration rapidly progresses, early diagnosis and management of the inferior alveolar nerve injuries are critical.[6] Radiographic evaluation is as important as the clinical inspection based on the subjective and objective sensory tests to determine the true extent of the damage.[2,7]

Panoramic radiography (PANO) has been the first-line extraoral imaging modality in every field of dentistry for more than 50 years. In digital PANO technique, the patient is positioned at the center of rotation between the X-ray source and the receptor, which usually rotate 180° in opposite directions. PANO produces a single, 2-dimensional (2D) image that includes structures of the maxilla and mandible.[8] Modern PANO devices also use specific modes for different diagnostic tasks. In the dentition mode (PANO-DENT), exposure is limited only to the frontal, right lateral, or left lateral area to segment the teeth views. Better orthogonality of the projections improves the view of interproximal structures.[9] The advantages of PANO include broad anatomical coverage, availability, low cost and less radiation dose, whereas image distortion,

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magnification, overlapping of the structures, and the absence of 3-dimensional (3D) visualization are its well-known drawbacks.[10] In cone beam computerized tomography (CBCT), on the other hand, the X-ray source and detector are fixed in a gantry that rotate around the patient's head. Data is stored as voxels from which 2D images from multiple planes, as well as 3D reconstructions, can be generated.[11,12] 2D image analysis can be done with 2 different techniques. Multiplanar reconstruction (MPR) method allows fast diagnosis whereas reformatted cross-sectional images (CROSS) enable the user to investigate closely positioned structures from predefined viewing angles.[13] As a true tomographic device, CBCT has a smaller footprint, lower cost, and dose exposure compared to medical CTs.[14] Artefacts and low soft tissue contrast resolution are its main disadvantages.[15] Both PANO and CBCT are frequently employed in the planning and postoperative evaluation of dental implant procedures.[10,16]

Although used for similar purposes, no study investigated the diagnostic potential of these devices in inferior alveolar nerve related complications of implant surgery. The aim of the present study is therefore to compare the diagnostic accuracies of PANO, PANO-DENT, MPR, and CROSS image presentation techniques in the detection of simulated injuries of the superior border of inferior alveolar canal in sheep mandible. The null hypothesis tested in this study is that there are no differences between the diagnostic accuracies or confidence levels of PANO, PANO-DENT, MPR, and CROSS techniques in the detection of different types of inferior alveolar canal border injuries.

Materials and Methods

Specimens and sample size estimation

Adult sheep hemimandibles obtained from animals bred for human consumption in similar dimensions were purchased from the same slaughterhouse. Soft tissues were stripped off and regions anterior to the mandibular foramen were sectioned. No previous article could be found from which to derive the data for sample size estimation. A pre-experimental study was therefore conducted and two area under the curve (AUC) values with least difference between them were found to be 0.91 and 0.87. Based on these values, assuming equal number of controls and simulated injuries, the minimum number of observations per imaging modality in each group required to reach 0.05 α probability level and 0.8 power (1-β) was calculated as 462, which was rounded up to 480 ($n = 480$) for practical reasons.[17] Accordingly, 40 implants (20 for injury, 20 for controls) were planned to be inserted in each group, two implants per hemimandible.

Surgical protocol and implant insertion

A modified version of the surgical protocol described by Metzger[18] was used in the present study. First, visible borders of the inferior alveolar canal on the medial side of the hemimandibles were traced with insoluble pen. A monocortical rectangular bone window, whose long edges are parallel to the course of the canal in the mandibular angle region, was prepared by using a diamond cutting disk in 1 cm diameter (Frios MicroSaw, Dentsply Friadent, Mannheim, Germany) (Figure 1a). Bone window was carefully removed intact and the superior borders of the canal and the nerve itself were visually identified (Figure 1b). Regions of the hemi-mandible remaining outside of the mandibular angle region were sectioned to form a 5-cm long rectangular bone block in 4-cm height. Superior and inferior basal borders of the blocks were minimally trimmed to create flat surfaces (Figure 1c). Relative implant positions were marked on the superior border of the blocks. The linear distance between the insertion point and the uppermost border of the canal was measured using a special, pre-calibrated caliper (Calipretto S 122-1000, Renfert, Hilzingen, Germany) with curved arm and nondestructive round tip.

A total of 120 dental implants (MIS Implants Technologies Ltd, Shlomi, Israel; Zimmer Biomet, Warsaw, Ind; Camlog Biotechnologies, Basel, Switzerland) made of commercially pure titanium were inserted according to their manufacturers' comments. Implant diameters were between 3.0 and 3.8 mm. Their length varied from 8 mm to 13 mm and selected according to the injury type. To simulate a pilot drill injury over which the implant is inserted (PDRILL group), the superior border of the canal was penetrated with the pilot drill and the implant was inserted within 1 to 2 mm above the injury site. An internal sinus floor augmentation kit with osteotomes (Sinus Lift Osteotomes Set, MK-0023, MIS Implants Technologies) was used to collapse the canal border inferiorly and the implant was inserted to support the convexity (COLL group) to simulate the pressure over the alveolar nerve with bone fragments. The recipient sites in the PENET group were prepared longer than usual to let the implant tip penetrate the canal's cortical border within 1 to 2 mm. No injury was created in control group (CONT) in which the implants were inserted within 1 to 2 mm distance to the superior border of canal (Figure 1d). Bone windows were then placed back. All cases were recorded and naked-eye inspection of the injuries was considered as the gold standard.

Radiographic templates

A cranium replica with maxilla and mandible in occlusion, was placed over two rectangular plastic utility shelves in similar dimensions that were glued along their long edges. Laser-cut acrylic beams were glued perpendicular to the shelves to stabilize the replica. Relative positions of the mandibular molar regions were traced bilaterally over the shelves and the mandible was removed. Thin sticky wax blocks (Boxing Wax Strips, Kerr Corporation, Orange, Calif) were positioned over those tracings. Bone blocks, covered with raw meat in 2-cm thickness on each side to simulate soft tissue, were placed over the sticky wax by melting and adapting it (Figure 1e). As the CBCT device used in this study scans patients in supine position, a holder was prepared from C-type silicone impression material (Zetaplus C-Silicone Impression Material, Zhermack SpA, Badia Polesine, Italy) to stabilize the skull replica and bone blocks during exposure (Figure 1f).

Image acquisition

Template holding the skull replica and bone blocks were adapted on a camera tripod (Slik 800GFL Deluxe, Slik Thailand

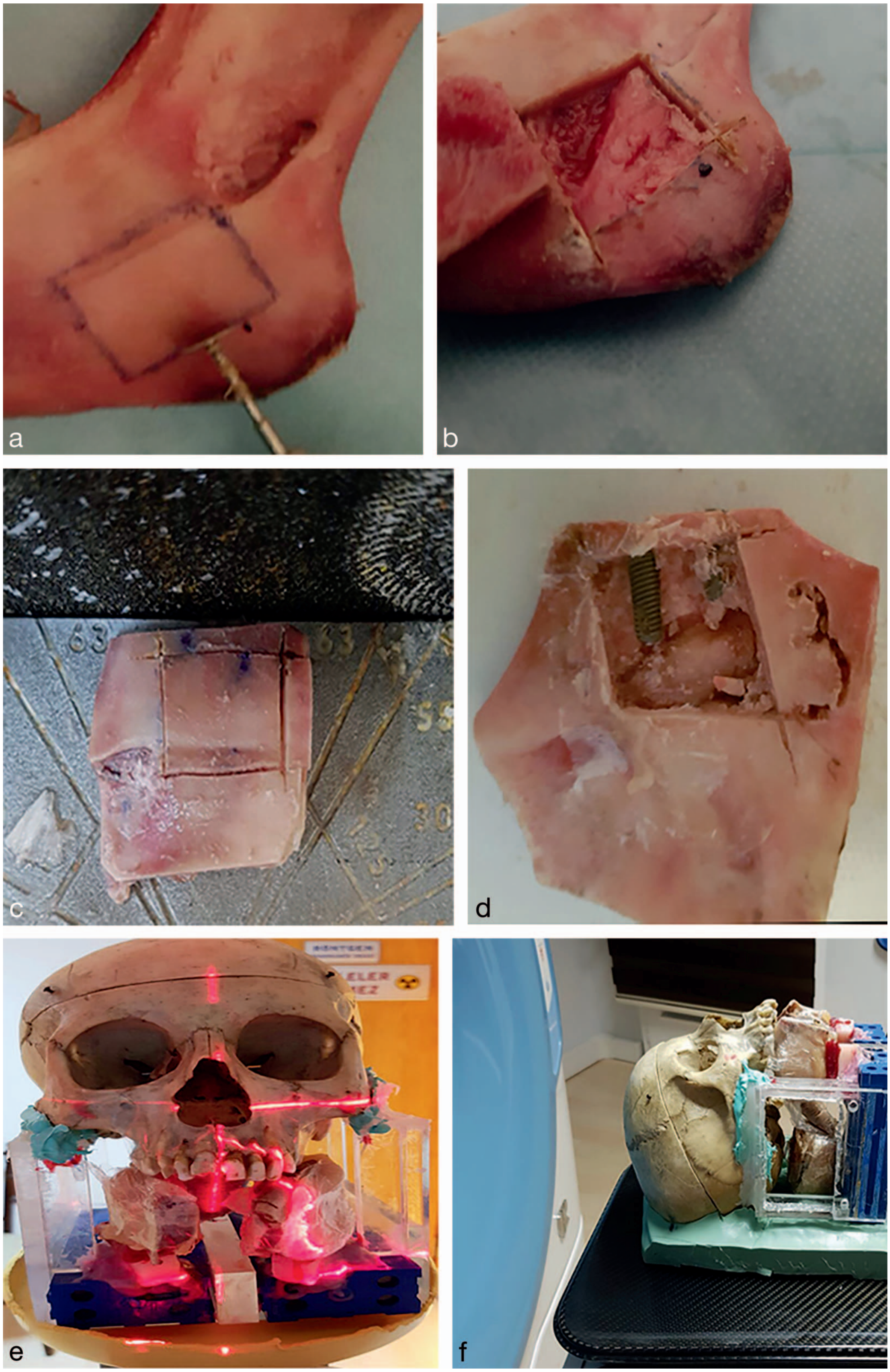

Figure 1. Borders (a) and separation (b) of the monocortical bone window; (c) downsizing of the hemimandibles to standard bone blocks; (d) clinical photograph of simulated injuries: canal penetration (left) and collapsing of the cortical border (right). Positioning of the radiographic phantom before panoramic (e) and cone beam computerized tomography imaging (f).

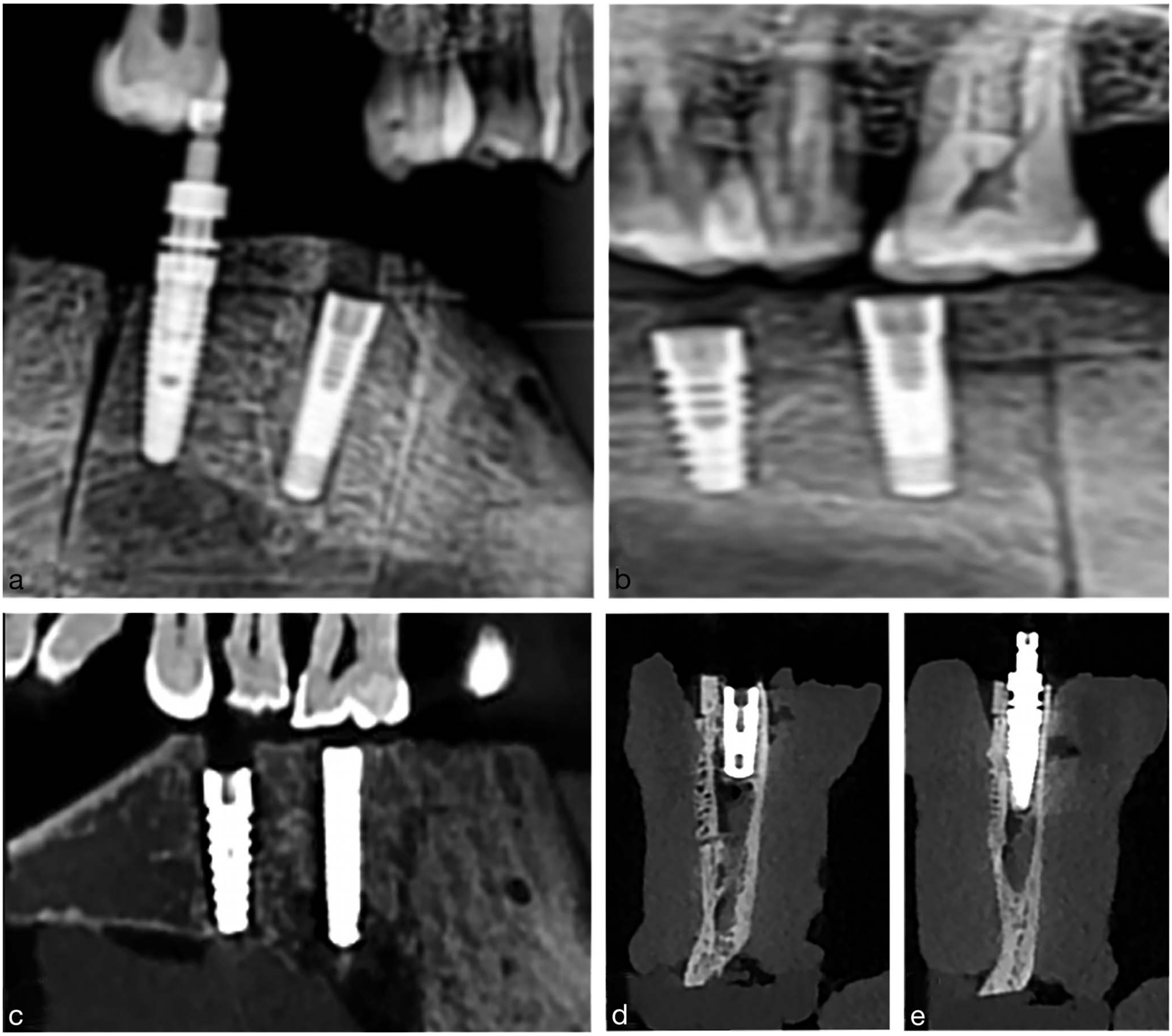

Figure 2. (a) Pilot drill injury (left) and collapsing of the superior border of the inferior alveolar canal (right) in standard panoramic radiography. (b) Images taken with the dentition mode of the panoramic radiography showing pilot drill injury (left) and control samples with no damage (right). (c) Pilot drill perforation (left) and collapsing of the canal border (right) in the multiplanar reconstructed image from sagittal plane. (d) The cross-sectional image of collapsing of the cortical border and the penetration of the implant tip into the inferior alveolar canal (e).

Co. Ltd., Pathum Thani, Thailand) and positioned in the PANO device NewTom Giano Panoramic (NewTom, Verona, Italy). Focal trough was selected in the same manner as in clinical conditions (Figure 1e). Exposure was done with 60 kV, 2 mA, 13-second parameters in each case by selecting standard and dentition modes. The replica construct was then placed in the silicone holder and positioned inside the gantry of NewTom 5G CBCT scanner (NewTom) with the help of lateral and medial beams (Figure 1f). After adjusting its position based on scout views, the exposure was done by selecting 12×8 FOV, boosted dose, 0.2-mm isotropic voxel size settings. Primary reconstruction was made at 0.2-mm axial slice thickness in high resolution and small field options. Final secondary reconstructions also were prepared at 0.2-mm slice thickness in all planar orientations for MPR (Figure 2c) and coronal reformatted CROSS views (Figure 2d and e).

Observers and reading sessions

Six observers (3 oral radiologists, 3 oral maxillofacial surgeons) who had more than 10 years of experience in their field were invited to examine the images. They were first calibrated on the manipulation of the imaging reading software (NNT Software, NewTom) by using sample images that were not included in the original dataset. Same software was used for PANO (Figure 2a), PANO-DENT (Figure 2b), MPR (Figure 2c), and CROSS (Figure 2d and e) images. Reading sessions were arranged to start at 10:00 AM in the morning, in a dimly lit, quiet room. The

TABLE

Comparisons of the diagnostic accuracies and confidence scores of the imaging modalities stratified by the type of injury*†

Type of Injury	Imaging Modality	Area Under the ROC Curve ± SE	Mean Confidence Score ± SD
PDRILL	PANO	0.52 ± 0.07a	2.70 ± 0.85b
	PANO-DENT	0.60 ± 0.07a	2.55 ± 0.78b
	MPR	0.85 ± 0.05A	3.40 ± 0.84B
	CROSS	0.90 ± 0.05A	3.55 ± 0.81B
PENET	PANO	0.85 ± 0.05	3.80 ± 0.68
	PANO-DENT	0.80 ± 0.06	3.90 ± 0.77
	MPR	0.87 ± 0.05	3.87 ± 0.82
	CROSS	0.90 ± 0.04	3.67 ± 0.88
COLL	PANO	0.77 ± 0.06	2.92 ± 0.82c
	PANO-DENT	0.80 ± 0.06	3.07 ± 0.97c
	MPR	0.87 ± 0.05	3.52 ± 1.01C
	CROSS	0.90 ± 0.04	3.62 ± 0.95C

*PDRILL indicates pilot drill injury; PENET, penetration injury; COLL, collapse type injury; PANO, panoramic radiography; PANO-DENT, panoramic radiography dentition mode; MPR, multiplanar reconstruction view; CROSS, cross-sectional view; SE, standard error; SD, standard deviation.

†Values indicated by uppercase letters are significantly different from their lowercase counterparts written in the same column.

computer system included a high-end PC connected to a 21.5-inch LED monitor at 1920×1080 resolution (Dell SE2219H, Dell Inc, Round Rock, Tex). Observers were free to manipulate brightness, contrast, gamma, zoom, and planar orientation of the images. During the sessions, observers were first asked determine whether an injury of the superior border of the canal is present (1) or absent (0). If the response is positive, then they had to determine whether it is a pilot drill injury (1), collapse damage (2), or full penetration (3). Observers also rated their final diagnostic confidence on a 5-item, intensity-based Likert type scale (1 point) strongly not confident, (2 points) not confident, (3 points) undecided, (4 points) confident, and (5 points) strongly confident. All images were evaluated twice with 4 weeks' interval for memory washout effect. Observers were blinded by preventing access to their first comments and others' interpretations as well.

Statistical analysis

The methodology was reviewed by an independent statistician. MedCalc (MedCalc Inc., Mariakerke, Belgium) software was used for sample size estimation and data analysis. The intra- and interobserver agreement scores were calculated with weighted kappa statistics and interpreted according to the criteria of Landis and Koch:[19] 0 to 0.20 was considered as poor agreement, 0.21 to 0.41 as fair, 0.41 to 0.60 as moderate, 0.61 to 0.80 as good, and above 0.81 as excellent. As those were higher than 0.6, first and second interpretations of all observers were considered as a single entity in each imaging modality and compared with the gold standard. The receiver operator characteristics curve (ROC) of each injury in each device was drawn and the AUC was calculated. The AUCs were statistically compared with post-hoc Z statistics and significantly higher values indicated higher accuracy of that modality for the corresponding type of injury. As the distribution of the confidence scores did not meet the assumptions of normality and homogeneity of variances, Kruskal-Wallis and Mann-Whitney U tests were used for multiple- and pairwise-comparisons, respectively. The confidence interval was set to 95% and $P < .05$ was considered significant.

RESULTS

The results were analyzed by an independent statistician. The null hypothesis has been rejected. Observers' background did not have an effect on the outcome. Intra-observer agreement scores varied between 0.73 and 0.89, which were classified as good and excellent agreements, respectively. As these scores were higher than 0.6 (good), first and second readings of each observer were considered together. Interobserver consistencies in the detection of simulated injuries for each imaging modality were found to be between 0.68 and 0.79. Thus, as the observers' were in good agreement with each other, all of their interpretations in each imaging modality and type of simulated injury were grouped and ROC curves were drawn by selecting the gold standard as the classification variable. In PDRILL injuries, AUC values of CROSS (0.90 ± 0.05) and MPR (0.85 ± 0.05) views of the CBCT were both significantly higher than those of PANO (0.52 ± 0.07) and PANO-DENT (0.60 ± 0.07) ($P < .05$). Similarly, observers' cumulative confidence to their final diagnosis in CROSS (3.55 ± 0.81) and MPR (3.40 ± 0.84) views were found to be higher than they expressed for PANO (2.70 ± 0.85) and PANO-DENT (2.55 ± 0.78) ($P < .05$). No significant differences were found between the diagnostic performance of the imaging modalities in the detection of simulated injuries in PENET and COLL groups. However, observers were significantly less confident of their final answers in PANO (2.92 ± 0.82) and PANO-DENT (3.07 ± 0.97) modes compared to CROSS (3.62 ± 0.95) and MPR (3.52 ± 1.01) in the detection of COLL type injuries ($P < .05$) (Table).

DISCUSSION

All injuries of the inferior alveolar canal's superior border do not necessarily lead to clinical symptoms of the nerve damage,[20] but once they have occurred, the injury can be very difficult to treat. Renton and Yilmaz[21] reported that 64% of its patients with persistent symptoms did not fully recover. On the other hand, it was also reported in a meta-analysis that 91% of the patients who have had reported altered sensation, have returned to normal within 1 year, whereas 3% still had persistent symptoms.[22] Extent of the injury and neurosensory changes during 4 to 8 weeks of observation period seem to be the most important prognostic determinants.[1,23,24]

CBCT and PANO were included in the present study as they are the two main imaging modalities used in the radiographic analysis of the canal injury. The sheep hemi-mandibles have been widely used in maxillofacial research and they can be easily obtained in large numbers. The canal injury model was modified from a nerve lateralization study,[18] and it was employed for the first time with acceptable results. Furthermore, we also added a human cranium replica and soft tissue layers to limit the effects of previously unexplored variables as there is no proven universal soft tissue equivalent material that can be used in PANO and CBCT simultaneously. Types of mechanical injuries we simulated in this experiment were derived from previously published reports.[2,25] All damages were created within the 1- to 2-mm limit because most of these injuries usually originate from minor radiographic miscalculations and the lengths of commercially available implants generally increase with 2-mm increments. Standard PANO, PANO-DENT, MPR, and CROSS techniques are proven visualization methods that enable accurate diagnosis. Six observers were included in the present study, as 5 is the minimum number suggested in previous studies.[26,27] Observers were selected among radiologists and oral surgeons, because it is highly probable that these two specialties would be handling such cases in realistic conditions. The observer's confidence variable was included to further increase the clinical relevance, since the lack of confidence in final radiographic diagnosis may lead to retakes or explorative surgery.

Radiological safety margins between the implant tip and the superior border of the canal has been investigated by various authors using either PANO or CBCT. Bornstein et al[16] advised against the use of CBCT for routine planning or follow-up of dental implants, but they also emphasized its diagnostic value in determining the extent of complications concerning the inferior alveolar nerve. Başa and Dilek[28] evaluated the density and thickness of the superior border of canal based on Hounsfield units calculated from CBCT to determine its relative resistance to implant drills. Authors concluded that the cortical bone density of the canal should be considered when making linear measurements during the planning phase, since the canal might not withstand the pressure of the drills. Similarly, Sammartino et al[29] used the boundary element method to model a mandible with 3 implants and tested the pressure of the construct over the canal under different loads. They reported that the distance between the tip of the implant and the canal correlated inversely with the pressure over the nerve. Authors suggested a minimum of 1.5-mm distance between the implant apex and the canal roof. Murat et al[30] compared the safety of making the linear measurements in intraoral radiographs with that of CBCT before implant placement. They inserted final drills in cadaveric mandibles and measured the distance between the drill tip and the nerve bundle after dissecting the specimens. Authors concluded that making measurements with CBCT was safer. Kütük et al[31] compared the frequency of neurosensory disturbances in patients with implants whose tips were less than 1 mm and between 1 to 2 mm in close proximity to the canal roof. Only 1 out of 14 patients in the first group was observed to show signs of hypoesthesia. In a similar study, Tüfekçioğlu et al[32] also tested the safety of inserting implants within 2 mm above the canal roof and reported that only 3 patients whose implants were placed within 0-mm distance to the canal developed neurosensory disturbances. The definition of safe distance to the inferior alveolar canal used in aforementioned articles was in accordance with the present study. However, findings of these latter retrospective series should be approached with caution as authors only used PANO to measure small distances and presented no evidence of observer reliability.

Our findings indicated that the diagnostic efficacies of standard PANO and PANO-DENT modes were not different from those of MPR and CROSS views of CBCT for the detection of full penetration injuries and collapsing of the canal border. In the absence of anatomical variations and with the aid of magnification correction, the panoramic devices have been found to produce accurate and reproducible vertical measurements in the molar region. In addition, the COLL and PENET injuries simulated in the present study involve a relatively large area, which can be easily detected by following the continuity of the superior border of the canal. Correct positioning and standard exposure of the specimens in panoramic radiography device, also supported by the zoom functions of the imaging software and expertise of the observers, may have led the PANO and PANO-DENT modes to show similar performance with CBCT. On the other hand, we should also note that the observers' confidence to their final diagnosis for COLL injuries were lower in PANO and PANO-DENT compared to CBCT views. This indicates that a clinician facing a similar problem may consider using advanced imaging methods, even though using only the panoramic views could have provided the same diagnostic information. The pilot drill injuries, however, did not include penetration of the implant tip, but a small hole that corresponds to the diameter of the pilot drill over which the implant tip was positioned. Therefore, PANO modes could not have presented enough diagnostic information regarding the integrity of the canal border, by limiting the observers' ability to distinguish the cortical border from the trabecular structure. In contrast, MPR and CROSS views of the CBCT allow multiplanar observation including the coronal orientation, from which the observers could have been able to better delineate the characteristics of the injury. Renton et al[33] described 30 cases with different degrees of neuropathy that occurred due to iatrogenic nerve injury associated with dental implants. The authors showed that the roof of the canal was in contact with the implants in 44% of cases, penetrated in 20%, and completely crossed in 20% by using CBCT. Interestingly, the latter study and that of Toit et al[34] mentioned implants inserted in close proximity of the canal roof. Although no complete penetration could be shown, the clinical symptoms suggested damage to the inferior alveolar nerve. These cases may be related to the pilot drill injuries simulated in this study, as most of them are late referrals that provide enough time for bone injury to heal while the nerve damage persisted.

The present study also had some potential limitations. Since the radiographic density of the superior border of the canal in human mandible may differ from that of the sheep, the interpretation of the findings was constrained to sheep mandible. Some discrepancies may occur in case other sources such as bovine bone and pig mandible are employed. Only one type of device per each imaging modality with standardized exposure as well as reconstruction settings were used for data collection. Therefore, the technical variations among panoramic and CBCT devices in the market may influence the outcomes of the study. In addition, dental implants have various kinds of surface topography that may alter the amount of X-ray beam attenuation. Implants with different surface properties as well as apical designs other than those used in the present experiment can hamper the interpretation of the results. Also, the diameter of pilot drill, which effects the detection of pilot drill injuries, can vary according to different implant systems. The digital intraoral radiography, on the other hand, offers better resolution than both systems from a technical standpoint. However, since some limitations, such as shallow floor of the mouth, gagging reflex, and curvature of the mandible, make it difficult to obtain images with parallel technique from the molar region in clinical settings, it was not included in the present study. Our findings should be further validated under clinical conditions by using multiple devices with different image reconstruction settings.

Conclusion

Within the limits of this experimental study, it can be concluded that the standard and dentition modes of digital PANO are as effective as CBCT in the detection of implant-related penetrating and collapsing injuries of the superior border of the inferior alveolar canal. However, MPR and CROSS views of the CBCT are more likely to provide more accurate and confident information than PANO in the detection of pilot drill injuries with implants inserted in close vicinity.

Abbreviations

AUC: area under the curve
CBCT: cone beam computerized tomography
COLL: collapse
CROSS: cross-sectional
MPR: multiplanar reconstruction
PANO: panoramic radiography
PANO-DENT: dentition mode
PDRILL: pilot drill
PENET: penetration
ROC: receiver operator characteristics
2D: 2-dimensional
3D: 3-dimensional

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Note

The authors declare no conflict of interest.

References

1. Meyer RA, Bagheri SC. Clinical evaluation of peripheral trigeminal nerve injuries. *Atlas Oral Maxillofac Surg Clin North Am*. 2011;19:15–33.

2. Juodzbalys G, Wang HL, Sabalys G. Injury of the inferior alveolar nerve during implant placement: a literature review. *J Oral Maxillofac Res*. 2011;2:e1.

3. Steinberg MJ, Kelly PD. Implant-related nerve injuries. *Dent Clin North Am*. 2015;59:357–373.

4. Bagheri SC, Meyer RA. Management of mandibular nerve injuries from dental implants. *Atlas Oral Maxillofac Surg Clin North Am*. 2011;19:47–61.

5. Pogrel MA, Jergensen R, Burgon E, Hulme D. Long-term outcome of trigeminal nerve injuries related to dental treatment. *J Oral Maxillofac Surg*. 2011;69:2284–2288.

6. Misch CE, Resnik R. Mandibular nerve neurosensory impairment after dental implant surgery: management and protocol. *Implant Dent*. 2010; 19:378–386.

7. Miloro M, Kolokythas A. Inferior alveolar and lingual nerve imaging. *Atlas Oral Maxillofac Surg Clin North Am*. 2011;19:35–46.

8. Lee JSK, Kang BC. Screening panoramic radiographs in a group of patients visiting a health promotion center. *Korean J Oral Maxillofac Radiol*. 2005;35:4.

9. Vandenberghe B, Jacobs R, Bosmans H. Modern dental imaging: a review of the current technology and clinical applications in dental practice. *Eur Radiol*. 2010;20:2637–2655.

10. Suomalainen A, Pakbaznejad Esmaeili E, Robinson S. Dentomaxillofacial imaging with panoramic views and cone beam CT. *Insights Imaging*. 2015;6:1–16.

11. De Vos W, Casselman J, Swennen GR. Cone-beam computerized tomography (CBCT) imaging of the oral and maxillofacial region: a systematic review of the literature. *Int J Oral Maxillofac Surg*. 2009;38:609–625.

12. Kau CH, Bozic M, English J, Lee R, Bussa H, Ellis RK. Cone-beam computed tomography of the maxillofacial region—an update. *Int J Med Robot*. 2009;5:366–380.

13. Pauwels R, Araki K, Siewerdsen JH, Thongvigitmanee SS. Technical aspects of dental CBCT: state of the art. *Dentomaxillofac Radiol*. 2015;44: 20140224.

14. Scarfe WC, Farman AG, Sukovic P. Clinical applications of cone-beam computed tomography in dental practice. *J Can Dent Assoc*. 2006;72: 75–80.

15. Scarfe WC, Farman AG. What is cone-beam CT and how does it work? *Dent Clin North Am*. 2008;52:707–730.

16. Bornstein MM, Horner K, Jacobs R. Use of cone beam computed tomography in implant dentistry: current concepts, indications and limitations for clinical practice and research. *Periodontol 2000*. 2017;73:51–72.

17. Faul F, Erdfelder E, Lang AG, Buchner A. G*Power 3: a flexible statistical power analysis program for the social, behavioral, and biomedical sciences. *Behav Res Methods*. 2007;39:175–191.

18. Metzger MC, Bormann KH, Schoen R, Gellrich NC, Schmelzeisen R. Inferior alveolar nerve transposition–an in vitro comparison between piezosurgery and conventional bur use. *J Oral Implantol*. 2006;32:19–25.

19. Landis JR, Koch GG. The measurement of observer agreement for categorical data. *Biometrics*. 1977;33:159–174.

20. Agbaje JO, de Casteele EV, Salem AS, Anumendem D, Lambrichts I, Politis C. Tracking of the inferior alveolar nerve: its implication in surgical planning. *Clin Oral Investig*. 2017;21:2213–2220.

21. Renton T, Yilmaz Z. Managing iatrogenic trigeminal nerve injury: a case series and review of the literature. *Int J Oral Maxillofac Surg*. 2012;41: 629–637.

22. Lin CS, Wu SY, Huang HY, Lai YL. Systematic review and meta-analysis on incidence of altered sensation of mandibular implant surgery. *PLoS One*. 2016;11:e0154082.

23. Bagheri SC, Meyer RA. When to refer a patient with a nerve injury to a specialist. *J Am Dent Assoc*. 2014;145:859–861.

24. Meyer RA, Bagheri SC. Nerve injuries from mandibular third molar removal. *Atlas Oral Maxillofac Surg Clin North Am*. 2011;19:63–78.

25. Worthington P. Injury to the inferior alveolar nerve during implant placement: a formula for protection of the patient and clinician. *Int J Oral Maxillofac Implants*. 2004;19:731–734.

26. Obuchowski NA. Sample size tables for receiver operating characteristic studies. *AJR Am J Roentgenol*. 2000;175:603–608.

27. Obuchowski NA. ROC analysis. *AJR Am J Roentgenol*. 2005;184:364–372.

28. Basa O, Dilek OC. Assessment of the risk of perforation of the mandibular canal by implant drill using density and thickness parameters. *Gerodontology*. 2011;28:213–220.

29. Sammartino G, Wang HL, Citarella R, Lepore M, Marenzi G. Analysis of occlusal stresses transmitted to the inferior alveolar nerve by multiple threaded implants. *J Periodontol*. 2013;84:1655–1661.

30. Murat S, Kamburoglu K, Kilic C, Ozen T, Gurbuz A. Nerve damage

assessment following implant placement in human cadaver jaws: an ex vivo comparative study. *J Oral Implantol*. 2014;40:76–83.

31. Kutuk N, Gonen ZB, Yasar MT, Demirbas AE, Alkan A. Reliability of panoramic radiography in determination of neurosensory disturbances related to dental implant placement in posterior mandible. *Implant Dent*. 2014;23:648–652.

32. Tufekcioglu S, Delilbasi C, Gurler G, Dilaver E, Ozer N. Is 2 mm a safe distance from the inferior alveolar canal to avoid neurosensory complications in implant surgery? *Niger J Clin Pract*. 2017;20:274–277.

33. Renton T, Dawood A, Shah A, Searson L, Yilmaz Z. Post-implant neuropathy of the trigeminal nerve. A case series. *Br Dent J*. 2012;212:E17.

34. Du Toit J, Gluckman H, Gamil R, Renton T. implant injury case series and review of the literature part 1: inferior alveolar nerve injury. *J Oral Implantol*. 2015;41:e144–e151.