

A Mechanics-Free Framework for Validating Rotational Registration Accuracy in ExacTrac Dynamic

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Purpose

Precise patient positioning is essential in stereotactic radiotherapy, where small angular errors can lead to clinically relevant changes in dose distribution. Rotational IGRT accuracy is conventionally validated by physically rotating the couch or phantom. However, this approach combines registration-algorithm performance with mechanical uncertainties such as backlash, sag, and finite motor resolution. We present a mechanics-free validation framework, demonstrated on ExacTrac Dynamic (ETD) across different isocentre locations and couch angles.

Materials and Methods

A set of known rigid rotations about the treatment isocentre were digitally applied to the reference CT scan of a head phantom. The phantom was aligned once to the baseline CT and kept fixed while ETD registered stereoscopic kV images to DRRs generated from each rotated CT. Global residual rotations were evaluated using the SO(3) geodesic angle (Figure 1).

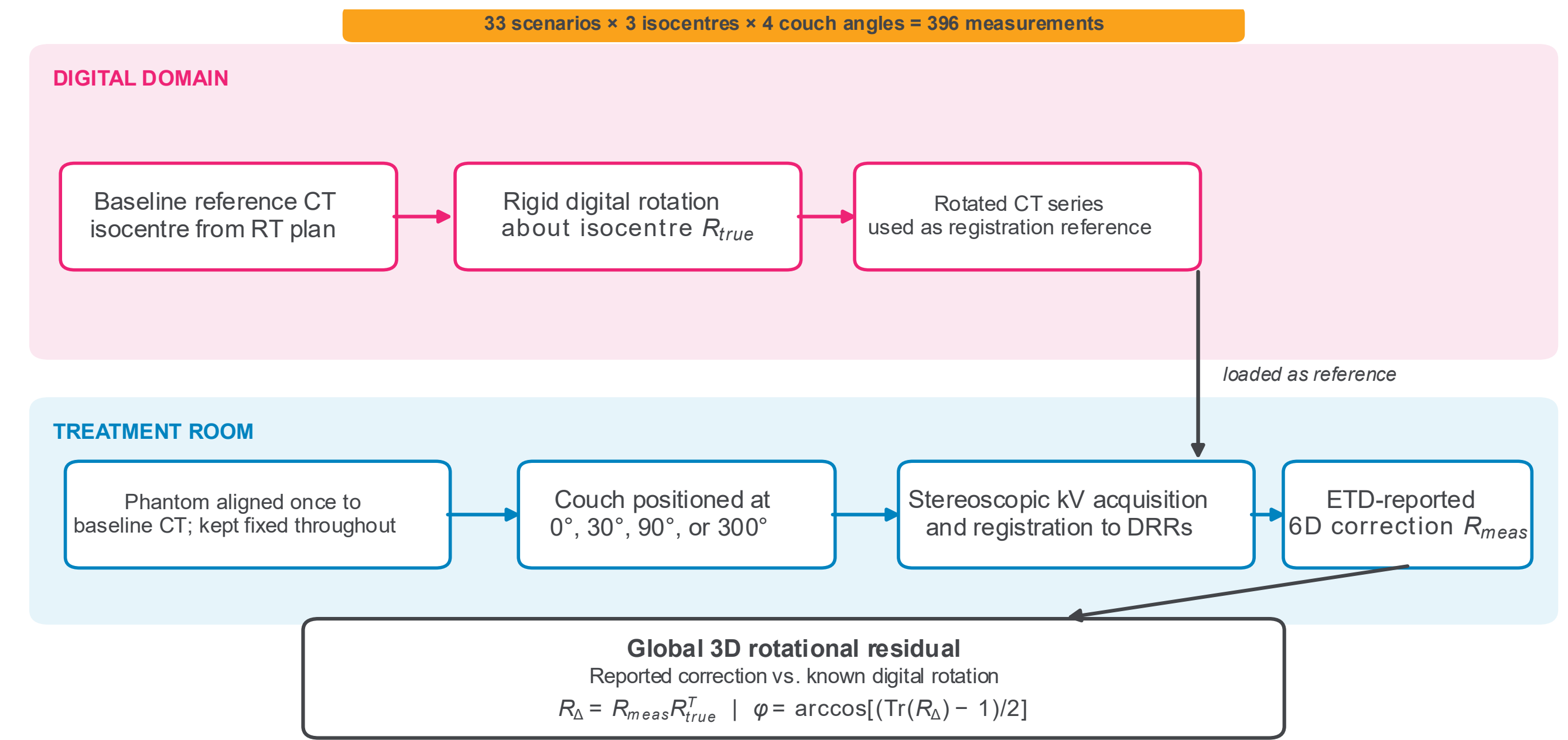


Figure 1. Overview of the validation framework, showing the separation between the digital reference-generation pathway and the treatment-room measurement pathway, with the final global rotational-error assessment.

Results

Measured and imposed rotations showed near-perfect agreement, with no systematic directional bias. ETD maintained high rotational accuracy for both single- and combined-axis rotations, with no loss of performance for combined rotations (Table 1). Global 3D errors remained stable across all isocentre locations and couch angles (Figure 2). All observed errors were well below the 0.5° rotational tolerance applied for stereotactic treatments at our institution.

Global 3D geodesic error, φ (°)

Error between imposed and ETD-reported rotations

	Mean	SD	Max
Single-axis n = 324	0.046	0.056	0.200
Combined-axis n = 72	0.062	0.061	0.174
All measurements N = 396	0.049	0.057	0.200

Tolerance used in SRS cases: 0.5°

Table 1. Global 3D rotational error measured using the SO(3) geodesic angle.

Robustness across spatial configuration

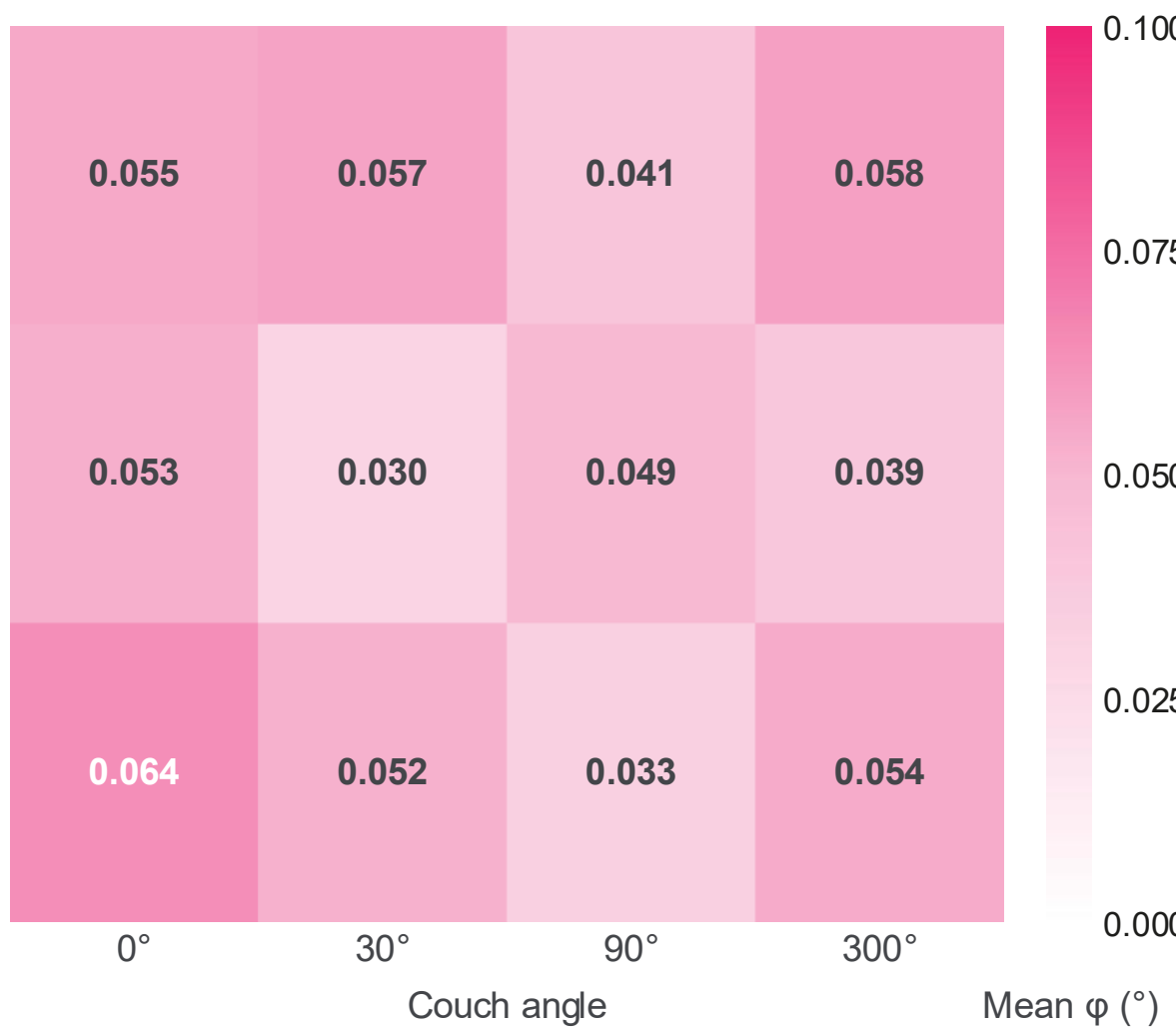


Figure 2. Mean global 3D rotational error by isocentre location and couch angle.

Conclusion

Digital ground truth removes couch mechanics from the measurement, allowing intrinsic registration accuracy to be assessed independently of positioning hardware. ExacTrac Dynamic showed highly precise rotational registration across all tested geometries, supporting its use in stereotactic workflows that demand accurate rotational positioning. The SO(3) geodesic angle provides a geometrically appropriate framework for quantifying composite rotational errors. This approach could potentially be extended to rotational quality assurance of other IGRT and even SGRT systems.