



Photon-counting detector CT versus cone-beam CT for postoperative cochlear implant imaging

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ABSTRACT

Purpose: To compare image-quality and radiation dose between photon-counting CT (PCD CT) and cone-beam CT (CBCT) for postoperative cochlear implantation (CI) imaging.

Methods and Materials: This retrospective study included 224 postoperative CI datasets from July 2019 to February 2026, including 112 PCD CT scans using three dosage protocols (regular dose [RD], low dose [LD], ultra-low dose [ULD]) and 112 120-kV CBCT scans. Two radiologists independently assessed image-quality using 5-point Likert scales. Objective image-quality was assessed using contrast-to-noise ratio (CNR). Groups were compared using Mann-Whitney U and Kruskal-Wallis tests. Predictors of image-quality were analyzed with linear mixed-effects models.

Results: Among 224 datasets from 196 patients (mean age, 58.8 ± 16.5 years; 118 women), PCD CT showed higher subjective overall image-quality than CBCT (median: 4.5 vs. 2.5; $p < 0.001$; $r = 0.82$) and higher ratings across all other imaging parameters ($p < 0.001$; $r \leq 0.66$ – 0.84). Image-quality differed between PCD CT protocols ($H = 13.05$; $p = 0.0015$; $\eta^2_H = 0.10$), with higher ratings for RD, while LD and ULD did not differ. CNR was higher across all PCD CT protocols than for CBCT ($p < 0.001$). Estimated effective dose was 0.3 mSv for RD, 0.24 mSv for LD and 0.16 mSv for ULD, and 0.15 mSv for CBCT. ULD showed improved image-quality with an estimated effective dose close to that of CBCT.

Conclusion: PCD CT was associated with higher image-quality and fewer artifacts than CBCT. ULD PC DCT retained higher image-quality ratings at a numerically similar dose, and may be advantageous for more precise postoperative evaluation, personalized device adjustments, and follow-up for radiosensitive or immobile patients.

1. Introduction

Cochlear implantation is a well-established therapeutic option for patients with severe sensorineural hearing loss, with more than 700,000 devices implanted worldwide. It has been shown to substantially improve speech perception and quality of life [1]. Treatment success depends on accurate intracochlear placement of the electrode array, and several factors must be considered. Electrode position within the scala tympani, insertion depth, and avoidance of scalar translocation directly

influence speech perception outcomes, residual hearing preservation, and long-term device performance [2,3]. Therefore, postoperative imaging plays an important role in assessing surgical outcomes and detecting potential complications [2,3]. Postoperative CI imaging must meet particularly high standards. Precise visualization of the intra-cochlear anatomy and closely spaced electrode contacts is essential for assessing scalar location, detecting complications such as tip-fold-over or electrode migration, and supporting anatomically adapted postoperative programming [2–4]. In many centers, cone-beam CT (CBCT) is

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commonly used for postoperative cochlear implant imaging because of its high spatial resolution, reliable visualization of osseous structures, and relatively low radiation dose [5]. Except in intraoperative settings, most CBCT systems require the patient to remain motionless in a seated or upright position throughout the acquisition, which can be challenging for elderly, cognitively impaired, or otherwise immobile patients and predisposes them to motion artifacts. Experimental and correlational studies have demonstrated the high accuracy of CBCT in assessing electrode insertion depth and scalar position [5]. However, CBCT remains susceptible to implant-related and motion artifacts, which may impair visualization of individual contacts and intracochlear anatomy and limit accurate anatomical frequency allocation [5].

Photon-counting detector computed tomography (PCD CT) is an emerging CT technology that directly converts individual X-ray photons into electrical signals, thereby reducing electronic noise and improving dose efficiency compared with conventional energy-integrating detector systems [7–9]. Previous studies have mainly compared PCD CT with conventional multislice CT systems and demonstrated improved visualization of temporal bone structures and reduced artifact burden. However, direct comparisons between PCD CT and CBCT for routine postoperative CI imaging remain limited [7–10].

This study aimed to evaluate the diagnostic image-quality of PCD CT in postoperative imaging after CI and to compare it with CBCT in adult patients undergoing routine clinical assessment.

2. Materials and methods

2.1. Study design and patient characteristics

2.1.1. Study design

This retrospective comparative study evaluated two consecutive

institutional imaging strategies for postoperative cochlear implant assessment in adult patients. Prior to June 2025, postoperative cochlear implant imaging was routinely performed using CBCT. After June 2025, adult postoperative examinations were performed using the newly implemented PCD CT protocol as part of a sequential institutional transition in imaging strategy. This retrospective study was approved by the local ethics committee, and written consent was waived (ethics approval no. 2026-2804).

2.1.2. Study population

Between July 2019 and February 2026, 239 postoperative imaging datasets (CBCT and PCD CT) acquired within 24 h after cochlear implant surgery were screened. Inclusion criteria were: (1) postoperative imaging after cochlear implantation with two implant types (MED-EL and Cochlear), (2) PCD CT or standard 120-kV CBCT, (3) age ≥ 18 years, and (4) complete imaging datasets. Reimplantations and electrode misplacements, including tip-fold-over, were not excluded. When multiple postoperative examinations were available for a single patient, each dataset was included to reflect routine clinical conditions and evaluate modality performance across all available examinations.

Of 123 screened CBCT examinations, 11 were excluded: 2 because of extensive otosclerosis-related cochlear alterations, 7 because of severe motion artifacts, and 2 because of non-diagnostic metal artifacts. Of 116 screened PCD CT examinations, 4 were excluded because of extensive otosclerosis-related cochlear alterations. To assess potential selection bias, a sensitivity analysis included the 9 non-diagnostic CBCT examinations affected by severe motion or metal artifacts, and assigned them the lowest overall image-quality score. Examinations excluded because of otosclerosis were not classified as imaging failures because their exclusion was based on altered cochlear anatomy rather than technical non-diagnostic image-quality. A flowchart of study population selection

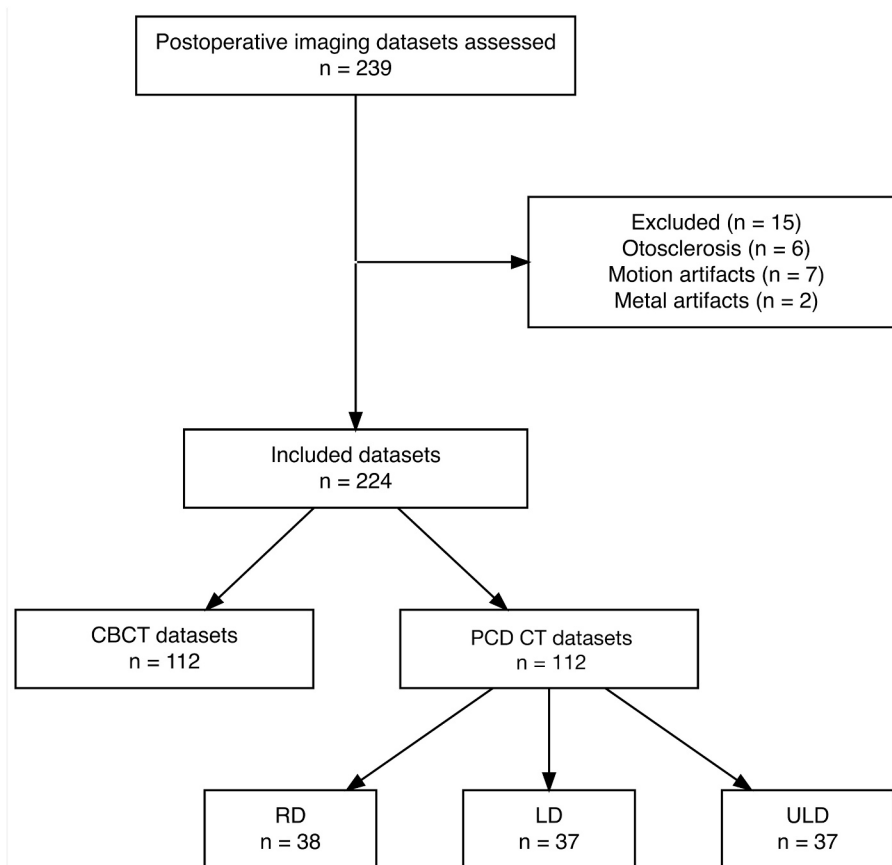


Fig. 1. Flowchart of the study population selection.

is shown in Fig. 1.

A sensitivity analysis using a single dataset per patient ($n = 196$) was performed to address potential clustering effects from repeated examinations.

2.2. Scan protocol

All examinations were performed using photon-counting CT (NAEOTOM Alpha, Siemens Healthineers; syngo CT VB20; CdTe detector) or cone-beam CT (Planmeca ProMax 3D Max, Planmeca Oy).

PCD CTs were acquired using three dose protocols: regular dose (RD), low dose (LD), and ultra-low dose (ULD), differing only in tube current–time product (RD: 74.5 ± 16.5 mAs; LD: 59.3 ± 5.7 mAs; ULD: 40.2 ± 3.8 mAs). All scans used 120 kV with automatic tube current modulation, 120×0.2 mm detector collimation, spiral pitch 0.85, and 1-second rotation. Reconstructed with a high-resolution kernel (Hr98), QIR (level Q1), 0.2 mm slices, 256×256 matrix, polychromatic mode. Metal artifact reduction was not applied. CBCT used a dedicated temporal bone protocol at 120 kV, 7 mA, 10 s acquisition, with 0.15 mm isotropic voxels, 668×668 matrix, and standardized exposure parameters without modulation. Details such as scan length, reconstruction FOV, and pixel size were documented for descriptive purposes. Detailed imaging parameters are summarized in Table 1.

2.3. Image evaluation

Two radiologists, with 5 and 10 years of head and neck imaging experience, independently evaluated the datasets both subjectively and

Table 1
Scan and reconstruction parameters of CBCT and PCD CT.

Parameter	CBCT	PCD CT ULD	PCD CT LD	PCD CT RD
Tube voltage (kV)	120	120	120	120
Tube current–time product (mAs), mean $\pm$ SD	7.0 ± 0.0	40.2 ± 3.8	59.3 ± 5.7	74.5 ± 16.5
CTDIvol (mGy), mean $\pm$ SD	14.7 $\pm$ 0.0	6.9 ± 0.7	10.1 ± 1.1	12.9 ± 2.8
DLP (mGy-cm), mean $\pm$ SD	—	77.7 ± 10.6	115.4 ± 17.7	143.1 ± 29.3
DAP (Gy-cm ²), mean $\pm$ SD	1.59 ± 0.0	—	—	—
Effective dose (mSv), mean $\pm$ SD	0.15 $\pm$ 0.00	0.16 ± 0.02	0.24 ± 0.04	0.30 ± 0.06
Pixel size at isocenter (mm ²)	0.150	0.423 ± 0.057	0.443 ± 0.058	0.412 ± 0.058
Collimation	—	120×0.2	120×0.2	120×0.2
Spiral pitch factor	—	0.85	0.85	0.85
Rotation time (s)	—	1.00	1.00	1.00
Convolution kernel	—	Hr98	Hr98	Hr98
Iterative reconstruction strength	—	Q1	Q1	Q1
Slice thickness (mm)	0.15	0.20	0.20	0.20
Matrix	668×668	256×256	256×256	256×256
Reconstruction field of view (mm)	—	108.2 ± 14.6	113.4 ± 14.9	107.9 ± 15.8
Reconstruction mode	—	Polychromatic	Polychromatic	Polychromatic
Scan length (cm), mean $\pm$ SD	—	11.29 ± 1.16	11.49 ± 1.55	11.20 ± 1.07

Abbreviations: PCD CT = photon-counting detector CT; CBCT = cone-beam CT; ULD = ultra-low dose; LD = low dose; RD = regular dose; CTDIvol = volume CT dose index; DLP = dose length product; DAP = dose area product. Continuous variables are presented as mean $\pm$ SD where applicable. A dash indicates that the parameter was not applicable or not available for the respective modality.

objectively. They assessed randomized datasets using a dedicated PACS viewer (Centricity RIS-i 7.0, GE Healthcare) with predefined window settings. The radiologists were blinded to patient identities and acquisition parameters; however, they could recognize the imaging modality because of distinctive modality-specific image features.

Subjective image-quality was rated using standardized 5-point Likert scales for overall image-quality, visibility of the intracochlear electrode position, individual electrode contacts, osseous spiral lamina, inner and outer cochlear walls, and implant-related artifacts (Table 2). Discrete parameters, including electrode position (scala tympani/scala vestibuli/scalar translocation), tip-fold-over (yes/no), and insertion depth as angular depth of insertion (continuous variables), were also assessed. Each reader independently determined these findings from the images. No independent surgical or clinical reference standard was available for routine in vivo postoperative imaging. Therefore, these analyses assessed interobserver agreement and reader-based evaluability rather than diagnostic accuracy.

For objective evaluation, contrast-to-noise ratio (CNR) was calculated using standardized 3-mm circular ROIs placed in the otic capsule, temporal bone, cerebellopontine angle, and air:

$$CNR = \frac{Mean(HU/GV)_{Bone} - Mean(HU/GV)_{Softtissue}}{standarddeviation(SD)_{Air}}$$

Given the fundamental differences in detector technology, reconstruction algorithms, and gray-value scaling between PCD CT and CBCT, CNR values were interpreted cautiously when comparing modalities.

2.4. Radiation dose

For PCD CT, the volumetric CT dose index (CTDIvol) and dose-length product (DLP) were obtained from protocols, and the effective dose (ED) was calculated as DLP times a conversion factor of 0.0021 mSv/(mGy-cm) [10]. For CBCT, dose-area product (DAP) and CTDIvol were recorded; ED was estimated using a device-specific factor of 0.0946 mSv/(Gy-cm²), based on anthropomorphic phantom measurements [11,12]. Radiation exposure was identical across all CBCT scans using a standardized protocol. Dose metrics differ between PCD CT and CBCT, so direct comparison is limited; CTDIvol for CBCT should be interpreted cautiously. The effective dose comparison also requires caution due to different dosimetry concepts. Radiation exposure was consistent across all CBCT examinations following a standard post-operative protocol.

2.5. Statistical evaluation

Statistical analyses were performed using R (version 4.5.2; R Foundation for Statistical Computing) with RStudio (version 2026.01.0 + 392; Posit Software). Continuous variables are reported as mean $\pm$ SD, ordinal data as median with IQR. Normality was assessed using the Shapiro-Wilk test. We compared baseline patient, implant, and procedural characteristics descriptively between the CBCT and pooled PCD CT cohorts.

Comparisons between PCD CT and CBCT were performed using the Mann-Whitney *U* test (effect size: r), as primary and most secondary endpoints were ordinal or non-normally distributed. Comparisons among PCD CT dose protocols (RD, LD, ULD) used the Kruskal-Wallis test (effect size: η^2), with post-hoc pairwise Wilcoxon tests and Holm correction. Associations between continuous variables were assessed using Spearman's rank correlation.

Interrater agreement for Likert parameters used quadratic-weighted Cohen's kappa with 95 % confidence intervals from 100,000 bootstrap resamples. For categorical endpoints, percentage agreement with 95 % Wilson intervals was reported as kappa was uninformative due to low variation. Non-assessable scalar ratings counted as disagreements. For insertion depth, reliability was assessed using ICC and Bland-Altman

Table 2
5-point Likert scale criteria for evaluating cochlear implant imaging quality.

Criteria	1	2	3	4	5
Overall image quality	Poor image quality	Acceptable image quality	Moderate image quality	Good image quality	Excellent image quality
Electrode position	Electrode position cannot be determined	25% of electrode position can be determined	50% of electrode position can be determined	75% of electrode position can be determined	100% of electrode position can be determined
Electrode contacts	Individual contacts cannot be kept apart	Separation of adjacent contacts can be seen at outer edge	Advanced separation between contacts but not complete	Some contacts completely separated from adjacent contacts	All contacts completely separated from adjacent contacts
Osseous spiral lamina	Not visible	Vaguely visible	Unambiguously visible	Vaguely visible along entire length	Unambiguously visible along entire length
Inner cochlear wall	Not visible	Vaguely visible but not over entire length	Vaguely visible over entire length	Unambiguously visible but not over entire length	Unambiguously visible over entire length
Outer cochlear wall	Not visible	Vaguely visible but not over entire length	Vaguely visible over entire length	Unambiguously visible but not over entire length	Unambiguously visible over entire length
Electrode-related artifacts	Severe artifacts, image interpretation impossible	Severe artifacts with strong impairment of interpretation	Severe artifacts with minor impairment of interpretation	Minor artifacts without impairment of interpretation	No artifacts

analysis. A linear mixed-effects model with random intercept for patients and reader was fitted to evaluate predictors of subjective image-quality. Fixed effects included imaging protocol, CNR, age, sex, and implant manufacturer. To account for imbalances in implant protocol, age, sex, and grouped implant/electrode configuration as fixed effects with random intercepts for patient and reader. Configurations were grouped as MED-EL FLEX28, FLEX26, or FLEXSOFT; Cochlear CI1012, CI1032, CI612, or CI632, and other configurations because of sparse

observations for the remaining categories.

A predefined paired analysis ($n = 9$) of patients with matched same-side examinations on both modalities used the Wilcoxon signed-rank test. Fisher's exact test was used for categorical variables with low event rates. Statistical significance was set at $p < 0.05$.

Table 3
Baseline patient, implant, and procedural characteristics.

Parameter	CBCT	PCD CT overall	PCD CT ULD	PCD CT LD	PCD CT RD
Imaging datasets, n	112	112	37	37	38
Unique patients, n	112	93	31	33	30
Age (years), mean $\pm$ SD (range)	60.0 $\pm$ 15.4 (18–89)	57.6 $\pm$ 17.5 (18–88)	54.3 $\pm$ 18.1 (18–84)	60.5 $\pm$ 15.5 (20–88)	58.1 $\pm$ 18.6 (20–84)
Sex					
Female	63 (56.2%)	55 (49.1%)	16 (43.2%)	21 (56.8%)	18 (47.4%)
Male	49 (43.8%)	57 (50.9%)	21 (56.8%)	16 (43.2%)	20 (52.6%)
Implanted side					
Left	48 (42.9%)	60 (53.6%)	19 (51.4%)	19 (51.4%)	22 (57.9%)
Right	64 (57.1%)	52 (46.4%)	18 (48.6%)	18 (48.6%)	16 (42.1%)
Patients contributing >1 dataset, n/N (%)	0/112 (0.0%)	18/93 (19.4%)	6/31 (19.4%)	4/33 (12.1%)	8/30 (26.7%)
Imaging within 24 h after surgery, n (%)	112 (100%)	112 (100%)	37 (100%)	37 (100%)	38 (100%)
Implant manufacturer					
Cochlear	55 (49.1%)	56 (50.0%)	17 (45.9%)	23 (62.2%)	16 (42.1%)
MED-EL	57 (50.9%)	56 (50.0%)	20 (54.1%)	14 (37.8%)	22 (57.9%)
Implant model					
Cochlear CI1012	6 (5.4%)	25 (22.3%)	4 (10.8%)	12 (32.4%)	9 (23.7%)
Cochlear CI1022	1 (0.9%)	3 (2.7%)	0 (0.0%)	1 (2.7%)	2 (5.3%)
Cochlear CI1032	3 (2.7%)	17 (15.2%)	9 (24.3%)	6 (16.2%)	2 (5.3%)
Cochlear CI24RE (CA)	0 (0.0%)	1 (0.9%)	0 (0.0%)	0 (0.0%)	1 (2.6%)
Cochlear CI522	0 (0.0%)	1 (0.9%)	0 (0.0%)	1 (2.7%)	0 (0.0%)
Cochlear CI612	26 (23.2%)	7 (6.2%)	3 (8.1%)	3 (8.1%)	1 (2.6%)
Cochlear CI622	4 (3.6%)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Cochlear CI632	15 (13.4%)	2 (1.8%)	1 (2.7%)	0 (0.0%)	1 (2.6%)
MED-EL Concerto	0 (0.0%)	3 (2.7%)	1 (2.7%)	1 (2.7%)	1 (2.6%)
MED-EL PULSAR CI100	0 (0.0%)	1 (0.9%)	0 (0.0%)	0 (0.0%)	1 (2.6%)
MED-EL SONATA Ti100	0 (0.0%)	1 (0.9%)	0 (0.0%)	0 (0.0%)	1 (2.6%)
MED-EL Synchrony 2	57 (50.9%)	51 (45.5%)	19 (51.4%)	13 (35.1%)	19 (50.0%)
MED-EL electrode array					
FLEX28/FLEX28 DEX	31 (27.7%)	30 (26.8%)	10 (27.0%)	9 (24.3%)	11 (28.9%)
FLEX26	9 (8.0%)	8 (7.1%)	2 (5.4%)	4 (10.8%)	2 (5.3%)
FLEXSOFT	17 (15.2%)	16 (14.3%)	8 (21.6%)	1 (2.7%)	7 (18.4%)
Other MED-EL arrays	0 (0.0%)	2 (1.8%)	0 (0.0%)	0 (0.0%)	2 (5.3%)

Abbreviations: PCD CT = photon-counting detector CT; CBCT = cone-beam CT; ULD = ultra-low dose; LD = low dose; RD = regular dose; SD = standard deviation. Values are given as n (%) unless otherwise indicated. Percentages for patient-level repeat examinations use the number of unique patients as the denominator. Individual patients could contribute more than one dataset.

3. Results

3.1. Study population

A total of 239 postoperative cochlear implant examinations were screened, comprising 123 CBCT and 116 PCD CT examinations. 11 CBCT examinations were excluded, including 2 because of extensive otosclerosis-related cochlear alterations, 7 because of severe motion artifacts, and 2 because of non-diagnostic metal artifacts. 4 PCD CT examinations were excluded because of extensive otosclerosis-related cochlear alterations. The final analysis included 224 datasets from 196 patients, comprising 112 CBCT and 112 PCD CT examinations (Fig. 1). Within the PCD CT group, 38 examinations were performed using the RD, 37 using the LD, and 37 using the ULD protocol.

The mean age was 58.8 ± 16.5 years (range 18–89 years), and 118 (52.7 %) were female. A total of 111 Cochlear CI systems and 113 MED-EL CI systems were implanted. Implant manufacturer distribution was similar between the CBCT and PCD CT cohorts, whereas the distribution of individual implant models differed. Detailed patient, implant, and procedural characteristics are provided in Table 3.

3.2. Subjective image evaluation

Representative examples of CBCT and PCD CT, along with two CI electrode types, are shown in Fig. 2. Cochlear electrode types provide 22 half-banded electrode contacts. MED-EL has 19 electrode contacts. The first five apical contacts (at the tip) are single, while the remaining 14 are usually paired.

Overall image-quality ratings were significantly higher for PCD CT than for CBCT (median [IQR]: 4.5 [4.0–4.6] vs. 2.5 [2.5–3.0]; $p < 0.001$; $r = 0.82$) (Fig. 3). These findings remained robust in a sensitivity analysis restricted to one data set per patient ($n = 196$, $p < 0.001$; $r = 0.82$), indicating that repeated examinations did not substantially influence the primary results. In an additional sensitivity analysis, the 9 excluded non-diagnostic CBCT examinations affected by severe motion or metal artifacts were classified as clinical failures and assigned the lowest overall image-quality score. The difference remained significant, with a median overall image-quality score of 4.5 (IQR, 4.0–4.6) for PCD CT ($n = 112$) and 2.5 (IQR, 2.5–3.0) for CBCT ($n = 121$; $p < 0.001$; $r = 0.83$). All additional Likert-based parameters were also significantly higher in the PCD CT group (all $p < 0.001$), including electrode position ($r = 0.78$), electrode contacts ($r = 0.66$), osseous spiral lamina ($r = 0.84$), the inner and outer cochlear walls (both $r = 0.84$), and artifact assessment ($r = 0.77$).

Within PCD CT, overall image quality varied significantly across dose protocols ($H = 13.05$, $p = 0.001$; $\eta^2_H = 0.10$), with higher ratings for RD, while LD and ULD did not differ. A dose-dependent association was more pronounced for visualizing the osseous spiral lamina ($H = 20.80$, $p = 0.001$; $\eta^2_H = 0.17$). Significant differences in PCD CT also appeared for electrode contact visibility ($H = 10.06$, $p = 0.0065$; $\eta^2_H = 0.074$) and artifact assessment ($H = 9.78$, $p = 0.001$; $\eta^2_H = 0.071$), but not for electrode position ($H = 1.67$, $p = 0.44$) or visualization of the cochlear walls (inner $H = 1.37$, $p = 0.50$; outer $H = 1.01$, $p = 0.60$). Artifact burden was higher in CBCT than in all PCD CT protocols (all $p < 0.001$). Within PCD CT, RD had slightly better artifact ratings than LD ($p = 0.048$); no difference between LD and ULD. Fig. 4 and Table 4 show detailed results. Interrater agreement for Likert-based parameters was substantial for overall image-quality (weighted $\kappa = 0.72$; 95 % CI, 0.67–0.77), electrode position visibility ($\kappa = 0.74$; 95 % CI, 0.67–0.80), electrode contact visibility ($\kappa = 0.72$; 95 % CI, 0.64–0.78), osseous spiral lamina visibility ($\kappa = 0.64$; 95 % CI, 0.56–0.71), inner cochlear wall visibility ($\kappa = 0.64$; 95 % CI, 0.55–0.72), outer cochlear wall visibility ($\kappa = 0.71$; 95 % CI, 0.62–0.78), and artifact assessment ($\kappa = 0.66$; 95 % CI, 0.58–0.74). Percentage agreement for scalar position was 97.3 % for CBCT (109/112; 95 % CI, 92.4–99.1 %) and 98.2 % for PCD CT (110/112; 95 % CI, 93.7–99.5 %), with non-assessable ratings counted as

disagreements and no significant difference between modalities ($p = 1.0$). Percentage agreement for in tip-fold-over was 95.5 % for CBCT (107/112; 95 % CI, 90.0–98.1 %) and 100 % for PCD CT (112/112; 95 % CI, 96.7–100 %), with no significant difference between modalities ($p = 0.060$). Interrater reliability for insertion depth was high (ICC = 0.881; 95 % CI: 0.845–0.908), with minimal bias in Bland-Altman analysis (mean difference 0.03).

3.3. Objective image evaluation

Estimated CNR values differed significantly across imaging modalities ($H = 158.0$, $p < 0.001$), though cross-modality interpretation should be cautious given differences in reconstruction and gray-value scaling. Median CNR was lowest for CBCT (9.2 [IQR 1.6]) and higher for all PCD CT protocols (ULD: 11.0[1.2]; LD: 13.4[1.1]; RD: 13.1[1.0]). Pairwise comparisons confirmed that all PCD CT protocols had significantly higher CNR than CBCT (all $p < 0.001$). Within PCD CT, LD and RD showed significantly higher CNR than ULD (both $p < 0.001$), whereas no significant difference was observed between LD and RD ($p = 0.42$). When pooling all PCD CT datasets, CNR remained significantly higher than for CBCT ($p < 0.001$; $r = 0.76$) (Fig. 5).

3.4. Radiation dose

The mean ED varied across PCD CT protocols, with 0.30 ± 0.06 mSv for RD, 0.24 ± 0.04 mSv for LD, and 0.16 ± 0.02 mSv for ULD.

A standardized acquisition protocol was used for CBCT, yielding a constant ED of 0.15 mSv. The estimated ED values of the ULD protocol and CBCT were numerically similar. However, direct comparison is limited by the different dosimetric approaches used (Fig. 6).

3.5. Multivariate analysis

A linear mixed-effects model with random intercepts for patient and reader was used to assess independent predictors of overall subjective image-quality. The primary model included imaging protocol, CNR, age, sex, and implant manufacturer as fixed effects.

Compared with the reference category RD, lower image-quality ratings were observed for LD ($\beta = -0.33$, $p = 0.01$) and CBCT ($\beta = -1.51$, $p < 0.001$), whereas no significant difference was observed for ULD ($\beta = -0.08$, $p = 0.60$). Higher CNR was independently associated with higher image-quality ratings ($\beta = 0.10$, $p = 0.003$). Age exhibited a slight negative correlation with image quality ($p = 0.056$), while sex and implant type were not significant predictors. Overall, the imaging modality was the most influential independent factor for image quality ($p < 0.001$). Adjusting for CNR, the differences between RD and ULD lost significance (Fig. 6). An additional sensitivity analysis, considering implant and electrode array configurations, included imaging protocol, age, sex, and grouped implant/electrode setup as fixed effects, with random intercepts for patient and reader. Lower overall image quality ratings persisted for LD ($\beta = 0.33$; 95 % CI, -0.58 to -0.07 ; $p = 0.013$), ULD ($\beta = -0.38$; 95 % CI, -0.64 to -0.12 ; $p = 0.004$), and CBCT ($\beta = -1.93$; 95 % CI, -2.14 to -1.72 ; $p < 0.001$) compared to RD. None of the grouped implant/electrode configurations significantly predicted overall image quality (all $p \geq 0.15$).

4. Discussion

PCD CT was associated with higher overall image quality than CBCT, as reflected in both readers' subjective assessments and objective metrics, with higher ratings across all evaluated parameters (electrode position, individual contacts, and intracochlear structures) and across all three dose protocols. The ultra-low-dose protocol yielded higher ratings than CBCT, despite numerically similar estimated effective doses, though differing dosimetric approaches limit direct comparison. These findings align with prior studies showing improved visualization of

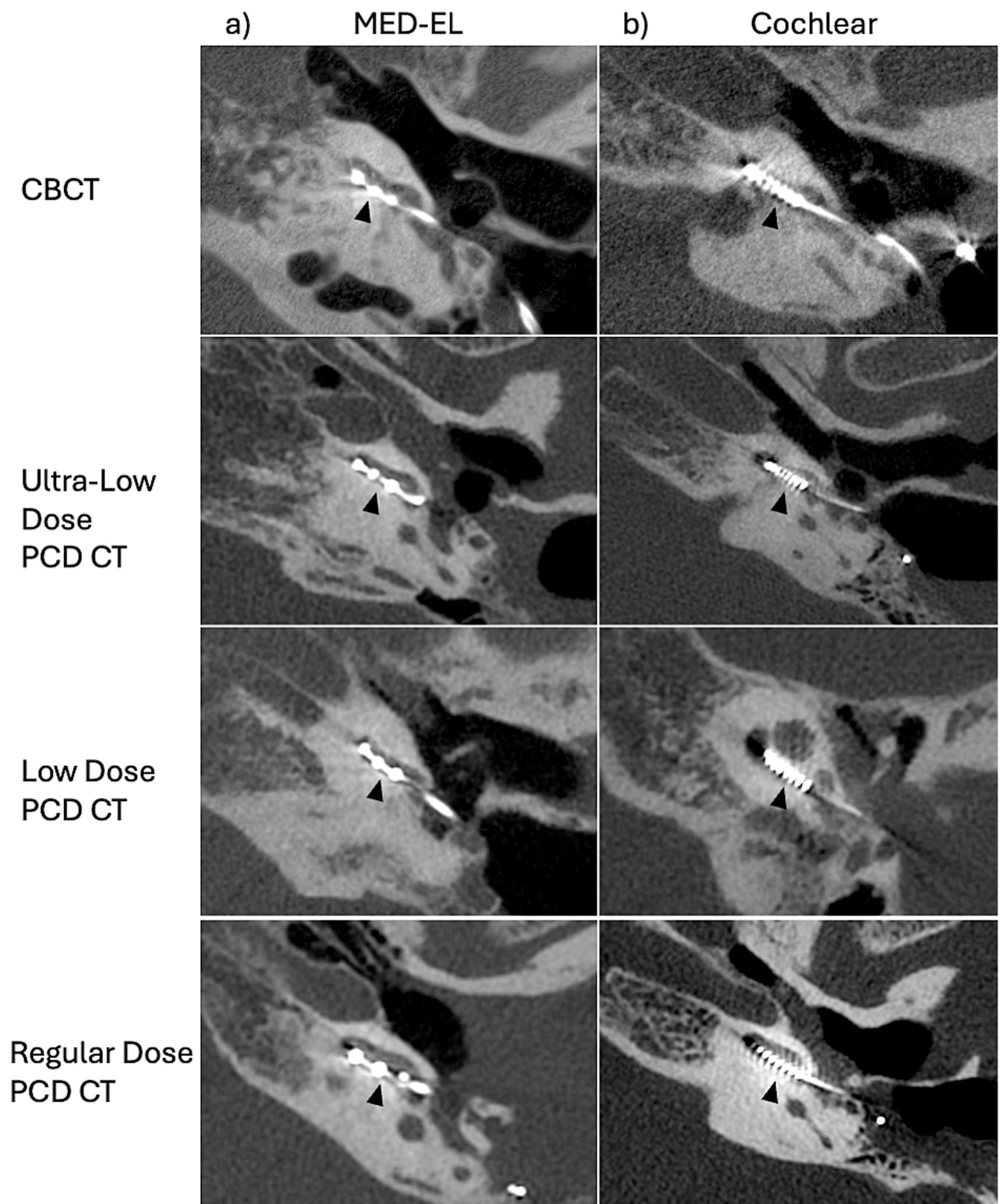


Fig. 2. Overview images of two different CI electrode types (a) MED-EL FLEX (FLEX26; FLEX28; FLEXSOFT) compared to (b) Cochlear (CI612; CI1012;; Cochlear CI1022) examined with 120 kV CBCT, and three PCD CT dose protocols (ULD, LD, RD). PCD CT protocols received higher reader ratings for the visibility of contacts, electrode position and reduced artifacts. RD: regular dose, LD: low dose, ULD: ultra low dose.

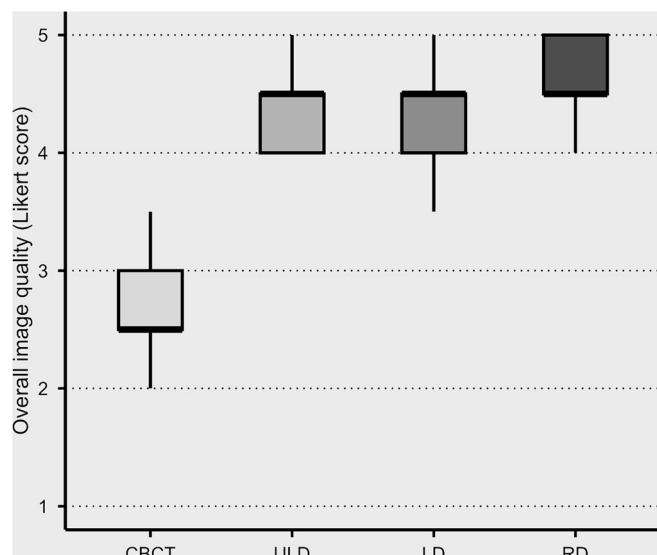


Fig. 3. Overall subjective image-quality comparison between CBCT and PCD CT. PCD CT demonstrates higher image-quality. RD: regular dose, LD: low dose, ULD: ultra low dose.

cochlear structures and reduced artifact burden with PCD CT versus

conventional multislice CT [7–9]; Tian et al. similarly reported better depiction of the cochlear walls, more precise electrode positioning, and fewer metal artifacts [6].

Table 4

Subjective assessment criteria: CBCT versus PCD CT comparison.

Parameter	CBCT	PCD CT ULD	PCD CT LD	PCD CT RD	p-value
Overall image quality	3 (2–3)	4 (4–5)	4 (4–5)	5 (4–5)	< .001
Electrode position	3 (3–4)	5 (4–5)	5 (4–5)	5 (5–5)	< .001
Electrode contact visibility	3 (3–4)	4 (3–5)	4 (3–5)	5 (4–5)	< .001
Osseous spiral lamina visibility	1 (1–2)	4 (3–4)	4 (3–5)	4 (4–5)	< .001
Inner cochlear wall visibility	3 (3–3)	5 (4–5)	5 (4–5)	5 (4–5)	< .001
Outer cochlear wall visibility	3 (3–3)	5 (4–5)	5 (4–5)	5 (4–5)	< .001
Artifacts	3 (2–3)	4 (4–5)	4 (4–5)	5 (4–5)	< .001

Abbreviations: CBCT = cone-beam computed tomography; PCD CT = photon-counting detector computed tomography; ULD = ultra-low dose; LD = low dose; RD = regular dose; IQR = interquartile range. Values are presented as median (IQR). *p*-values indicate overall differences between imaging modalities (CBCT, ULD, LD, RD) assessed using the Kruskal-Wallis test.

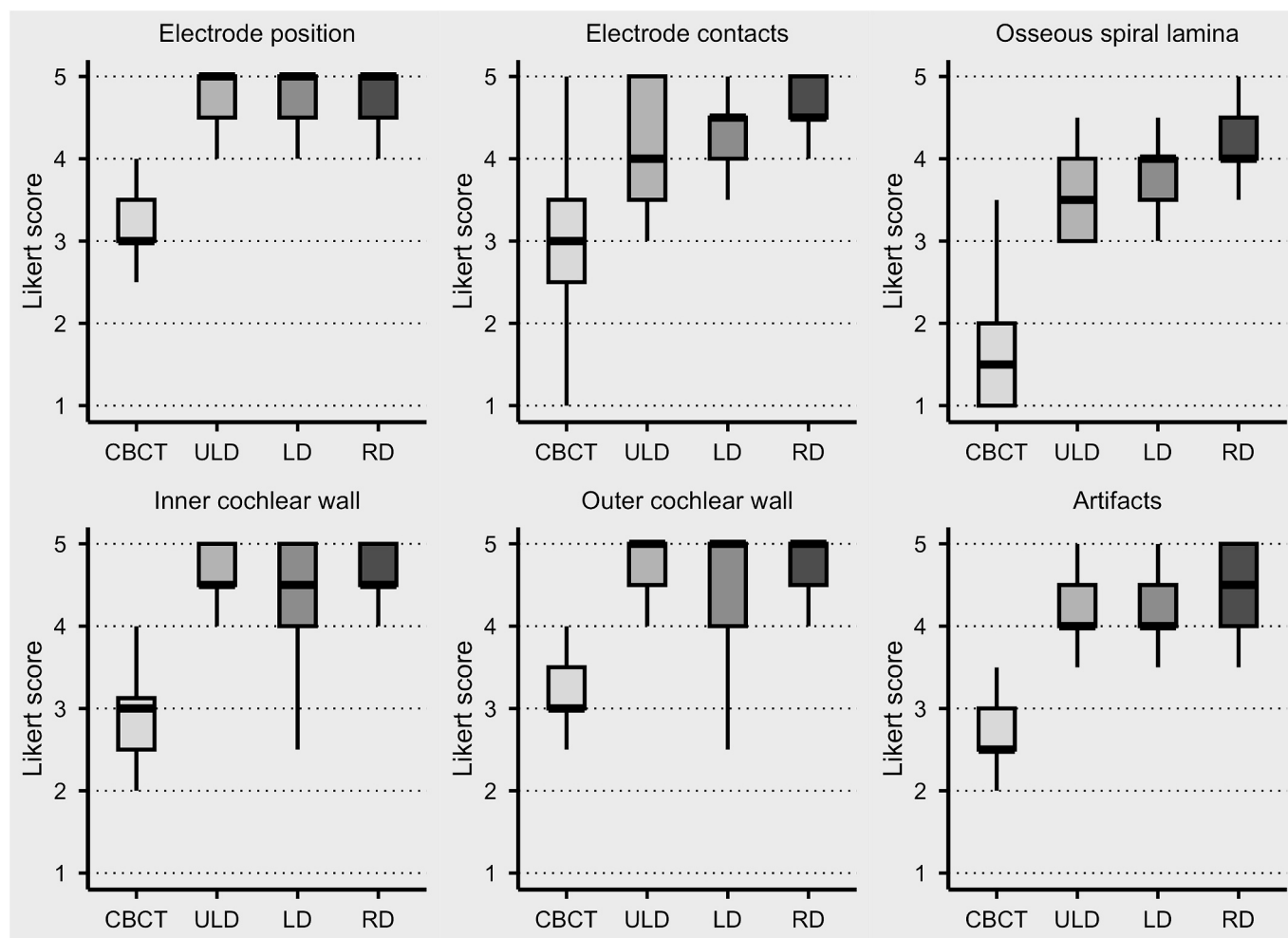


Fig. 4. Overview of subjective evaluation of all assessment criteria. All PCD CT protocols performed better than CBCT. Significant dose-dependent differences were found for the osseous spiral lamina, contact visibility, and artifacts in the PCD CT protocols. No significant differences were found for criteria such as electrode position and depiction of the cochlear walls.

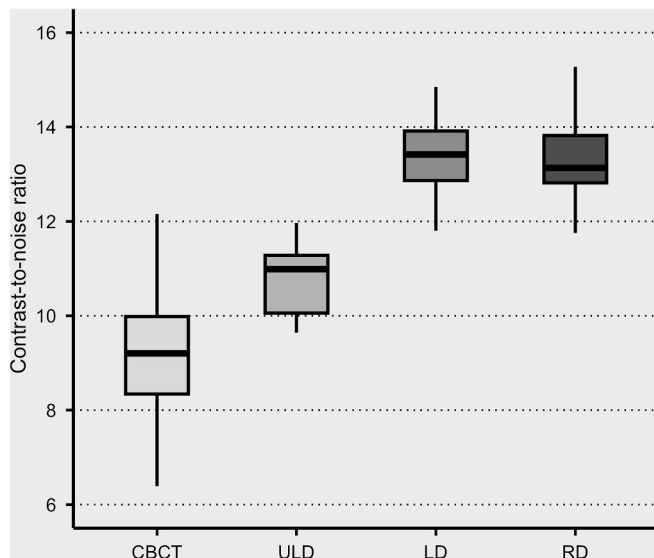


Fig. 5. The comparison of contrast to noise ratio (CNR) in CBCT versus PCD CT. The CNR ratio was significantly higher in all PCD CT examinations protocols (RD: regular dose, LD: low dose, ULD: ultra low dose).

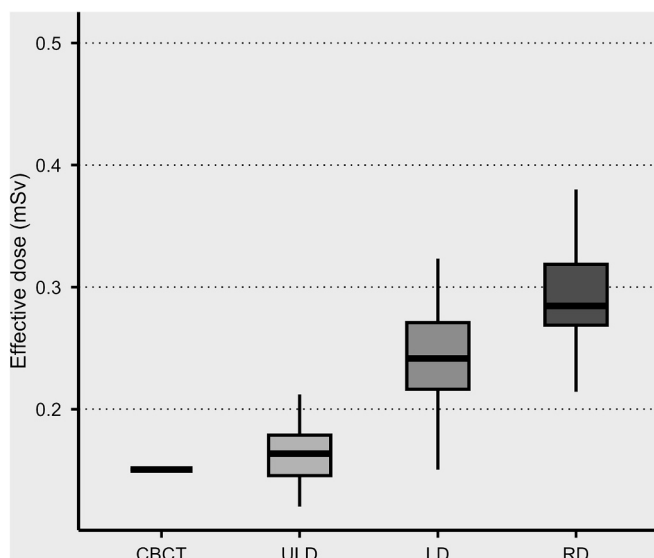


Fig. 6. Comparison of effective dose levels between CBCT and PCD CT. The effective dose was 0.30 ± 0.06 mSv in the RD group, 0.24 ± 0.04 mSv in the LD group, and 0.16 ± 0.02 mSv in the ULD group. The estimated effective dose values of the ULD PCD CT protocol (0.16 mSv) were numerically similar to those of CBCT (0.15 mSv); however, a direct comparison is limited by the different dosimetric approaches. RD: regular dose, LD: low dose, ULD: ultra low dose.

Whereas earlier work compared PCD CT with multislice CT, the present study evaluated PCD CT against CBCT for routine postoperative CI imaging. CBCT is an established modality because of its high spatial resolution and reliable bone depiction, but implant-related metal artifacts remain a significant limitation, impairing assessment of individual contacts and intracochlear anatomy [5,13,14]. Our findings confirm that the advantages of PCD CT persist in routine practice.

The improved image quality may reflect detector technology that directly converts individual X-ray photons into electrical signals, reducing electronic noise and improving dose efficiency evidenced by higher estimated CNR values. Ultra-high-resolution settings (0.2 mm collimation and slice thickness) further enabled detailed depiction of

delicate cochlear structures despite small CBCT voxel sizes [8,9]. PCD CT also showed fewer metal artifacts, likely owing to the energy-resolving properties of photon-counting detectors, which improve handling of beam hardening and support advanced reconstruction, such as virtual monochromatic imaging and metal artifact reduction [15,16]. Reduced artifacts were associated with improved visualization of electrode contacts and intracochlear anatomy.

The ULD protocol achieved higher image quality than CBCT at estimated effective doses of 0.16 and 0.15 mSv, respectively. This combination of higher quality and reduced artifact burden may be particularly relevant for patients with increased cumulative radiation exposure or heightened radiosensitivity, including those undergoing repeated follow-up examinations and individuals with cancer-predisposition syndromes. Although pediatric patients were not included, similar considerations may apply to children, who are more radiosensitive than adults. However, direct dose comparison remains challenging owing to fundamental differences in dosimetric concepts CT dose is based on the dose-length product (DLP), whereas CBCT dose derives from the dose-area product (DAP) and phantom-based conversion factors so effective-dose comparisons should be interpreted cautiously [12,17].

Improved visualization of intracochlear structures may support postoperative assessment of electrode position, insertion depth, and scalar location, parameters previously associated with audiological outcomes after CI, and may facilitate detection of complications such as scalar translocation or tip fold-over, aiding personalized management such as device programming or follow-up imaging [2]. However, this study did not evaluate whether better visualization affected diagnostic confidence, complication detection, or anatomy-based programming decisions.

4.1. Limitations

This retrospective, single-center study comparing CBCT with PCD CT may carry bias and limited generalizability. No independent standard for electrode-position parameters was available, as routine ground truths such as micro-CT, histology, intraoperative radiography, transimpedance recordings, and validated imaging are not usually accessible in clinical practice [18–21]. Our results therefore reflect image quality, evaluability, and interobserver agreement rather than diagnostic accuracy, precluding determination of sensitivity and specificity; validation would require micro-CT, histology, or intraoperative radiographic and electrophysiological confirmation in models or in vivo. Multiple examinations per patient were included, though sensitivity analyses confirmed robust results. Subjective assessment is observer-dependent, with possible influence from acquisition, reconstruction, and gray-value characteristics beyond detector technology. Few paired exams limited dose comparisons, and only one reconstruction setting (QIR Q1) was tested; higher levels could improve quality. Pediatric patients were excluded, requiring research in younger groups and diverse settings. Finally, PCD CT is currently available in few centers, and its higher costs may restrict widespread use in resource-limited facilities.

5. Conclusion

In postoperative cochlear implant imaging, the ULD PCD-CT protocol provided higher image quality and lower artifact burden than CBCT at a comparable estimated effective dose, though direct dose comparison is limited by differing dosimetric approaches. Clearer depiction of the electrode array and cochlear microanatomy may benefit clinical assessment of electrode position, scalar location, and insertion depth, informing device decisions such as processor map optimization or reprogramming. Its supine, position-independent acquisition makes ULD PCD-CT useful for immobile or difficult patients and for repeated follow-up imaging, especially in radiosensitive and pediatric populations. These findings position ULD PCD-CT as a promising, dose-conscious alternative to CBCT, pending confirmation in larger studies

with comparable dosimetry, standardized image-quality metrics, and clinical outcomes.

CRedit authorship contribution statement

Iris Burck: Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Software, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Marius Tillmanns:** Writing – review & editing, Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Simon Bernatz:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Jennifer Gotta:** Writing – review & editing, Investigation, Formal analysis. **Jan-Erik Scholtz:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Marina Kurtz:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Methodology, Formal analysis, Data curation, Conceptualization. **Vitali Koch:** Writing – review & editing, Visualization, Investigation, Formal analysis. **Juha Koivisto:** Writing – review & editing, Software, Methodology, Formal analysis, Conceptualization. **Silke Helbig:** Writing – review & editing, Visualization, Investigation, Formal analysis, Conceptualization. **Martin Leinung:** Writing – review & editing, Visualization, Methodology, Investigation. **Benjamin Ernst:** Writing – review & editing, Visualization, Methodology, Investigation. **Timo Stöver:** Writing – review & editing, Visualization, Supervision, Resources, Methodology. **Thomas J. Vogl:** .

Ethics declaration

Studies in human

This study was performed in compliance with relevant laws, regulatory frameworks and guidelines where the research took place. This study was approved by the Ethikkommission des Fachbereichs Medizin Universitätsklinikum der Goethe-Universität Haus 1, 2. OG, Zimmer 207–211 Theodor-Stern-Kai 7 60590 Frankfurt am Main. (Approval No. no. 2026–2804).

Written informed consent to take part in the study and to publish the article has been obtained from all participants or their legal representatives. The privacy rights of participants have been observed.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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