

Supplementary Information

Dual-Path Phantom Quality Assurance for CyberKnife Fiducial Tracking: Internal Mode Comparison and Independent Image-Analysis Cross-Check

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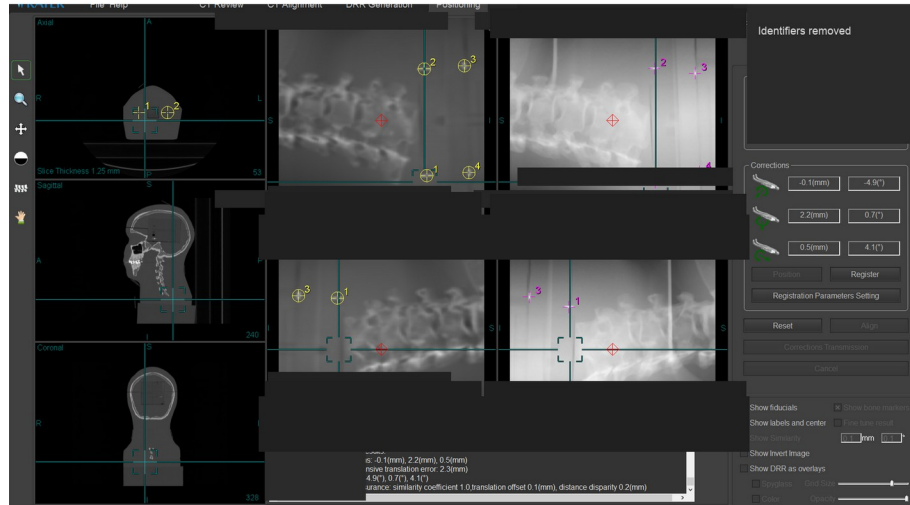
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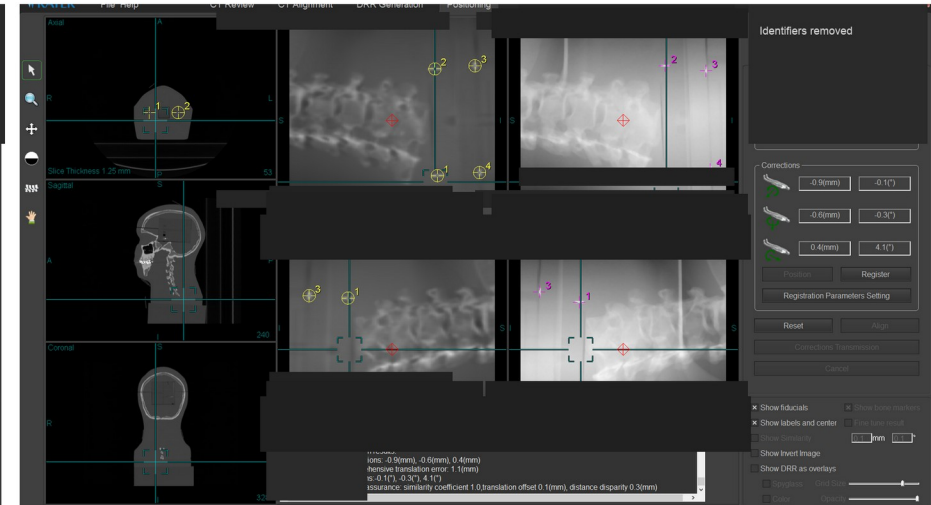
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a Automatic Rayer fiducial extraction

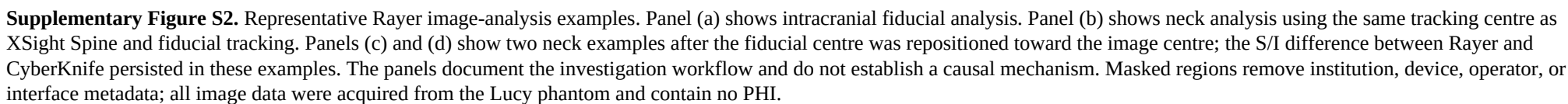


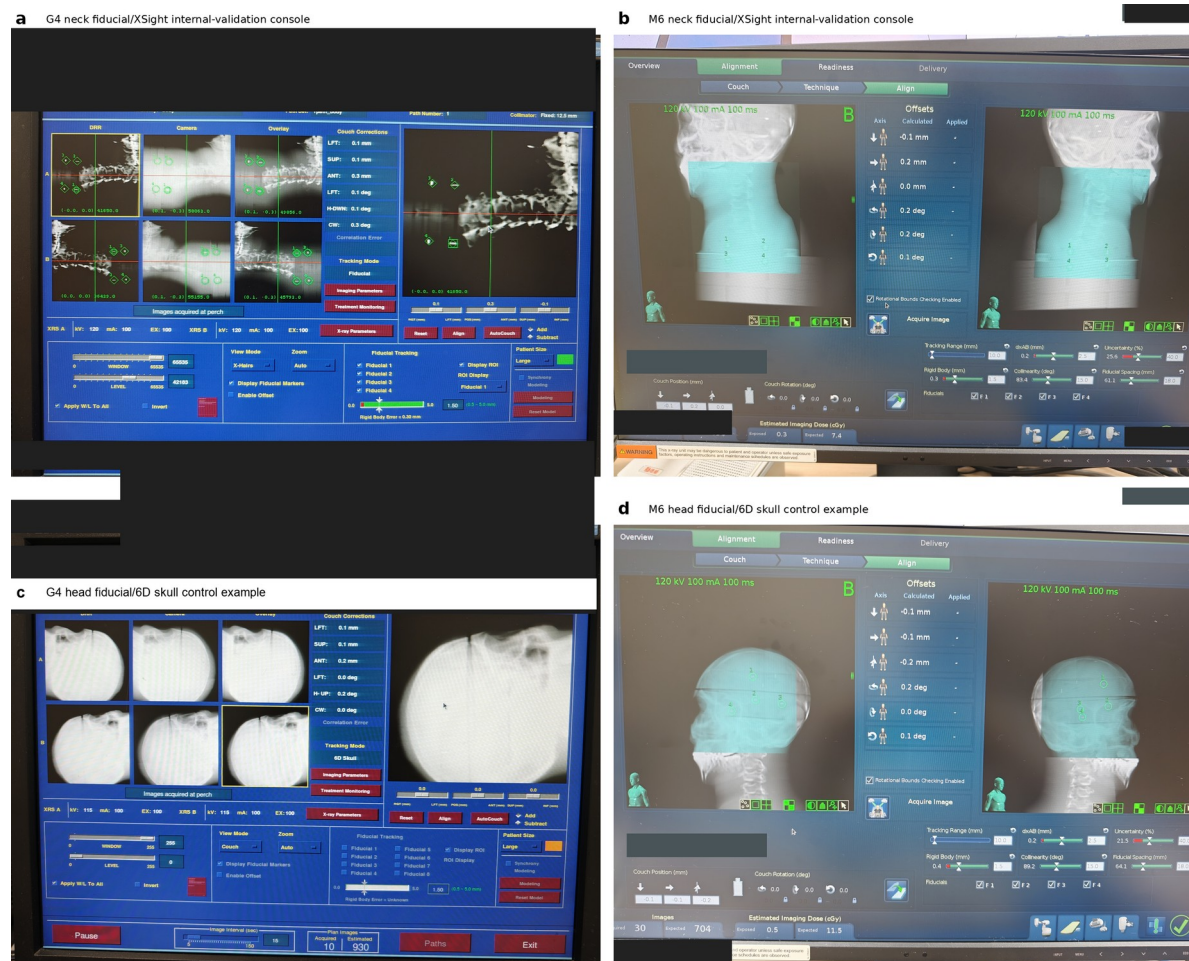
b After operator refinement of the A-1 centroid



Supplementary Figure S1. Representative Rayer output before and after operator refinement of one automatically detected fiducial. In panel (a), Rayer automatically identified the fiducials and generated six-dimensional output; the A-1 marker was judged slightly off-centre. In panel (b), the operator refined the A-1 marker position and Rayer recalculated the output. The panels illustrate the operator-review step within this phantom QA workflow. Masked regions remove institution, device, operator, or interface metadata; all image data were acquired from the Lucy phantom and contain no protected health information (PHI).

b Neck: shared XSight/fiducial tracking center





Supplementary Figure S3. Representative CyberKnife console examples for internal tracking-mode comparison. Panels show G4 neck fiducial versus XSight Spine, M6 neck fiducial versus XSight Spine, G4 head fiducial versus 6D Skull, and M6 head fiducial versus 6D Skull comparisons. The examples document the image and console outputs used in the internal-validation workflow and are not intended for device ranking. Masked regions remove institution, device, operator, or interface metadata; all images were acquired from the Lucy phantom and contain no PHI.

Supplementary Table S1. Field structure of the paired-measurement dataset.

Field	Meaning	Unit	Example	Role in Bland–Altman analysis
row_id	Unique row identifier	NA	1	Not used
group_code	Group code including validation type, device, region and data type	NA	IVG4-H-T	Included
device	CyberKnife system generation	NA	G4	Included
anatomical_site	Head or neck phantom region	NA	Head	Included
validation_type	Internal or external validation	NA	Internal	Included
comparison_group	Eight-group analysis label	NA	IVG4-H	Included
tracking_mode_reference	Reference measurement source	NA	Fiducial Tracking	Not used
tracking_mode_test	Comparator measurement source	NA	6D Skull Tracking	Not used
translation_or_rotation	Translation or rotation data category	NA	Translation	Included
axis	Directional axis	NA	Lat	Included
unit	Measurement unit	NA	mm	Included
reference_value	Reference value from fiducial tracking or CyberKnife log	mm or °	0.1	Included
test_value	Comparator value from 6D skull, XSight spine, or Rayer	mm or °	0.1	Included
difference_value	Reference minus test value used for Bland–Altman y-axis	mm or °	0	Included
mean_value	Mean of paired values used for Bland–Altman x-axis	mm or °	0.1	Included
sample_group	Full plotting/analysis subgroup	NA	IVG4-H Translation Lat	Not used
traceability_record	Study-specific measurement-record identifier	NA	G4 phantom QA record	Traceability only
comparison_context	Region and comparator used for paired analysis	NA	G4 head: fiducial vs 6D skull	Traceability only
included_in_analysis	Analysis inclusion flag	NA	Yes	Not used
exclusion_reason	Reason if not included or separated	NA		Not used
notes	Data-quality note	NA		Not used

Supplementary Table S2. Descriptive summary of G4 and M6 independent device cohorts.

Device	Region	Validation	Data type	N	Mean difference	P value	CR	Unit	Between-device inference
G4	Head	Internal	Translation	54	0.0315	0.1233	0.2934	mm	No
G4	Head	Internal	Rotation	54	−0.0556	0.0012	0.2558	°	No
G4	Neck	Internal	Translation	54	0.1704	<0.0001	0.4463	mm	No
G4	Neck	Internal	Rotation	54	−0.1574	<0.0001	0.4764	°	No
M6	Head	Internal	Translation	54	0.0815	0.0009	0.3657	mm	No
M6	Head	Internal	Rotation	54	0.0463	0.0716	0.3705	°	No
M6	Neck	Internal	Translation	54	−0.0315	0.2855	0.4209	mm	No
M6	Neck	Internal	Rotation	54	−0.0130	0.7249	0.5233	°	No
G4	Head	External	Translation	66	0.1530	<0.0001	0.4795	mm	No
G4	Head	External	Rotation	66	−0.0485	0.0042	0.2751	°	No
G4	Neck	External	Translation	72	−0.1444	0.0002	0.6687	mm	No
G4	Neck	External	Rotation	72	0.0250	0.2635	0.3696	°	No
M6	Head	External	Translation	84	0.0869	<0.0001	0.2713	mm	No
M6	Head	External	Rotation	84	−0.0643	<0.0001	0.2885	°	No
M6	Neck	External	Translation	90	−0.1467	<0.0001	0.5259	mm	No
M6	Neck	External	Rotation	90	−0.0456	0.0941	0.5056	°	No

Supplementary Table S3. Axis-level Bland–Altman results for internal and external validation. The G4 neck external-validation Lng (S/I) CR=1.0824 mm exceeded the 1.0-mm operational threshold, whereas the corresponding M6 neck Lng (S/I) CR=0.8362 mm remained below the threshold. Pooled G4 neck translation CR=0.6687 mm is retained as the three-axis summary.

Device	Region	Validation	Axis	N	Mean difference	95% LoA	P value	CR	Unit	Threshold status
G4	Neck	Internal	Lat (L/R)	18	0.1389	−0.1982 to 0.4760	0.0032	0.4259	mm	Within operational threshold
G4	Neck	Internal	Vrt (A/P)	18	0.1944	0.0234 to 0.3655	<0.0001	0.4158	mm	Within operational threshold
G4	Neck	Internal	Lng (S/I)	18	0.1778	−0.1815 to 0.5370	0.0007	0.4933	mm	Within operational threshold
G4	Neck	Internal	Translation (mm)	54	0.1704	−0.1285 to 0.4693	<0.0001	0.4463	mm	Within operational threshold
G4	Neck	Internal	Pitch (UP/DWN)	18	−0.1167	−0.5043 to 0.2710	0.0228	0.4407	°	Within operational threshold
G4	Neck	Internal	Yaw (CW/CCW)	18	−0.1556	−0.5924 to 0.2813	0.0087	0.5227	°	Within operational threshold
G4	Neck	Internal	Roll (LFT/RGT)	18	−0.2000	−0.4515 to 0.0515	<0.0001	0.4620	°	Within operational threshold
G4	Neck	Internal	Rotation (°)	54	−0.1574	−0.5238 to 0.2090	<0.0001	0.4764	°	Within operational threshold
G4	Head	Internal	Lat (L/R)	18	0.0722	−0.1588 to 0.3032	0.0187	0.2654	mm	Within operational threshold
G4	Head	Internal	Vrt (A/P)	18	−0.0500	−0.3372 to 0.2372	0.1659	0.2958	mm	Within operational threshold
G4	Head	Internal	Lng (S/I)	18	0.0722	−0.2193 to 0.3638	0.055	0.3167	mm	Within operational threshold
G4	Head	Internal	Translation (mm)	54	0.0315	−0.2580 to 0.3210	0.1233	0.2934	mm	Within operational threshold
G4	Head	Internal	Pitch (UP/DWN)	18	−0.0778	−0.2856 to 0.1300	0.0063	0.2530	°	Within operational threshold
G4	Head	Internal	Yaw (CW/CCW)	18	0.0389	−0.1529 to 0.2307	0.11	0.2014	°	Within operational threshold
G4	Head	Internal	Roll (LFT/RGT)	18	−0.1278	−0.3032 to 0.0476	<0.0001	0.3029	°	Within operational threshold
G4	Head	Internal	Rotation (°)	54	−0.0556	−0.2892 to 0.1781	0.0012	0.2558	°	Within operational threshold
M6	Neck	Internal	Lat (L/R)	18	0.0222	−0.3786 to 0.4231	0.6507	0.3920	mm	Within operational threshold
M6	Neck	Internal	Vrt (A/P)	18	−0.2389	−0.4307 to −0.0471	<0.0001	0.5040	mm	Within operational threshold
M6	Neck	Internal	Lng (S/I)	18	0.1222	−0.1429 to 0.3874	0.0013	0.3518	mm	Within operational threshold
M6	Neck	Internal	Translation (mm)	54	−0.0315	−0.4517 to 0.3888	0.2855	0.4209	mm	Within operational threshold
M6	Neck	Internal	Pitch (UP/DWN)	18	−0.0667	−0.3597 to 0.2264	0.0757	0.3133	°	Within operational threshold
M6	Neck	Internal	Yaw (CW/CCW)	18	−0.1111	−0.7378 to 0.5155	0.1586	0.6468	°	Within operational threshold
M6	Neck	Internal	Roll (LFT/RGT)	18	0.1389	−0.3558 to 0.6335	0.0321	0.5524	°	Within operational threshold
M6	Neck	Internal	Rotation (°)	54	−0.0130	−0.5406 to 0.5147	0.7249	0.5233	°	Within operational threshold
M6	Head	Internal	Lat (L/R)	18	0.1444	−0.1795 to 0.4684	0.0017	0.4234	mm	Within operational threshold
M6	Head	Internal	Vrt (A/P)	18	0.1389	−0.1394 to 0.4172	0.0007	0.3837	mm	Within operational threshold
M6	Head	Internal	Lng (S/I)	18	−0.0389	−0.3090 to 0.2312	0.2476	0.2733	mm	Within operational threshold
M6	Head	Internal	Translation (mm)	54	0.0815	−0.2506 to 0.4136	0.0009	0.3657	mm	Within operational threshold
M6	Head	Internal	Pitch (UP/DWN)	18	0.0833	−0.1319 to 0.2986	0.005	0.2654	°	Within operational threshold
M6	Head	Internal	Yaw (CW/CCW)	18	−0.1222	−0.4554 to 0.2109	0.0072	0.4027	°	Within operational threshold
M6	Head	Internal	Roll (LFT/RGT)	18	0.1778	−0.0697 to 0.4253	<0.0001	0.4234	°	Within operational threshold
M6	Head	Internal	Rotation (°)	54	0.0463	−0.3163 to 0.4089	0.0716	0.3705	°	Within operational threshold
G4	Head	External	Lat (L/R)	22	−0.0682	−0.2433 to 0.1070	0.0018	0.2171	mm	Within operational threshold
G4	Head	External	Vrt (A/P)	22	0.1636	0.0089 to 0.3184	<0.0001	0.3546	mm	Within operational threshold
G4	Head	External	Lng (S/I)	22	0.3636	0.2671 to 0.4601	<0.0001	0.7189	mm	Within operational threshold
G4	Head	External	Translation (mm)	66	0.1530	−0.2239 to 0.5300	<0.0001	0.4795	mm	Within operational threshold
G4	Head	External	Pitch (UP/DWN)	22	−0.1318	−0.3840 to 0.1204	0.0001	0.3570	°	Within operational threshold
G4	Head	External	Yaw (CW/CCW)	22	0.0182	−0.2210 to 0.2574	0.4923	0.2364	°	Within operational threshold

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Device	Region	Validation	Axis	N	Mean difference	95% LoA	P value	CR	Unit	Threshold status
G4	Head	External	Roll (LFT/RGT)	22	-0.0318	-0.2359 to 0.1723	0.1665	0.2089	°	Within operational threshold
G4	Head	External	Rotation (°)	66	-0.0485	-0.3086 to 0.2116	0.0042	0.2751	°	Within operational threshold
G4	Neck	External	Lat (L/R)	24	0.0667	-0.2687 to 0.4020	0.0688	0.3533	mm	Within operational threshold
G4	Neck	External	Vrt (A/P)	24	0.0417	-0.1579 to 0.2412	0.0568	0.2117	mm	Within operational threshold
G4	Neck	External	Lng (S/I)	24	-0.5417	-0.7573 to -0.3261	<0.0001	1.0824	mm	Exceeds 1.0-mm operational threshold
G4	Neck	External	Translation (mm)	72	-0.1444	-0.7545 to 0.4656	0.0002	0.6687	mm	Within operational threshold
G4	Neck	External	Pitch (UP/DWN)	24	0.0542	-0.1284 to 0.2367	0.0091	0.2079	°	Within operational threshold
G4	Neck	External	Yaw (CW/CCW)	24	0.1083	-0.3428 to 0.5594	0.0305	0.4900	°	Within operational threshold
G4	Neck	External	Roll (LFT/RGT)	24	-0.0875	-0.4057 to 0.2307	0.0146	0.3556	°	Within operational threshold
G4	Neck	External	Rotation (°)	72	0.0250	-0.3439 to 0.3939	0.2635	0.3696	°	Within operational threshold
M6	Head	External	Lat (L/R)	28	0.0464	-0.1343 to 0.2272	0.0129	0.1995	mm	Within operational threshold
M6	Head	External	Vrt (A/P)	28	0.0214	-0.1328 to 0.1756	0.161	0.1571	mm	Within operational threshold
M6	Head	External	Lng (S/I)	28	0.1929	0.0744 to 0.3113	<0.0001	0.3955	mm	Within operational threshold
M6	Head	External	Translation (mm)	84	0.0869	-0.1256 to 0.2994	<0.0001	0.2713	mm	Within operational threshold
M6	Head	External	Pitch (UP/DWN)	28	-0.0643	-0.2724 to 0.1438	0.0035	0.2400	°	Within operational threshold
M6	Head	External	Yaw (CW/CCW)	28	-0.1000	-0.3558 to 0.1558	0.0004	0.3186	°	Within operational threshold
M6	Head	External	Roll (LFT/RGT)	28	-0.0286	-0.3297 to 0.2725	0.3338	0.3009	°	Within operational threshold
M6	Head	External	Rotation (°)	84	-0.0643	-0.3254 to 0.1968	<0.0001	0.2885	°	Within operational threshold
M6	Neck	External	Lat (L/R)	30	0.0500	-0.1409 to 0.2409	0.0087	0.2117	mm	Within operational threshold
M6	Neck	External	Vrt (A/P)	30	-0.0700	-0.3332 to 0.1932	0.0079	0.2929	mm	Within operational threshold
M6	Neck	External	Lng (S/I)	30	-0.4200	-0.5692 to -0.2708	<0.0001	0.8362	mm	Within operational threshold
M6	Neck	External	Translation (mm)	90	-0.1467	-0.5895 to 0.2962	<0.0001	0.5259	mm	Within operational threshold
M6	Neck	External	Pitch (UP/DWN)	30	0.1200	-0.1684 to 0.4084	0.0001	0.3684	°	Within operational threshold
M6	Neck	External	Yaw (CW/CCW)	30	-0.0167	-0.5969 to 0.5636	0.76	0.5714	°	Within operational threshold
M6	Neck	External	Roll (LFT/RGT)	30	-0.2400	-0.5339 to 0.0539	<0.0001	0.5521	°	Within operational threshold
M6	Neck	External	Rotation (°)	90	-0.0456	-0.5460 to 0.4549	0.0941	0.5056	°	Within operational threshold

Supplementary Table S4. Configuration context and coordinate conventions for external validation. The entries document the study configuration and axis/sign mapping used for paired comparison; no service-level physical mechanism is inferred.

Device / scope	Confirmed configuration context	Evidence type	Role in analysis	Interpretation
CyberKnife G4	January 2026 measurements used the Fixed collimator. Relevant Local configuration values remained unchanged during the study acquisition interval.	configuration record	Documents local acquisition context before external comparison	Contextual record; no service-level mechanism inferred.
CyberKnife M6	January 2026 measurements used the Fixed collimator; Iris was unavailable and MLC was not used. Relevant Local configuration values remained unchanged during the study acquisition interval.	configuration record	Documents local acquisition context before external comparison	Contextual record; no service-level mechanism inferred.
G4 translation axes	CyberKnife log convention: +INF/-SUP, +LFT/-RGT, +ANT/-POS; analysis labels: Lng (S/I), Lat (L/R), Vrt (A/P).	axis/sign convention	Defines direction mapping for paired comparison	Bland-Altman difference was calculated as reference minus test.
G4 rotation axes	CyberKnife log convention: +RROLL/-LROLL, +H-UP/-H-DN, +CCW/-CW; analysis labels: Roll, Pitch, Yaw.	axis/sign convention	Defines rotation mapping for paired comparison	Bland-Altman difference was calculated as reference minus test.
G4/M6 plan configuration	FIXED denotes Fixed-collimator plans; MLC configuration parameters were not used in this study.	analysis metadata	Confirms the collimator context of external-validation records	Only the confirmed Fixed-collimator context is used.
Three-axis summaries	Translation pools Lat/Vrt/Lng; rotation pools Pitch/Yaw/Roll.	analysis definition	Explains pooled translation and rotation results	Axis-level results remain available in Supplementary Table S3.

Supplementary Table S5. Focused quality-control review of the G4 neck XSight direction-consistent offset pattern.

QA check	Result	Focused QA interpretation	QA implication
Outlier assessment	The G4 neck XSight direction-consistent pattern persisted after outlier review.	The observation was not driven primarily by a small number of extreme values.	The axis-level pattern remained after outlier assessment.
Column-pairing review	No evidence was found that head/neck or fiducial/reference columns were cross-paired.	A simple column-pairing artifact was not identified.	The observed mean differences were retained without causal attribution.
Data-entry review	The direction-consistent pattern remained after data-entry verification.	A simple transcription explanation was not identified.	The reported numerical results were unchanged after data-entry review.
Axis-level pattern	Translation-axis mean differences were positive and rotation-axis mean differences were negative in the G4 neck internal comparison.	The finding is direction-consistent within this dataset.	The pattern is reported as a focused QA observation; no physical mechanism is assigned.
Pooled agreement	Pooled G4 neck XSight CR values remained below the 1.0 mm/1.0° operational phantom QA threshold.	The pooled result summarizes overall three-axis agreement, while axis-level findings remain reported separately.	The phantom result is not interpreted as a patient-safety or device-ranking conclusion.
Potential contributors	Coordinate-reporting conventions, calibration settings, software version, and plan-mode switching are possible review targets.	These factors were not tested separately.	No causal factor was assigned.