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## 1. Specific XCAT Parameter Ranges of Training Dataset

| Name | RangeDown | RangeUp | Type |
|---|---|---|---|
| gender | 0 | 1 | int |
| phantom_long_axis_scale | 0.9 | 1.1 | float |
| min_diaphragm_motion | 0.5 | 2 | float |
| max_diaphragm_motion | 2 | 12 | float |
| max_AP_exp | 0.4 | 1.8 | float |
| hrt_motion_y | 0 | 2 | float |
| hrt_motion_z | 0 | 2 | float |
| hrt_motion_rot_xz | -5 | 5 | float |
| hrt_motion_rot_yx | -5 | 5 | float |
| hrt_motion_rot_zy | -5 | 5 | float |
| phantom_short_axis_scale | 0.9 | 1.1 | float |
| phantom_height_scale | 0.9 | 1.1 | float |
| torso_long_axis_scale | 0.9 | 1.1 | float |
| torso_short_axis_scale | 0.9 | 1.1 | float |
| abdomen_skin_long_axis_scale | 0.9 | 1.1 | float |
| abdomen_skin_short_axis_scale | 0.9 | 1.1 | float |
| pelvis_skin_long_axis_scale | 0.9 | 1.1 | float |
| pelvis_skin_short_axis_scale | 0.9 | 1.1 | float |
| chest_skin_long_axis_scale | 0.9 | 1.1 | float |
| chest_skin_short_axis_scale | 0.9 | 1.1 | float |
| bones_scale | 0.9 | 1.1 | float |
| hrt_scale | 0.9 | 1.1 | float |
| rdiaph_liv_scale | 0.9 | 1.1 | float |
| ldiaph_scale | 0.9 | 1.1 | float |
| d_ZY_rotation | -5 | 5 | float |
| d_XZ_rotation | -5 | 5 | float |
| d_YX_rotation | -5 | 5 | float |
| X_tr | -2 | 2 | float |
| Y_tr | -2 | 2 | float |
| Z_tr | -2 | 2 | float |
| vol_liver | 1200 | 2000 | float |
| vol_stomach | 300 | 800 | float |
| vol_pancreas | 70 | 160 | float |
| vol_rkidney | 100 | 180 | float |
| vol_lkidney | 100 | 180 | float |

Table S1. Specific XCAT Parameter Ranges of Training Dataset

## 2. Specific Scanning Information for Two Centers

Fifty-three liver-cancer patients were recruited from Center1, each of them received regular 4D-MRI scanning and T1-w (breath holding) 3D-MRI scans. The MR scans were performed using a 3 T MR-Sim scanner (uMR Omega, United Imaging, China).

| | T1w 3D MRI | | |
|---|---|---|---|
| | **Parameters 1** | **Parameters 2** | **Parameters 3** |
| **Contrast-enhanced** | TRUE | TRUE | FALSE |
| **Acquisition mode** | Breath Hold | Breath Hold | Breath Hold |
| **Fat suppression** | Yes | Yes | Yes |
| **Turbo factor** | 29 | 29 | 29 |
| **Flip angle (°)** | 13 | 12 | 12 |
| **Parallel imaging factor** | 3 | 2.4 | 2.4 |
| **Acceleration factor (PE)** | 3.81 | 2.48 | 2.48 |
| **TR (ms)** | 4.11 | 4.2 | 4.2 |
| **TE (ms)** | 1.3 | 1.3 | 1.3 |
| **Bandwidth (Hz/pixel)** | 1500 | 1140 | 1140 |
| **Acquisition matrix size** | 288×178 | 304×188 | 304×188 |
| **Voxel size ($mm^3$)** | 1.46×1.39×6mm | 1.46×1.39×6mm | 1.46×1.39×6mm |
| **Acquisition time** | 15.7s | 15s | 15s |

Table S2. MRI parameters from Center1. 3D: three-dimensional.

Eight prospectively collected patients from Center 2 constituted the clinical evaluation cohort, including patients undergoing radiotherapy for liver tumors. Each patient underwent commercial 4D-MRI as well as T1-weighted and T2-weighted 3D-MRI. The complete cohort was used for external evaluation of ZeroShot-4DRecon, JointMorph, and ANTs, whereas the DDEM-specific training and internal-validation split is described in the main manuscript. Detailed imaging parameters are listed in **Table S3**. The MR scans were performed using a 1.5 T MR-Sim scanner (Philips, Amsterdam, Netherlands).

| | **LQ-4D-MRI** | **T1w 3D MRI** | **T2w 3D MRI** |
|---|---|---|---|
| **No. of Patients** | 8 | 8 | 8 |
| **Contrast-enhanced** | No | No | No |
| **Acquisition mode** | Free breathing | None | Bellow gating |
| **Sequence** | 4D THRIVE | SoS Vane | TSE MultiVane |
| **Fat suppression** | SPIR | No | Yes |
| **Turbo factor** | 45 | 44 | 39 |
| **Flip angle (°)** | 10 | 10 | 90 |
| **Parallel imaging (factor)** | CS-SENSE | SENSE | SENSE |
| **Acceleration factor (PE)** | 9 | 1.8 | 1.8 |
| **Partial Fourier** | 0.625(Y)/0.8(Z) | N/A | N/A |
| **TR (ms)** | 3.5 | 6.3 | 5227 |
| **TE (ms)** | 1.57 | 1.77/3.7 | 70 |
| **Bandwidth (Hz/pixel)** | 500 | 545 | 629 |
| **Acquisition matrix size** | 140×140×53 | 376×376×78 | 300×300×95 |
| **Voxel size ($mm^3$)** | 3.0×3.0×3.0 | 1.2×1.2×3.0 | 1.5×1.5×3.0 |
| **Acquisition time** | 64 s | 218s | 353s |
| **No. of frames** | 87 | N/A | N/A |

Table S3. MRI parameters from Center2. 3D: three-dimensional; 4D: four-dimensional; CS-SENSE: compressed sensing-sensitivity encoding; LQ: low-quality; MultiVane: Motion Correction with Radial

Blades; SoS: Stack of Stars; SENSE MRI: sensing-sensitivity encoding magnetic resonance imaging; T2w: T2-weighted; TE: echo time; THRIVE: T1-weighted High Resolution Isotropic Volume Examination; TR: repetition time; TSE: Turbo Spin Echo.