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Development and dosimetric verification of epoxy-$BaSO_4$ bone-equivalent composites for mandibular and cervical regions in radiotherapy planning

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Abstract

This study aimed to develop epoxy-barium sulfate ($BaSO_4$) composites as bone-equivalent materials for the mandibular and cervical vertebral regions of a Rando phantom and to evaluate their radiological and dosimetric accuracy in radiotherapy planning. Epoxy-based composite samples were prepared by incorporating $BaSO_4$ into the epoxy matrix to obtain bone-equivalent materials for the mandibular and cervical vertebral regions. The samples were imaged using a planning computed tomography (CT) system, and the resulting Hounsfield Unit (HU) values were analysed. Planning CT scans were acquired for both the original Rando phantom and the phantom incorporating epoxy-$BaSO_4$ inserts. Based on these images, treatment plans were recalculated in the treatment planning system while maintaining identical monitor unit (MU) settings and beam geometry. Isodose distributions and dose-volume histogram (DVH) parameters were comparatively evaluated between the original and modified phantom configurations. Strong linear relationship was observed between $BaSO_4$ content and HU values (R^2>0.95). Composites containing 5% and 3% $BaSO_4$ produced HU values consistent with the reference ranges for the mandibular and cervical vertebral regions, respectively. Dose parameters for the planning target volume (PTV) and organs at risk (OARs) remained within ±2% clinical acceptance limits, and a high degree of overlap was observed in the isodose distributions. Epoxy-$BaSO_4$ composites demonstrated region-specific HU values and yielded dosimetric results within clinically acceptable limits in the treatment planning system. These findings suggest that epoxy-$BaSO_4$-based materials provide a feasible approach for radiotherapy planning-oriented quality assurance and educational phantom development. Future studies incorporating different beam energies and experimental dose verification may further clarify the applicability of these materials.

Keywords: Epoxy, epoxy-barium sulfate, bone-equivalent phantom, computed tomography, hounsfield unit, radiotherapy planning, dose-volume histogram

Introduction

Phantoms used in radiotherapy are essential tools for simulating patient anatomy, verifying dose distributions and supporting quality assurance procedures. Rando-type anthropomorphic phantoms, in particular, are widely used because they contain structures that represent different tissue densities and anatomical regions, making them valuable for clinical training, dose verification and treatment planning studies [1]. However, their high cost, limited availability and the irreversible damage that can occur during repeated drilling or placement of detectors restrict their long-term use. These limitations have increased the need for reproducible, lower-cost and radiologically stable tissue-equivalent materials that can preserve anatomical fidelity.

Recent advancements in dual-energy computed tomography (DECT) technology have significantly improved the accuracy of HU-Stopping Power Ratio (SPR) conversions used in advanced radiotherapy planning. Yagi et al. showed that DECT-based SPR calibration in Rando phantoms and hydroxyapatite bone models significantly reduced range and dose prediction errors compared with single-energy CT [2]. Peters et al. subsequently published a consensus guide recommending a stepwise approach for HU-SPR calibration with tissue-equivalent phantoms and Hounsfield look-up tables (HLUTs), with the aim of reducing variation between centres [3]. Taken together, these reports underline an important point: materials used in phantoms should exhibit predictable attenuation behaviour and stable HU values

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under clinical imaging protocols. Polymer-based composites are increasingly being investigated with this goal in mind. Epoxy resin, in particular, is attractive because it offers good dimensional stability, mechanical robustness and a relatively uniform distribution of added fillers [4-6]. When high atomic number materials such as barium sulphate ($BaSO_4$, Z=56) are incorporated into epoxy, the resulting mixture can achieve strong radiopacity due to its higher mass attenuation coefficient. Previous studies have shown that polymer matrices modified with $CaCO_3$, $SrCO_3$ or hydroxyapatite can reach CT numbers up to roughly 1500 HU, approaching cortical bone ranges [5]. Brunner et al. reported that epoxy-based materials used in proton and carbon-ion therapy could reproduce CT-derived and experimental SPR values within a few percent, supporting their suitability for advanced radiotherapy applications [6]. These findings suggest that adding $BaSO_4$ to an epoxy matrix is a realistic way to obtain bone-equivalent behaviour that is relevant for both imaging and dose calculation.These findings underline that $BaSO_4$ not only enhances radiopacity but also contributes critically to imaging and dosimetric accuracy.

Even so, the number of studies that specifically target anatomically complex regions, such as the mandible and cervical vertebrae, is still limited. In these regions, cortical and trabecular components coexist, and their HU values differ markedly. A material that is intended to replace bone in such locations must be able to reproduce clinically relevant HU ranges with good internal homogeneity [7]. Moreover, being able to tailor composite inserts to match the HU "windows" of particular anatomical sites in a Rando-like phantom would be especially useful for region-specific dose verification and for training purposes in head-and-neck radiotherapy. Unlike previous epoxy-based phantom studies that primarily focus on global tissue equivalence, the present work introduces a region-specific optimisation strategy by tailoring $BaSO_4$ concentrations to match the HU windows of anatomically complex mandibular and cervical vertebral bone structures within a Rando phantom.

The aim of this study was to develop epoxy-$BaSO_4$ composites as bone-equivalent materials specifically for the mandibular and cervical vertebra regions and to evaluate their dosimetric accuracy in radiotherapy planning. The produced composite blocks were integrated into a Rando phantom, imaged with planning CT, and their HU values and recalculated dose distributions were comparatively analyzed. The findings are expected to provide a reference model for low-cost, reproducible, and clinically compatible phantom production in radiotherapy applications.

Material and Methods

Bone-equivalent inserts were prepared using a two-component bisphenol-A-based epoxy resin and barium sulphate ($BaSO_4$, ≥99% purity, Sigma-Aldrich). The $BaSO_4$ content was adjusted to five different weight fractions: 0%, 3%, 5%, 7% and 10%. For each composition, the epoxy and filler were mixed on a magnetic stirrer at 300 rpm for 10 minutes to obtain a homogeneous blend. The mixtures were then placed under vacuum for 5 minutes to remove air bubbles.

The degassed mixtures were poured into silicone moulds with internal dimensions of 3 × 3 × 2 cm. Curing was carried out at room temperature (23 ± 2°C) for 24 hours. After full hardening, the blocks were removed from the moulds and any surface irregularities were corrected. To minimise imaging artefacts during CT acquisition, the block surfaces were gently polished using 600-grit sandpaper (Figure 1).

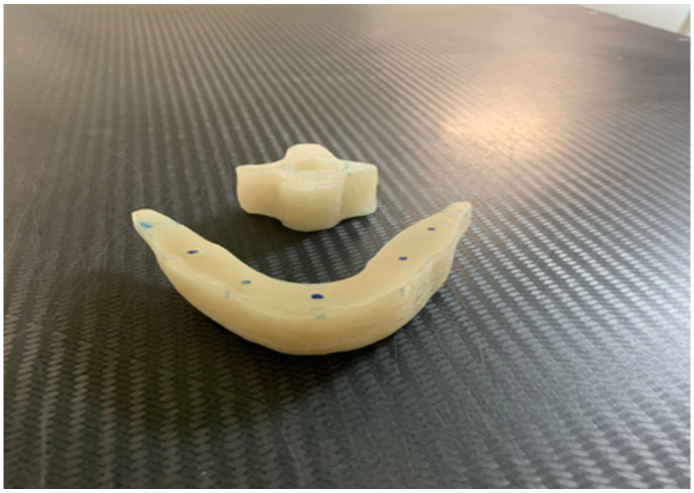

Figure 1. CT images of epoxy-$BaSO_4$ composite inserts for the cervical and mandibular regions

Phantom Integration

The epoxy-$BaSO_4$ blocks were integrated into a modified Rando phantom to represent the mandibular and cervical vertebral bone regions. During this process, the overall structure of the original Rando phantom was preserved and only the bone-equivalent segments were replaced with the newly prepared composite inserts. Both the unmodified (original) phantom and the epoxy-$BaSO_4$ modified configuration were scanned for comparative analysis. For each scan, a standard head-and-neck immobilisation mask was used, and the phantom was aligned with in-room laser systems to ensure reproducible positioning (Figure 2).

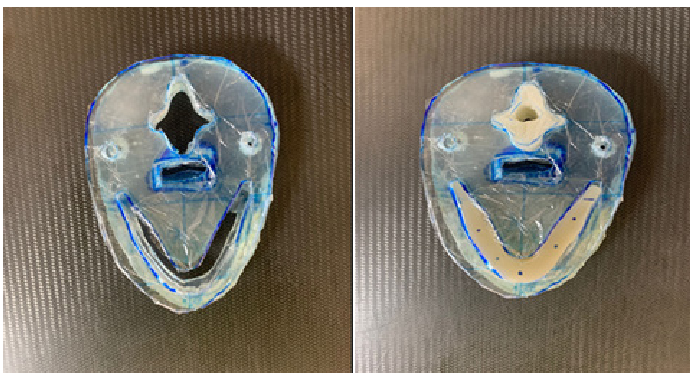

Figure 2. Integration of epoxy-$BaSO_4$ bone-equivalent inserts into the Rando phantom

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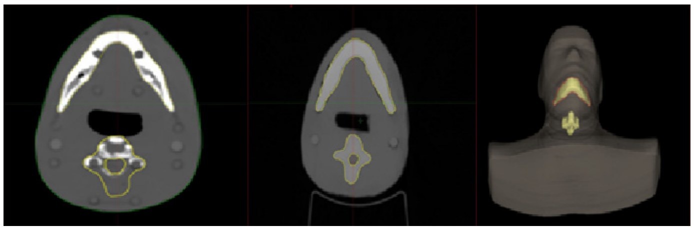
Planning CT Imaging

CT scans were acquired on a Somatom Definition AS scanner (Siemens Healthineers, Erlangen, Germany). The imaging protocol included a tube voltage of 120 kVp, tube current of 200 mAs, slice thickness of 1 mm, a matrix size of 512 × 512 and a field of view (FOV) of 25 cm. All images were exported in DICOM format and transferred to the treatment planning system. After import, the institution's standard HU-electron density calibration curve was applied within the planning system to verify the data set. This calibrated CT set served as the reference for contouring and plan optimisation (Supplementary Figure S1).

Supplementary Figure S1. Planning CT setup of the Rando phantom with epoxy-$BaSO_4$ bone-equivalent inserts

Radiotherapy Planning

All treatment planning procedures were performed on the calibrated CT data. Planning was carried out in the Eclipse v15.6 Treatment Planning System (Varian Medical Systems, Palo Alto, CA, USA). On the CT images, mandible, spinal cord and nearby OARs were contoured on the planning CT dataset (Supplementary Figure S2).



Supplementary Figure S2. Representative CT views showing target and organ-at-risk contours in the treatment planning system

The planning target volume (PTV) was defined as a geometrical volüme encompassing the mandibular bone region within the phantom. This PTV was created solely for dosimetric comparison purposes and does not represent a patient-specific clinical target. A non-coplanar beam arrangement with 6 MV photon energy was used, and the isocentre was placed in the central mandibular region. The prescription dose was 212 cGy per fraction for 33 fractions (total dose 69.96 Gy). Organ-at-risk (OAR) constraints were applied during optimisation, and for both the PTVs and OARs, Dmax, Dmean and D98 values were recorded. Using identical beam geometry and monitor unit (MU) settings, the optimised plan was then recalculated on both the original Rando phantom and the phantom containing the epoxy-$BaSO_4$ bone-equivalent blocks. This approach allowed any differences in dose distribution to be attributed to the change in material rather than to planning parameters.

Image Analysis and Dosimetric Comparison

From the planning CT images, mean Hounsfield Unit (HU) values were obtained for each composite group using the Eclipse treatment planning system, and their relationship with $BaSO_4$ fraction was examined. For each epoxy-$BaSO_4$ composite block, three independent circular regions of interest (ROIs) were manually placed in the central portion of the insert to avoid edge effects and partial volume artefacts. HU values were recorded as mean ± standard deviation (SD). For dosimetric evaluation, the treatment plans were recalculated on both phantom configurations with the same MU and beam geometry. Isodose distributions were then compared visually by overlaying selected isodose lines, particularly around the planning target volume (PTV), to inspect differences in dose gradients and high-dose regions.

Dose-volume histograms (DVHs) were generated for both plans. In the DVH analysis, the following parameters were evaluated:

- **For the PTVs:** D98, Dmean and Dmax
- **For critical organs:** selected dose constraints such as Dmax, Dmean and V30. For each metric, the absolute difference (in cGy) and the relative difference (percentage) between the original and epoxy-$BaSO_4$-modified phantoms were calculated. Relative differences were interpreted with respect to a predefined clinical acceptance range of ±2% [8].

Different acceptance criteria were applied for HU and dose comparisons because they reflect different clinical endpoints. For CT number accuracy, international and professional guidance documents report that HU values may vary depending on scan protocol and reconstruction settings, and tolerances on the order of ±20 HU are commonly cited for CT calibration and quality assurance [9]. In this study, HU agreement was therefore evaluated using a relative acceptance window of ±10% to account for the inherently wide HU range of bone-equivalent structures and protocol-dependent variability, while ensuring that the fabricated inserts remained within the intended mandibular and cervical vertebral HU windows. In contrast, a stricter ±2% tolerance was applied to dosimetric metrics, as small dose deviations may directly affect plan acceptability and ±2% is widely used as a clinical QA benchmark for TPS-based dose agreement [8].

Statistical Analysis

All analyses were performed using IBM SPSS Statistics v26 (IBM Corp., Armonk, NY, USA). The relationship between $BaSO_4$ fraction and HU values was assessed using linear regression, and the coefficient of determination (R^2) was reported. Results were expressed as mean ± standard deviation (SD). DVH comparisons (PTV/OAR metrics) were evaluated descriptively without inferential testing, as identical MU and geometry were maintained between the two configurations. All parameters were assessed according to the predefined clinical acceptance criterion ($|\Delta\_rel| \leq 2\%$). No inferential statistical testing was performed; therefore, p-values were not calculated.

Ethical Approval

This study did not involve human participants, identifiable patient data or animal experiments. As the work was entirely phantom-based, ethical committee approval was not required.

Results

Variation of HU Values with $BaSO_4$ Concentration in Epoxy-$BaSO_4$ Composites

To examine the relationship between $BaSO_4$ content and CT number, mean HU values were plotted against the filler fraction and analysed using linear regression. As the $BaSO_4$ percentage increased, HU values rose in a monotonic fashion, and the data were well described by a straight line (R^2>0.95). This behaviour indicates that the HU response of the epoxy-$BaSO_4$ system can be controlled in a predictable way by adjusting the filler fraction (Table 1, Figure 3).

Table 1. Mean ± SD HU values of epoxy-$BaSO_4$ composites at different filler ratios

$BaSO_4$ ratio (%)	Minimum HU	Maximum HU	Mean ± SD (HU)
0.0	106	124	113 ± 4
2.5	402	454	423 ± 14
5.0	726	773	746 ± 11
7.5	1026	1054	1040 ± 7
10.0	1302	1358	1325 ± 14

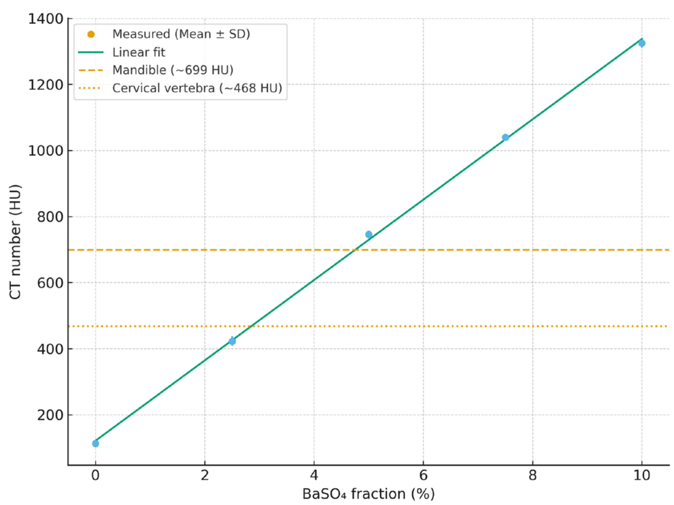


Figure 3. Relationship between $BaSO_4$ fraction (%) and measured HU values

In Table 1, HU values are reported as Mean ± SD for each $BaSO_4$ level; for every composition, three independent ROIs (n=3) were placed within the central portion of the block to avoid edge or interface effects. All CT scans were obtained with the same imaging protocol (120 kVp, 200 mAs, 1 mm slice thickness, 512 × 512 matrix, 25 cm FOV; Somatom Definition AS, Siemens Healthineers, Germany).

A linear trend in HU values was observed as $BaSO_4$ concentration increased. The measured HU range encompassed the radiological density spectrum from cancellous to cortical bone, demonstrating that the composites possess clinically suitable radiopacity characteristics for tissue equivalence. These results confirm that the material can be adjusted to simulate various bone densities in a predictable manner (Figure 3).

Each point represents the mean ± SD (n=3). The solid line indicates the linear least-squares fit (R^2>0.95). Dashed horizontal lines represent the reference HU values for the mandible (~699 HU) and cervical vertebra (~468 HU) derived from the original phantom. Clinically relevant compositions, corresponding to 5% $BaSO_4$ for the mandible and 3% $BaSO_4$ for the cervical vertebra, are highlighted with square markers. All measurements were acquired using identical CT imaging protocols.

Anatomical Reference Comparisons

HU values obtained from the original Rando phantom's mandibular and cervical vertebral regions showed strong agreement with those measured in the epoxy-$BaSO_4$ composite inserts. For the mandible, a 5% $BaSO_4$ concentration yielded 681 ± 51 HU, corresponding to a relative deviation of approximately $|\Delta\_rel| \approx 2.6\%$ from the original value (699 HU). For the cervical vertebra, a 3% $BaSO_4$ concentration resulted in 430 ± 30 HU, with a $|\Delta\_rel| \approx 8.1\%$ deviation from the original value (468 HU), remaining within the ±10% anatomical correspondence threshold (Table 2).

Table 2. Comparison of HU values between the original Rando phantom and epoxy-$BaSO_4$-modified phantom (mandible and cervical regions)

Region	Original phantom (Mean ± SD, HU)	Epoxy-$BaSO_4$ phantom (Mean ± SD, HU)
Mandible	699 ± 361	681 ± 51
Cervical	468 ± 205	430 ± 30

The comparison of mean HU values obtained from the original Rando phantom and the epoxy-$BaSO_4$-modified phantom is presented in Table 2. The results indicate that epoxy-$BaSO_4$ composites accurately reproduce the density ranges of bone tissues in both mandibular and cervical regions within a ±10% deviation margin. This close agreement demonstrates that the fabricated bone-equivalent structures were produced with high anatomical accuracy and that the phantom provides reliable tissue simulation in terms of radiological homogeneity These results are consistent with the linear trend observed in Figure 3.

CT-Based Imaging Analysis of Epoxy-$BaSO_4$ Composites

To further assess the radiological behaviour and internal uniformity of the composite blocks, CT-based image analysis was performed in a water-equivalent environment. Figure 4A shows a representative axial CT slice where five epoxy-$BaSO_4$ blocks with different filler fractions were placed in succession. Visual inspection reveals clear contrast differences between the blocks, consistent with increasing $BaSO_4$ content, while the interiors of individual blocks appear homogeneous without obvious streaking.

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A line profile drawn approximately through the centres of the blocks (Figure 4B) provides a quantitative view of these differences. Along this profile, HU values increase in a stepwise manner as the $BaSO_4$ fraction rises. The plateau segments corresponding to the interior of each block are relatively flat, which supports the assumption of intrablock homogeneity. The narrow drops at the edges of the plateaus are consistent with partial volume and edge effects rather than true material inhomogeneity.

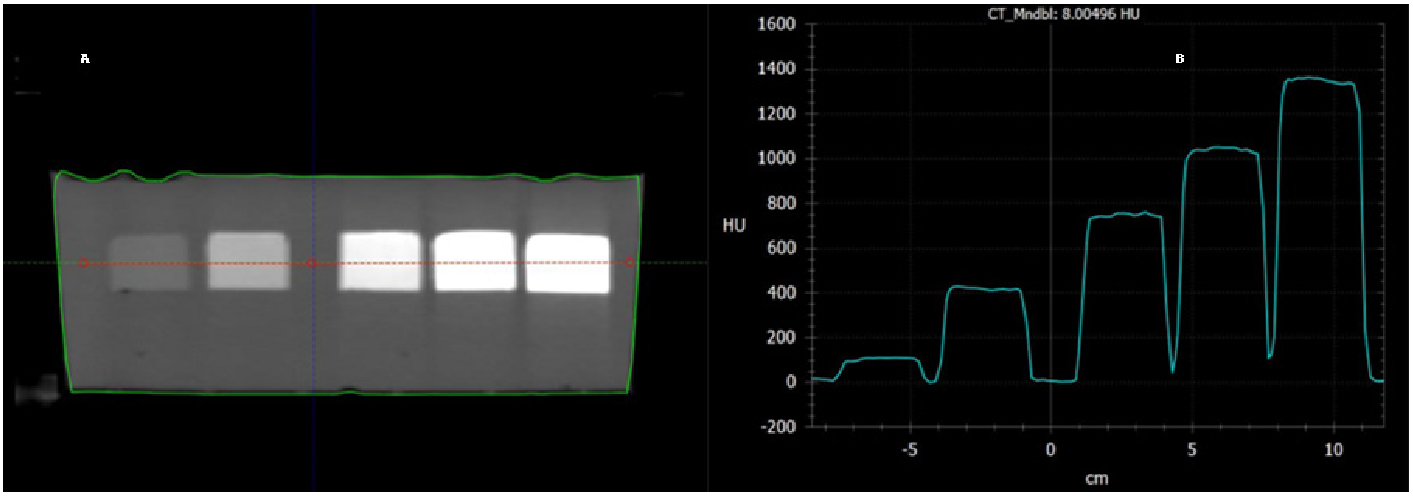

Figure 4. CT-based imaging analysis of epoxy-$BaSO_4$ composites. (A) Axial CT image of five blocks placed in a water-equivalent medium; contrast increases with $BaSO_4$ fraction, and block interiors remain visually homogeneous. The red line indicates the position of the HU profile. (B) HU profile along the same line; stepwise increases correspond to higher $BaSO_4$ fractions. Flat plateau regions reflect intrablock uniformity, whereas narrow drops at the edges are attributed to partial volume and edge effects

Taken together, the CT images and HU profile confirm that the epoxy-$BaSO_4$ composites exhibit stable, filler-dependent radiopacity and maintain internal uniformity under clinical imaging conditions.

Treatment Planning and Dose Distribution Analysis

Treatment plans generated using the planning CT data were recalculated on both the original Rando phantom and the epoxy-$BaSO_4$-modified phantom, maintaining identical beam geometry and monitor unit (MU) values. In both configurations, a homogeneous dose distribution around the planning target volume (PTV) was achieved, and spinal cord and parotid gland doses remained within institutional clinical constraints.

Isodose analysis: The 69.96 Gy isodose contours exhibited a high degree of overlap between the two configurations, with no significant deviation observed in high-dose regions. Figure 5A-B presents side-by-side isodose comparisons for the original and epoxy-$BaSO_4$-modified phantoms.

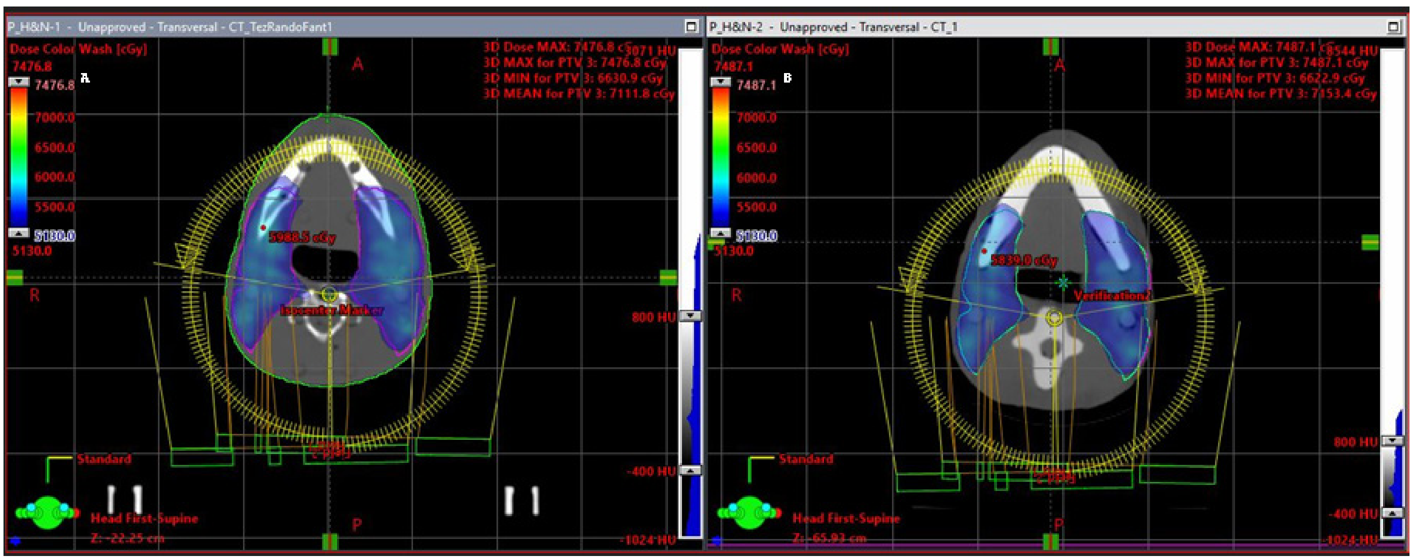

Figure 5. Comparative isodose distribution between the original (A) and epoxy-$BaSO_4$-modified (B) Rando phantoms

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For PTV, D98, Dmean, and Dmax parameters, and for selected OARs, Dmax, Dmean, and V30 metrics were compared according to the predefined clinical acceptance criterion (≤2%). All reported metrics remained within the ±2% limit, with the maximum deviation (~2%) observed for PTV Dmax. This finding is consistent with the isodose congruence shown in Figure 6A-B. The treatment planning algorithm accurately accounted for HU increases due to $BaSO_4$ incorporation, generating consistent dose calculations. In the epoxy-$BaSO_4$ configuration, contour differences in the TPS dose outputs were <1%, considered clinically negligible.

Figure 6. Dose-volume histogram (DVH) comparison between the original and epoxy-$BaSO_4$-modified phantoms for target volumes (PTVs) and organs at risk (OARs)

These comparisons demonstrate that the epoxy-$BaSO_4$ composite exhibits behavior consistent with clinical acceptance standards for plan quality and dose distribution, confirming its reliability as a bone-equivalent material for radiotherapy applications.

Statistical Evaluation of Clinical Dose Parameters

To quantify the dosimetric agreement between the two phantom configurations, clinical dose parameters were compared for three target volumes (PTV1, PTV2, PTV3) and selected critical structures (spinal cord, left and right parotid glands). D98, Dmean and Dmax values were extracted from the DVHs, and absolute (cGy) as well as relative (%) differences were calculated.

In Table 3, all PTV and OAR parameters show relative differences within the ±2% clinical tolerance used in this study. The largest deviation (1.87%) was observed for the mean dose to the right parotid gland. For the spinal cord, Dmax differed by only 0.39%. These findings suggest that the incorporation of $BaSO_4$-based bone-equivalent inserts did not introduce any dosimetrically meaningful discrepancies in clinically relevant structures.

Table 3. Comparison of clinical dose parameters between the original Rando phantom and epoxy-$BaSO_4$-modified phantom

Structure	Parameter	Original phantom (cGy)	Epoxy-$BaSO_4$ phantom (cGy)	Absolute difference (cGy)	Relative difference (%)
PTV1	D98	5233.72	5198.12	35.60	0.68%
PTV2	D98	5308.43	5291.46	16.97	0.32%
PTV3	D98	5886.40	5903.68	17.28	0.29%
Parotid left	Dmean	2092.15	2065.34	26.81	1.28%
Parotid right	Dmean	2159.43	2199.83	40.40	1.87%
Spinal cord	Dmax	3576.83	3590.82	13.99	0.39%

The DVH curves for both phantom configurations are presented in Figure 6. The curves for PTV1-PTV3 and for the spinal cord and parotid glands almost completely overlap, reflecting the small numerical differences in D98, Dmean and Dmax. The similarity in the slopes and positions of the DVH curves further supports the conclusion that the treatment planning system modelled density heterogeneities consistently for both phantoms.

Overall, the DVH-based analysis confirms that the epoxy-$BaSO_4$-modified phantom provides a dose response that is effectively equivalent to that of the original Rando phantom under the planning conditions tested.

The close overlap of the curves and the small differences in D98, Dmean and Dmax (≤2%) indicate clinically negligible dosimetric deviations.

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Discussion

This study evaluated the radiological and dosimetric suitability of epoxy-$BaSO_4$ composites as bone-equivalent materials for mandibular and cervical vertebral regions. The results demonstrated a strong linear increase in HU values with increasing $BaSO_4$ concentration (R^2>0.95), with 5% and 3% filler levels closely corresponding to the HU ranges of mandibular and cervical vertebra regions, respectively. This linear trend aligns with the model expectations reported by Sudhyadhom (2020) regarding the relationship between HU and electron density [4]. The observed HU increase can therefore be attributed to the higher electron density associated with the high atomic number (Z=56) of $BaSO_4$.

The HU enhancement observed in epoxy-$BaSO_4$ composites is consistent with previous studies on filler optimization. Cook et al. (2023) reported a similar linear increase in HU values in polymer-$BaSO_4$-based phantoms developed for proton therapy, with a strong correlation (R^2=0.98) between HU and stopping power values [10]. This supports the radiological predictability of the HU-%$BaSO_4$ relationship found in the present study. Similarly, Alshipli et al. (2018) showed that epoxy-resin composites containing Rhizophora spp. particles exhibited a stable linear X-ray attenuation response across CT energies between 40-120 kVp [11]. Our findings confirm that higher atomic number fillers such as $BaSO_4$ provide greater radiopacity in epoxy matrices. Likewise, Khallouqi et al. (2023) compared an epoxy-based pediatric head phantom with a PMMA model and found that the epoxy phantom demonstrated superior dose calculation accuracy and CT compatibility [12]. Furthermore, Yücel and Safi (2021) reported that epoxy-$BaSO_4$ phantoms could simulate pediatric tissue-equivalent HU values within ±5 HU [13]. Collectively, these studies confirm that the HU increase trend observed here is consistent with literature findings in terms of both radiological homogeneity and dosimetric accuracy.

Dosimetric analysis revealed that D98, Dmean, and Dmax parameters computed by the planning system showed no clinically significant differences between the two phantom configurations. The near-complete overlap of the 69,96 Gy isodose curves confirmed that the heterogeneity correction algorithm accurately modeled the density variations introduced by $BaSO_4$. This finding is consistent with Brunner et al. (2024), who verified that epoxy-based tissue-equivalent materials in proton and carbon-ion therapy maintained stopping power values within the clinical acceptance range (±2%) [6]. Muralidhar et al. (2023) also demonstrated that $CaCO_3$-epoxy and HA-epoxy systems yielded planning parameters within 2% error limits, confirming that epoxy-based composites provide dosimetric stability regardless of filler composition [14]. In addition, Sekkat et al. (2025) found, through Monte Carlo simulations and experimental measurements, that the attenuation coefficients of $BaSO_4$-loaded phantoms agreed with clinical tissue values within ±3% over the 40-120 kVp range [7]. These findings further support the ±2% dose variation observed in our study as being consistent with international dosimetric standards for algorithmic and clinical accuracy [15,16].

The findings of the present study indicate that the epoxy-$BaSO_4$ composite phantom may offer potential practical advantages beyond its radiological and dosimetric performance. The combined consideration of the mechanical properties of the epoxy matrix and the radiological stability of $BaSO_4$ suggests that such composites could provide a suitable material framework for repeated use in quality assurance (QA) applications. However, further experimental investigations are required to verify the long-term mechanical and radiological stability of these materials. Compared with commercial Rando-type phantoms, this material offers a cost-effective and customizable alternative, enabling modular and replaceable component designs for user-centered applications. Filippou and Tsoumpas (2018) highlighted that 3D-printed and composite-based phantom systems provide cost-efficient solutions for clinical training, dose verification, and algorithm calibration [1]. Therefore, the present study provides a feasible material and design framework for the development of bone-equivalent phantom components in radiotherapy.

A limitation of the present study is that all dosimetric evaluations were performed using a single photon energy of 6 MV. It is well recognised that Hounsfield Unit (HU) response and heterogeneity correction algorithms in treatment planning systems exhibit a certain degree of energy dependence, particularly in the presence of high-density materials. Although 6 MV photon beams are widely used in head-and-neck radiotherapy and are therefore clinically relevant for the investigated mandibular and cervical regions, the applicability of the present findings to higher photon energies (e.g., 10 MV) or to particle therapy modalities requires further investigation. Consequently, the conclusions of this work should be interpreted within the context of 6 MV photon beam irradiation under the investigated planning conditions. Future studies incorporating multi-energy analyses and experimental dose verification are warranted to further characterise the energy-dependent behaviour of epoxy-$BaSO_4$ bone-equivalent materials. Another limitation of this study is that dose verification was based exclusively on treatment planning system (TPS) recalculations. No independent experimental dose measurements were performed. Therefore, the present work should be regarded as a planning-system-based dosimetric validation rather than a full end-to-end dosimetric verification.

Conclusion

This study demonstrated that epoxy-$BaSO_4$ composites can serve as suitable bone-equivalent materials for clinical phantom applications. The 3-5% $BaSO_4$ concentrations provided strong agreement with the measured HU values of mandibular and cervical vertebral regions, while dose-volume analyses (D98, Dmean, Dmax) remained within the ±2% clinical tolerance range, confirming the dosimetric accuracy of the material. These findings indicate it is believed that the present study, by presenting a reproducible and CT-compatible model integrating tissue equivalence, will provide a useful foundation for future phantom development and validation studies in radiotherapy. Moreover, this study introduced a comprehensive methodological framework that extends the concept of tissue equivalence beyond radiological density, integrating dose response, heterogeneity correction, and plan quality parameters. Future investigations should evaluate these composites under different irradiation energies (photon, proton, and electron) and assess their long-term mechanical and radiological stability to further strengthen clinical validation.

In conclusion, epoxy-$BaSO_4$-based systems may be considered a new reference platform for radiotherapy quality assurance (QA) applications, offering advantages in standardization, reproducibility, and cost-effectiveness.

Ethical Approval
This study did not involve human participants, identifiable patient data or animal experiments. Ethical committee approval was not required.

Patient Consent
This study did not involve human participants, identifiable patient data or animal experiments.

Conflict of Interest
The authors declare no conflict of interest.

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