RESEARCH ARTICLE

Artefacts in multimodal imaging of titanium, zirconium and binary titanium–zirconium alloy dental implants: an *in vitro* study

¹Ralf Smeets, ¹Maximilian Schöllchen, ²Tobias Gauer, ³Ghazal Aarabi, ¹Alexandre T Assaf, ¹Carsten Rendenbach, ¹Benedicta Beck-Broichsitter, ¹Jan Semmusch, ⁴Jan Sedlacik, ¹Max Heiland, ⁴Jens Fiehler and ⁴Susanne Siemonsen

¹Department of Oral and Maxillofacial Surgery, University Medical Center Hamburg-Eppendorf, Hamburg, Germany;

²Department of Radiotherapy and Radiation Oncology, University Medical Center Hamburg-Eppendorf, Hamburg, Germany;

³Department of Prosthetic Dentistry, Center for Dental and Oral Medicine, University Medical Center Hamburg-Eppendorf, Hamburg, Germany; ⁴Department of Diagnostic and Interventional Neuroradiology, University Medical Center Hamburg-Eppendorf, Hamburg, Germany

Objectives: To analyze and evaluate imaging artefacts induced by zirconium, titanium and titanium–zirconium alloy dental implants.

Methods: Zirconium, titanium and titanium–zirconium alloy implants were embedded in gelatin and MRI, CT and CBCT were performed. Standard protocols were used for each modality. For MRI, line–distance profiles were plotted to quantify the accuracy of size determination. For CT and CBCT, six shells surrounding the implant were defined every 0.5 cm from the implant surface and histogram parameters were determined for each shell.

Results: While titanium and titanium–zirconium alloy induced extensive signal voids in MRI owing to strong susceptibility, zirconium implants were clearly definable with only minor distortion artefacts. For titanium and titanium–zirconium alloy, the MR signal was attenuated up to 14.1 mm from the implant. In CT, titanium and titanium–zirconium alloy resulted in less streak artefacts in comparison with zirconium. In CBCT, titanium–zirconium alloy induced more severe artefacts than zirconium and titanium.

Conclusions: MRI allows for an excellent image contrast and limited artefacts in patients with zirconium implants. CT and CBCT examinations are less affected by artefacts from titanium and titanium–zirconium alloy implants compared with MRI. The knowledge about differences of artefacts through different implant materials and image modalities might help support clinical decisions for the choice of implant material or imaging device in the clinical setting.

Dentomaxillofacial Radiology (2017) **46**, 20160267. doi: [10.1259/dmfr.20160267](https://doi.org/10.1259/dmfr.20160267)

Cite this article as: Smeets R, Schöllchen M, Gauer T, Aarabi G, Assaf AT, Rendenbach C, et al. Artefacts in multimodal imaging of titanium, zirconium and binary titanium–zirconium alloy dental implants: an *in vitro* study. *Dentomaxillofac Radiol* 2017; **46**: 20160267.

Keywords: dental implants; artefacts; MRI; CBCT; spiral CT

Introduction

Advanced imaging techniques such as MRI, CT and CBCT play an increasingly important role in not only diagnostic imaging of the maxillofacial region but also

pre- and post-operative diagnosis and monitoring in dental implantology.^{1–5}

Standard CT and CBCT provide excellent three-dimensional images of bones, allowing precise pre-operative implant planning, but are inferior to MRI in imaging soft-tissue structures.^{6,7} However, when imaging titanium implant placement and peri-implant bone

Correspondence to: Dr Ralf Smeets. E-mail: r.smeets@uke.de

The authors Smeets and Schöllchen contributed equally to this study.

Received 27 June 2016; revised 10 November 2016; accepted 15 November 2016

structure and adjacent soft tissues, CT and CBCT are typically impaired by streaking artefacts, with frequent appearance at interfaces between materials with very low and very high radio-opacity.⁸

In comparison with CT and CBCT, MRI provides a diagnostic tool that requires no ionizing radiation but exhibits excellent soft-tissue contrast for detailed imaging of the periodontal soft tissue, detection of inflammatory processes and diagnosis as well as staging and restaging of tumours.^{9,10}

However, the suitability of MRI as a diagnostic tool in head and neck imaging and especially dental imaging is highly dependent on the presence and magnitude of susceptibility artefacts.^{11–13} Susceptibility artefacts are caused by the presence of metallic materials and their higher susceptibility compared with surrounding tissues, which induces inhomogeneity in the magnetic field.^{11,14} Particularly, ferromagnetic components of these materials alter the precession frequencies of protons in the adjacent tissues causing signal loss and spatial distortion in the surrounding area.¹⁵ This also applies to titanium implants, which are commonly used in dental implantology. Hence, in the presence of metallic implants, the usefulness of MRI, especially for diagnosis and monitoring of tumours and inflammatory processes of the maxillofacial region, is severely limited. Especially in primary tumour diagnostics and restaging, these artefacts can decrease image quality to such an extent that sufficient evaluation of tumour size, recurrence or osseous tumour invasion is highly limited in close implant surroundings.^{14,16–19}

In recent years, metal-free implants composed of zirconium are increasingly considered a reasonable alternative to titanium implants and are implanted with increasing frequency. Zirconium implants are reported to exhibit tooth-like colour, leading to preferred use in the aesthetic zone, reduced plaque accumulation and superior biocompatibility with improved soft-tissue attachment, reduced inflammatory response and lower risk of inducing allergic reactions in comparison with titanium implants.^{20–25} Furthermore, osseointegration and mechanical stability of zirconium are reported to be comparable with that of titanium implants with superior cosmetic results and comparable success rates.^{26–29}

A number of *in vitro* studies evaluated the extent of artefacts caused by dental implants in CT, CBCT and MRI. The studies mainly focused on pre-operative planning and measurement accuracy in dental implantology while applying dedicated imaging techniques.^{30–32} Nevertheless, focal inflammation detection or regional tumour restaging rely on the visibility of periodontal soft tissues adjacent to dental implants, but are dependent on the implant material and applied imaging modality. Recent advances in dental MRI applying dedicated sequence protocols and head coils have led to improved image quality and broadened variety of indications.^{33,34} Even though CBCT is at present not considered a standard tool in oncologic imaging, a recent study showed a similar or even superior image quality of

CBCT compared with CT using equalized dose levels, predicting a growing overlap of indications for CBCT and CT when it comes to diagnostics of hard-tissue structures.³⁵ In addition, Hendrikx *et al*³⁶ pointed out its potential when it comes to diagnostics of mandibular invasion or erosion in patients with oral squamous cell carcinoma.

The present *in vitro* study aimed to analyze and evaluate artefacts induced by titanium, titanium–zirconium alloy and zirconium dental implants in MRI, CT and CBCT in a simulated clinical setting by explicitly applying standard clinical protocols for each imaging modality. Quantity and quality of artefacts arising from dental implants will differ, depending on different implant materials and different scan devices. This can lead to differences in image quality and minor diagnostic values.

Methods and materials

Implant phantoms

Zirconium (ZrO₂), titanium (Ti) and titanium–zirconium (Ti–ZrO₂) alloy implants were separately embedded in a 3% gelatin phantom. The gelatin phantoms were chosen to provide a similar setup for all three modalities and to achieve maximum comparability. To avoid air–gelatin boundaries in the vicinity of the implants, the remaining space in containers was filled with sodium chloride (0.9%). Details on materials and sizes of implants are provided in Table 1. Unfortunately, the vendor could give no sufficient information concerning electron density. The approximate physical density is 98 GPa.

The embedded samples were scanned by two CT scanners, one generally employed for radiation therapy and diagnostic radiology (SOMATOM Definition AS Open; Siemens, Berlin, Germany) and the other for diagnostic purposes in the emergency unit (Brilliance 64; Philips, Berlin, Germany); by a CBCT (Planmeca SCS MedSeries® H20, Finland), and a 3.0-T MR scanner (Skyra; Siemens, Berlin, Germany), respectively.

Standard clinical protocols were used for each modality and the phantoms were positioned according to the implant location in the mandible. Since the degree of image distortion relies upon not only the shape, size and susceptibility of dental materials but also the sequence type and protocol parameters, applied imaging protocols were consistent with protocols for dental imaging in MRI and soft-tissue head and neck imaging in CT of our institutes.

Imaging

For 3.0-T MRI, the imaging protocol consisted of a *T*₂ weighted (T2w) space sequence [echo time = 139 ms, repetition time = 2500 ms, slice thickness = 1 mm, 0.94 × 0.94-mm voxel size, matrix 192 × 192, field of view (FOV) 180 mm] and a *T*₁ weighted (T1w) volumetric interpolated brain examination technique

Table 1 Implants used in the study (including information about length and diameter by the manufacturer)

Material		Manufacturer	Length including platform (mm)	Diameter of body (mm)
Titanium	Titanium (Ti)	Straumann®	12	4.1
Roxolid®	85% titanium, 15% Zirconium (Ti-ZrO ₂)	Straumann®	13	4.1
Zirconium	Zirconium (ZrO ₂)	Straumann®	16	4.1

(echo time = 2.46 ms, repetition time = 5.8 ms, slice thickness = 0.5 mm, 0.5×0.5 mm voxel size, matrix 384×384 , FOV 192 mm) using a 20-channel head coil.

On the Siemens CT scanner, a spiral technique was used with 120 kV and 183 mAs, 512×512 matrix, 0.9-mm pixel spacing, 0.6-mm slice thickness and convolution kernel H31s. On the Philips CT scanner, a spiral CT technique was carried out using 143 mAs, 120 kV, 512×512 matrix, 0.48-mm pixel spacing, 1-mm slice thickness and convolution kernel B.

For the CBCT scans, the voxel size was automatically set to 400 μ m in the standard scan protocol with a 200×100 -mm FOV. This volume was chosen in order to achieve comparability between the different image modalities. Tube settings were 90 kV and 8 mA with 13.6-s exposure time.

The three phantom samples were placed in the same position and level for all scans to ensure reproducibility.

MRI data evaluation

Two researchers (SS and MS) independently measured the implant length and diameter as indicated by signal voids on T1w and T2w images. Identical window width and level on axial, coronal and sagittal reformatted images were applied using open-source OsiriX software (OsiriX Foundation, Geneva, Switzerland). Mean values for each measurement were calculated for further analyses.

Since signal voids in MR images show a different behaviour and distribution in comparison with CT and CBCT, we chose line-distance profiles as previously

used to describe artefacts in MRI.³⁰ 10 regions of interest by parallel lines perpendicular to the implant axis were defined using the software Analyze (Analyze Software Package v. 11.0; Biomedical Imaging Resource, Mayo Foundation, Rochester, NY) within the slice of the maximum extent of the artefact in coronal reformations for each material and sequence (Figure 1a). 1 line-distance profile was then calculated for each material from the median values of all 10 defined regions of interest by parallel lines in T1w and T2w images.

CT and CBCT data evaluation

Axial images perpendicular to the implant longitudinal axis were used for data evaluation. To take into account the radial distribution of CT and CBCT artefacts,³² circular regions of interest (cROIs) of 4.1-mm diameter outlining the implant were defined for each implant material within axial slices in CT and CBCT scans. These binary regions of interest (ROIs) were then dilated repeatedly until an area of 3-cm radius from the implant surface was covered using FSL v. 5.0 (FMRIB, Oxford, UK). From these circles, corresponding binary shells surrounding the implant were defined by subtraction with 0.5-, 1-, 1.5-, 2-, 2.5- and 3-cm distance from the implant surface (0.5-cm cROI, 1.0-cm cROI, 1.5-cm cROI, 2.0-cm cROI, 2.5-cm cROI, 3.0-cm cROI) (Figure 1b).

X-ray attenuation expressed as voxelwise grey values for CBCT and in Hounsfield units (HU) for CT were extracted from each defined ROI and documented. To evaluate the effect of artefacts with increasing distance from the implant surface, variance, skewness and kurtosis were extracted from each of the defined shells. In addition, artefact-free volumes of interest (rROI) were defined in gel phantoms for CT and CBCT to provide variance, skewness and kurtosis as well as mean values and standard deviations as reference.

Statistical analysis

All statistical analyses were performed using the software R (v. 3.2.0).

The accuracy of size determination in MRI scans and corresponding ratios was calculated for T1w and T2w sequences for each material to assess the extent of artefacts produced by each implant material and compare these between sequence techniques. The percentage of size overestimation was calculated as the size measured on T1w and T2w MR images (corresponding to signal void) divided by the actual size of the implants (manufacturer data) (Table 1). The extent of artefacts on T1w and T2w images was compared using paired *t*-test.

Figure 1 (a) An example of a line-distance profile on a T₁ weighted coronal reconstruction image; (b) circular regions of interest defined as shells around the implant (black circle) in CT and CBCT scans with radius 0.5–3.0 cm measured from the implants.

As artefacts in CT and CBCT can result in values above and below reference values, we focused our data analysis on histogram parameters including skewness, kurtosis and variance.

To assess the artefacts in CT and CBCT, distributions of HU from CT and grey values from CBCT of the defined cROIs were compared with the corresponding distributions of value in rROIs by determination of skewness and kurtosis. Distributions of grey values and HU from cROIs and rROIs were compared using the Kolmogorov–Smirnov test. For comparison of variances of cROIs and rROIs, F-test statistics were applied. Significance level was set at $p < 0.01$.

Results

Examples of artefacts on MR, CT and CBCT images are illustrated in [Figure 2](#).

Artefacts in MRI

In MRI scans, all implants presented a hypointense signal on T1w and T2w scans. In both sequences, zirconium implants could be accurately delineated, while Ti and Ti–ZrO₂ implants produced extensive signal voids owing to strong susceptibility artefacts. Corresponding line–distance profiles are presented in [Figure 3](#).

In comparison, artefacts were significantly more extensive on T2w than on T1w scans ($p < 0.01$). In Ti, an implant diameter overestimation of 140.7/186.4% (T1w/T2w) and 88.5/145.5% length could be observed, while the size of the ZrO₂ implant was overestimated by only 0.6/24.3% in diameter and 0.0/3.9% in length. Ti–ZrO₂ could be sized with an accuracy of 134.7/182.9% in diameter and 75.0/101.5% in length ([Table 2](#) can be referred for more details).

Artefacts in CT and CBCT

Boxplots of the surrounding area of each implant material as defined by the corresponding circular ROIs on CT and CBCT images are displayed in [Figure 4](#).

Figure 2 Example images of artefacts induced by titanium, zirconium and zirconium dental implants in 3.0-T MRI, CT and CBCT. T1w, T₁ weighted; T2w, T₂ weighted.

Figure 3 Line-distance profiles as defined on T_1 weighted (T1w) (a) and T_2 weighted (T2w) (b) MR scans for each implant material in transverse and longitudinal directions. Dark grey areas are identifying the actual size of the implant according to manufacturer information (Table 1) and light grey regions are indicating the total signal.

HU and grey values derived from reference ROIs of Siemens CT, Philips CT and CBCT displayed a normal distribution with values of skewness and kurtosis close

to zero. In CBCT, grey value distributions in all cROIs for all implant materials differed significantly from the distribution of the reference values derived from

Table 2 Length and diameter as measured and corresponding percentages of implant size overestimation for T_1 weighted (T1w) and T_2 weighted (T2w) MR images

Material	MR sequence	Mean length (mm)	Mean diameter (mm)	Actual size length (mm)	Actual size diameter (mm)	Δ length to actual size (mm)	Δ diameter to actual size (mm)	% overestimation length	% overestimation diameter
Titanium	T1w	20.64	9.87	12.00	4.10	8.64	5.77	71.98	140.67
	T2w	26.08	11.74	12.00	4.10	14.08	7.64	117.29	186.40
Titanium–zirconium	T1w	22.75	9.62	13.00	4.10	9.75	5.52	75.00	134.70
	T2w	26.20	11.60	13.00	4.10	13.20	7.50	101.54	182.93
Zirconium	T1w	16.00	4.13	16.00	4.10	0.00	0.03	0.00	0.61
	T2w	16.63	5.10	16.00	4.10	0.63	1.00	3.91	24.33

Δ , difference.

Figure 4 Boxplots displaying distributions of Hounsfield units for Siemens (a) and Philips CT (b) and grey values for CBCT (c) within each circular region of interest (ROI) defined by outer distance of 0.5–3 cm from the implant surface and corresponding reference values.

corresponding rROIs ($p < 0.001$). Values of variance, skewness and kurtosis for each cROI and material are displayed in Figure 5.

In both CT and CBCT scans, variances were significantly ($p < 0.001$) different from variances in the reference ROIs for all shells, even 3-cm distance from the implant surface. In both CT scans, ZrO₂ presented with significantly higher variance measured within the shell directly surrounding the implant in comparison with

Ti-ZrO₂ and Ti. Variance values for Ti-ZrO₂ were lower than for ZrO₂ but higher than for Ti in all shells for both CTs. In comparison, skewness and kurtosis were higher for Ti-ZrO₂ and Ti within the most central shell. Skewness and kurtosis within the most central shell were lower for ZrO₂ in CBCT.

For CBCT, Ti-ZrO₂ displayed the highest variance followed by ZrO₂, while Ti presented the lowest variance, which was close to reference even in the most central shell. In comparison, ZrO₂ showed the highest kurtosis and skewness, followed by Ti and TiZrO₂.

Discussion

In the present *in vitro* study, zirconium implants produced minimal artefacts when imaged with 3.0-T MRI, while artefacts on T2w images were more pronounced than those on T1w images. Diameter and length of zirconium implants measured on MR images were exact (<1-mm difference) when measured on T1w images, indicating the least amount of artefact induction. Corresponding measurements on T2w images differed by only 3.9% in length but by 24.3% in diameter from the actual size.

Titanium exhibited the most pronounced artefacts in MRI, closely followed by titanium–zirconium alloy, indicating that the substitution of 15% titanium content by zirconium in titanium–zirconium alloy did not lead to a significant reduction of artefacts. Our observations are in line with previous studies reporting extensive signal voids in MRI when imaging titanium in comparison with ceramic implants with only minor distortions.³⁰ In accordance with previous studies, signal voids seemed to be more prominent in transverse than in longitudinal direction, *i.e.* perpendicular to the main magnetic field.³⁷ Measurements of accuracy of size determination are not only of interest in perioperative and post-operative evaluation of the implant location itself, but are also an indicator of visibility and image quality to detect pathologic changes in the direct vicinity of the implant.

In contrast to MRI, in CT and CBCT, beam hardening and streak artefacts are commonly observed when imaging ceramic implants. To demonstrate differences between CT scanners and protocols, all implants were imaged with two different imaging systems from two different vendors. Nevertheless, our results indicate that the extent of artefacts differs slightly between scanners but follows the same scheme.

In both CT scanners, zirconium implants displayed the most pronounced artefacts and highest variance. Nevertheless, the skewness and kurtosis of the distribution of HU for zirconium were increased in comparison with reference, but were lower than those of titanium and zirconium within the first shell, indicating a more balanced induction of artefacts resulting in voxels with very high and very low HU. In comparison, beyond the first shell, skewness values decreased clearly below reference, even up to 3 cm from the implant

Figure 5 Values of variance, skewness and kurtosis for each defined circular region of interest (cROI). Black dotted lines are indicating the corresponding gel reference value.

surface indicating a tendency towards very low values, *i.e.* negative HU values in both CT scans. This phenomenon was more pronounced on Siemens than on the Philips scanner. These observations are in line with previous studies reporting the least amount of artefact induction for titanium in CT scans.³⁰ Therefore, independent of scanner model or protocol, titanium–zirconium alloy implants lead to only a minimal increase in artefact induction in comparison with titanium but remain well below the amount and extent of artefacts induced by zirconium.

In comparison with artefacts in CT, where titanium–zirconium alloy and titanium artefacts displayed similar patterns or distributions, in CBCT, titanium and zirconium showed similarities in artefact induction, while titanium–zirconium alloy displayed a completely different and more pronounced pattern of artefacts. To exclude differences in implant placement or movement as reason for this observation, CBCT scans were repeated but displayed the same phenomenon. In contrast, in a similar study by Sancho-Puchades *et al*,³² dental implants provided by the same vendor

were evaluated in CBCT, displaying the most pronounced intensity of artefacts in the vicinity of zirconium implants, followed by titanium–zirconium and titanium. However, in contrast to our study, the zirconium implant diameter used in their study was greater than the diameters of titanium and titanium–zirconium implants, which might also have led to an increase in artefact induction and impaired comparability. Nevertheless, the reason for the observed amplification of artefact induction when combining titanium and zirconium to titanium–zirconium alloy goes beyond the scope of this study, since the pattern of artefact distribution in CBCT is multifactorial, taking into account the interaction between different effects such as beam hardening, scatter, quantum noise and exponential gradient effect.^{17,18}

Overall, a similar geometric pattern for the distribution of artefacts was detected for the different implant materials in both CTs and CBCT, but beam hardening artefacts represented by high grey values or HU were more pronounced in CT scans. In comparison, in CBCT, artefacts resulting in very low grey values dominated (Figure 2). A decrease in artefact intensity was found with increasing distance from the implant surface.

Even though our study was particularly chosen to simulate a clinical setting, a limitation of the present study was its *in vitro* setup. However, careful positioning of the implants in the scanners and the application of standard protocols dedicated for dental imaging in patients in the clinical setting were followed to obtain measurements closely reflecting the *in vivo* situation. Nevertheless, especially for CBCT, it is only partially possible to simulate a clinical situation, since *in vivo* the presence of adjacent anatomical structures influences the grey value measurements.³⁸ This also partially applies to MRI and CT measurements. Therefore, the intensity and geometric distribution of artefacts in MRI, CT and CBCT could have been modified by the *in vitro* setup. Further studies are needed to test whether the differences in artefact induction reported here will hold true after osseous insertion and *in vivo*.

Even though only state-of-the-art devices were used, there are differences in image presentation and artefact behaviour within each modality due to different reconstruction algorithms, artefact suppression modes and other technical specifications, which vary in different scanner models. A general statement regarding

artefact behaviour for a whole modality, *e.g.* CBCT as a modality, is difficult and was not intended by the present study. In this intermodality comparison, we therefore focused on relative differences within the three modalities and between materials. To find differences within each modality, other studies should be performed.

Besides assessment of osseointegration or inflammatory processes in the vicinity of the implant, artefacts can limit image quality in the diagnostics of patients with cancer, who run through a routine restaging process including frequent oncologic imaging. Especially for those patients, impairment of image quality through implant materials depending on the imaging modality used should be taken into consideration to achieve the highest quality in the diagnostics of primary or recurrent cancer. This can be achieved by either the specific choice of implant material with prior knowledge of cancerous disease or the choice of image modality for restaging, taking into account the implant material.

In conclusion, the knowledge about the amount and distribution of artefacts through different implant materials in various image modalities and settings might help support the decision for choice of implant material in the clinical setting, accounting for the image modality needed for future diagnostic or monitoring purposes.

Within the limitations of the present *in vitro* study, zirconium implants are the most suited for MRI and especially in T1w sequences display only minimal artefacts, promising no significant reduction in image quality. In comparison, titanium as well as titanium–zirconium alloy implants displays vast artefacts, leading to a relevant reduction of diagnostic image quality in the vicinity of the implant in T1w and T2w images. In CT, titanium displays the least amount of artefact induction, which is only slightly increased when imaging titanium–zirconium alloy implants, while zirconium implants are the least suited for CT. Especially for radiation therapy planning, titanium implants might allow for the most accurate dose calculation, application and diagnostic quality, while zirconium implants display extensive artefacts that could lead to miscalculations. In CBCT, titanium displays the least amount of artefact induction, which clearly increases when imaging titanium–zirconium alloy implants, similar to zirconium.

References

1. New PF, Rosen BR, Brady TJ, Buonanno FS, Kistler JP, Burt CT, et al. Potential hazards and artifacts of ferromagnetic and nonferromagnetic surgical and dental materials and devices in nuclear magnetic resonance imaging. *Radiology* 1983; **147**: 139–48. doi: [https://doi.org/10.1016/0730-725x\(84\)90131-0](https://doi.org/10.1016/0730-725x(84)90131-0)
2. Bachmann G, Rössler R, Klett R, Rau WS, Bauer R. The role of magnetic resonance imaging and scintigraphy in the diagnosis of pathologic changes of the mandible after radiation therapy. *Int J Oral Maxillofac Surg* 1996; **25**: 189–95. doi: [https://doi.org/10.1016/s0901-5027\(96\)80027-0](https://doi.org/10.1016/s0901-5027(96)80027-0)
3. Lee SS, Kim HK, Choi SC, Lee JI. Granulocytic sarcoma occurring in the maxillary gingiva demonstrated by magnetic resonance imaging. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2001; **92**: 689–93. doi: <https://doi.org/10.1067/moe.2001.118287>
4. Vidiri A, Ruscito P, Pichi B, Pellini R, Covello R, Sperduti I, et al. Oral cavity and base of the tongue tumors. Correlation between clinical, MRI and pathological staging of primary tumor. *J Exp Clin Cancer Res* 2007; **26**: 575–82.
5. Li C, Yang W, Men Y, Wu F, Pan J, Li L. Magnetic resonance imaging for diagnosis of mandibular involvement from head

- and neck cancers: a systematic review and meta-analysis. *PLoS One* 2014; **9**: e112267. doi: <https://doi.org/10.1371/journal.pone.0112267>
6. Fortin T, Camby E, Alik M, Isidori M, Bouchet H. Panoramic images versus three-dimensional planning software for oral implant planning in atrophied posterior maxillary: a clinical radiological study. *Clin Implant Dent Relat Res* 2013; **15**: 198–204. doi: <https://doi.org/10.1111/j.1708-8208.2011.00342.x>
  7. Pertl L, Gashi-Cenkoglu B, Reichmann J, Jakse N, Pertl C. Preoperative assessment of the mandibular canal in implant surgery: comparison of rotational panoramic radiography (OPG), computed tomography (CT) and cone beam computed tomography (CBCT) for preoperative assessment in implant surgery. *Eur J Oral Implantol* 2013; **6**: 73–80.
  8. Buzug TM. Image quality and artifacts. *Computed tomography: from photon statistics to modern cone-beam CT*. Berlin, Germany: Springer; 2008. pp. 403–69.
  9. Imamura H, Sato H, Matsuura T, Ishikawa M, Zeze R. A comparative study of computed tomography and magnetic resonance imaging for the detection of mandibular canals and cross-sectional areas in diagnosis prior to dental implant treatment. *Clin Implant Dent Relat Res* 2004; **6**: 75–81. doi: <https://doi.org/10.1111/j.1708-8208.2004.tb00029.x>
  10. Pompa V, Galasso S, Cassetta M, Pompa G, De Angelis F, Di Carlo S. A comparative study of magnetic resonance (MR) and computed tomography (CT) in the pre-implant evaluation. *Ann Stomatol (Roma)* 2010; **1**: 33–8.
  11. Tymofiyeva O, Vaegler S, Rottner K, Boldt J, Hopfgartner AJ, Proff PC, et al. Influence of dental materials on dental MRI. *Dentomaxillofac Radiol* 2013; **42**: 20120271. doi: <https://doi.org/10.1259/dmfr.20120271>
  12. Abbaszadeh K, Heffez LB, Mafee MF. Effect of interference of metallic objects on interpretation of T1-weighted magnetic resonance images in the maxillofacial region. *Oral Surg Oral Med Oral Pathol Oral Radiol Endod* 2000; **89**: 759–65. doi: <https://doi.org/10.1067/moe.2000.105942>
  13. Eggers G, Rieker M, Kress B, Fiebach J, Dickhaus H, Hassfeld S. Artefacts in magnetic resonance imaging caused by dental material. *MAGMA* 2005; **18**: 103–11. doi: <https://doi.org/10.1007/s10334-005-0101-0>
  14. Klinker T, Daboul A, Maron J, Gredes T, Puls R, Jaghsi A, et al. Artifacts in magnetic resonance imaging and computed tomography caused by dental materials. *PLoS One* 2012; **7**: e31766. doi: <https://doi.org/10.1371/journal.pone.0031766>
  15. Starcuková J, Starcuk Z, Hubáľková H, Linetskiy I. Magnetic susceptibility and electrical conductivity of metallic dental materials and their impact on MR imaging artifacts. *Dent Mater* 2008; **24**: 715–23. doi: <https://doi.org/10.1016/j.dental.2007.07.002>
  16. Zhang Y, Zhang L, Zhu XR, Lee AK, Chambers M, Dong L. Reducing metal artifacts in cone-beam CT images by pre-processing projection data. *Int J Radiat Oncol Biol Phys* 2007; **67**: 924–32. doi: <https://doi.org/10.1016/j.ijrobp.2006.09.045>
  17. Schulze RK, Berndt D, d'Hoedt B. On cone-beam computed tomography artifacts induced by titanium implants. *Clin Oral Implants Res* 2010; **21**: 100–7. doi: <https://doi.org/10.1111/j.1600-0501.2009.01817.x>
  18. Schulze R, Heil U, Gross D, Bruellmann DD, Dranischnikow E, Schwanecke U, et al. Artefacts in CBCT: a review. *Dentomaxillofac Radiol* 2011; **40**: 265–73. doi: <https://doi.org/10.1259/dmfr/30642039>
  19. Hong H, Jin S, Koo H, Roh J, Kim J, Cho K, et al. Clinical values of 18F-FDG PET/CT in oral cavity cancer with dental artifacts on CT or MRI. *J Surg Oncol* 2014; **110**: 696–701. doi: <https://doi.org/10.1002/jso.23691>
  20. Scarano A, Piattelli M, Caputi S, Favero GA, Piattelli A. Bacterial adhesion on commercially pure titanium and zirconium oxide disks: an *in vivo* human study. *J Periodontol* 2004; **75**: 292–6. doi: <https://doi.org/10.1902/jop.2004.75.2.292>
  21. Rimondini L, Cerroni L, Carrassi A, Torricelli P. Bacterial colonization of zirconia ceramic surfaces: an *in vitro* and *in vivo* study. *Int J Oral Maxillofac Implants* 2002; **17**: 793–8.
  22. Grössner-Schreiber B, Griepentrog M, Hausteil I, Müller WD, Lange KP, Briedigkeit H, et al. Plaque formation on surface modified dental implants. An *in vitro* study. *Clin Oral Implants Res* 2001; **12**: 543–51.
  23. Welander M, Abrahamsson I, Berglundh T. The mucosal barrier at implant abutments of different materials. *Clin Oral Implants Res* 2008; **19**: 635–41. doi: <https://doi.org/10.1111/j.1600-0501.2008.01543.x>
  24. Degidi M, Artese L, Scarano A, Perrotti V, Gehrke P, Piattelli A. Inflammatory infiltrate, microvessel density, nitric oxide synthase expression, vascular endothelial growth factor expression, and proliferative activity in peri-implant soft tissues around titanium and zirconium oxide healing caps. *J Periodontol* 2006; **77**: 73–80. doi: <https://doi.org/10.1902/jop.2006.77.1.73>
  25. Warashina H, Sakano S, Kitamura S, Yamauchi KI, Yamaguchi J, Ishiguro N, et al. Biological reaction to alumina, zirconia, titanium and polyethylene particles implanted onto murine calvaria. *Biomaterials* 2003; **24**: 3655–61. doi: [https://doi.org/10.1016/s0142-9612\(03\)00120-0](https://doi.org/10.1016/s0142-9612(03)00120-0)
  26. Özkurt Z, Kazazoglu E. Zirconia dental implants: a literature review. *J Oral Implantol* 2011; **37**: 367–76. doi: <https://doi.org/10.1563/AAID-JOI-D-09-00079>
  27. Blaschke C, Volz U. Soft and hard tissue response to zirconium dioxide dental implants—a clinical study in man. *Neuro Endocrinol Lett* 2006; **27**(Suppl. 1): 69–72.
  28. Oliva J, Oliva X, Oliva JD. One-year follow-up of first consecutive 100 zirconia dental implants in humans: a comparison of 2 different rough surfaces. *Int J Oral Maxillofac Implants* 2007; **22**: 430–5.
  29. Pirker W, Kocher A. Immediate, non-submerged, root-analogue zirconia implant in single tooth replacement. *Int J Oral Maxillofac Surg* 2008; **37**: 293–5. doi: <https://doi.org/10.1016/j.ijom.2007.11.008>
  30. Düttenhoefer F, Mertens M, Vizkelety J, Gremse F, Stadelmann V, Sauerbier S. Magnetic resonance imaging in zirconia-based dental implantology. *Clin Oral Implants Res* 2015; **26**: 1195–202. doi: <https://doi.org/10.1111/clr.12430>
  31. Månsson S, Müller GM, Wellman F, Nittka M, Lundin B. Phantom based qualitative and quantitative evaluation of artifacts in MR images of metallic hip prostheses. *Phys Med* 2015; **31**: 173–8. doi: <https://doi.org/10.1016/j.ejmp.2014.12.001>
  32. Sancho-Puchades M, Hämmerle CH, Benic GI. *In vitro* assessment of artifacts induced by titanium, titanium-zirconium and zirconium dioxide implants in cone-beam computed tomography. *Clin Oral Implants Res* 2015; **26**: 1222–8.
  33. Assaf A, Zrnc T, Remus C, Khokale A, Habermann C, Schulze D, et al. Early detection of pulp necrosis and dental vitality after traumatic dental injuries in children and adolescents by 3-Tesla magnetic resonance imaging. *J Craniomaxillofac Surg* 2015; **43**: 1088–93. doi: <https://doi.org/10.1016/j.jcms.2015.06.010>
  34. Assaf A, Zrnc T, Remus C, Schönfeld M, Habermann C, Riecke B, et al. Evaluation of four different optimized magnetic-resonance-imaging sequences for visualization of dental and maxillo-mandibular structures at 3 T. *J Craniomaxillofac Surg* 2014; **42**: 1356–63. doi: <https://doi.org/10.1016/j.jcms.2014.03.026>
  35. Veldhoen S, Schöllchen M, Hanken H, Precht C, Hennes FO, Schön G, et al. Performance of cone-beam computed tomography and multidetector computed tomography in diagnostic imaging of the midface: a comparative study on phantom and cadaver head scans. *Eur Radiol* 2016. doi: <https://doi.org/10.1007/s00330-016-4387-2>
  36. Hendrikx AW, Maal T, Dieleman F, Van Cann EM, Merks MA. Cone-beam CT in the assessment of mandibular invasion by oral squamous cell carcinoma: results of the preliminary study. *Int J Oral Maxillofac Surg* 2010; **39**: 436–9. doi: <https://doi.org/10.1016/j.ijom.2010.02.008>
  37. Matsuura H, Inoue T, Konno H, Sasaki M, Ogasawara K, Ogawa A. Quantification of susceptibility artifacts produced on high-field magnetic resonance images by various biomaterials used for neurosurgical implants. Technical note. *J Neurosurg* 2002; **97**: 1472–5. doi: <https://doi.org/10.3171/jns.2002.97.6.1472>
  38. Bryant JA, Drage NA, Richmond S. Study of the scan uniformity from an i-CAT cone beam computed tomography dental imaging system. *Dentomaxillofac Radiol* 2008; **37**: 365–74. doi: <https://doi.org/10.1259/dmfr/13227258>