

Supplementary Material

Implementation details of quantitative trajectory analysis and composite risk scoring

1. Overview

This supplementary material describes the implementation details of the quantitative trajectory analysis used in this study, including trajectory sampling, distance computation, and composite risk score formulation. These details are provided to ensure transparency and reproducibility of the proposed decision-support framework.

2. Trajectory sampling

Each candidate puncture trajectory was defined as a three-dimensional straight line between the fixed entry point and the target lesion.

The trajectory was discretized at regular intervals (sampling step: 1.0 mm), and all distance-based metrics were calculated along the entire trajectory.

3. Distance map generation

For each segmented organ (trachea, aorta, pulmonary artery, pulmonary veins), a three-dimensional Euclidean distance map was generated using voxel-based distance transformation. Distances between the trajectory and each organ were calculated by sampling the distance map values at each trajectory point. In the actual implementation used for the composite risk score in this case, the evaluated structures were the trachea, aorta, and a heart-labeled segment representing the adjacent pulmonary artery and pulmonary veins.

4. Distance-based metrics

For each candidate trajectory, the following metrics were derived:

Minimum distance to the pulmonary artery/pulmonary venous surrogate region (d_h)

The minimum three-dimensional distance between the trajectory and the heart-labeled segment representing the adjacent pulmonary artery and pulmonary veins.

Minimum distance to the aorta (d_a)

The minimum three-dimensional distance between the trajectory and the aorta.

Minimum distance to the trachea (d_t)

The minimum three-dimensional distance between the trajectory and the trachea.

Tracheal near-contact segment length (l_t)

The cumulative length of trajectory segments located within 5 mm of the trachea.

Tracheal contact indicator (I_t)

A binary variable indicating direct contact or penetration of the trachea (1 = contact present, 0 = no contact).

5. Composite risk score formulation

The composite risk score (R_{total}) was defined as the sum of four components:

$$R_{\text{total}} = R_{\text{cat}} + R_{\text{vas}} + R_{\text{syn}} + R_{\text{air}}$$

5.1 Catastrophic risk (R_{cat})

Direct tracheal contact or penetration was treated as an unacceptable catastrophic event and penalized with a large constant:

$$R_{\text{cat}} = P \times I_t$$

where $P = 100$.

This term was intended to ensure that any trajectory directly contacting the trachea would be strongly disfavored in the ranking.

5.2 Vascular proximity risk (R_{vas})

Proximity to major vessels was modeled as the sum of inverse distances:

$$R_{\text{vas}} = \frac{1}{d_h + \epsilon} + \frac{1}{d_a + \epsilon}$$

where d_h and d_a denote the minimum distances to the pulmonary artery/pulmonary venous surrogate region and the aorta, respectively, and ϵ is a small constant introduced to avoid division by zero. This term was used to assign higher risk to trajectories located closer to either vascular structure.

5.3 Synergistic vascular risk (R_{syn})

Simultaneous proximity to multiple major vessels was assumed to increase risk nonlinearly. A multiplicative synergy term was introduced

$$R_{\text{syn}} = \gamma \cdot \frac{1}{d_h + \epsilon} \cdot \frac{1}{d_a + \epsilon}$$

where $\gamma = 15$.

This term was included to penalize trajectories simultaneously close to both vascular regions more strongly than trajectories close to only one structure.

5.4 Airway proximity risk (R_{air})

Airway risk was modeled using both minimum distance and near-contact segment length:

$$R_{\text{air}} = u_{\text{air}} \cdot \frac{1}{d_t + \epsilon} + v_{\text{air}} \cdot \frac{l_t}{L_{\text{needle}}}$$

where d_t is the minimum distance to the trachea, l_t is the cumulative trajectory length within 5 mm of the trachea, $L_{\text{needle}} = 20$ mm is the evaluation length, $u_{\text{air}} = 0.5$, and $v_{\text{air}} = 2.0$. This formulation was used to reflect not only the closest approach to the trachea but also the extent of sustained near-airway passage along the trajectory.

6. Parameter settings

The weighting coefficients were selected empirically to reflect clinical priorities in this case. The largest penalty was assigned to tracheal contact or penetration ($P = 100$), treating it as a catastrophic event. Simultaneous proximity to the pulmonary artery/pulmonary venous surrogate region and the aorta was additionally emphasized through a synergy term ($\gamma = 15$). In contrast, the single-vessel proximity terms were kept relatively modest. Airway proximity was evaluated using both minimum tracheal distance and near-contact segment length, with coefficients $u_{\text{air}} = 0.5$ and $v_{\text{air}} = 2.0$. These coefficients were not intended for absolute risk prediction or universal use, but rather to provide an internally consistent heuristic for relative ranking of candidate trajectories within the same patient. In this case, the clinical priority was to avoid airway injury first while also accounting for vascular proximity. Alternative coefficient settings could be considered in other anatomical or procedural contexts, but such modifications would require separate validation. Formal sensitivity analysis regarding coefficient variation was not performed.

7. Interpretation and usage

The composite risk score was used exclusively for relative comparison among candidate trajectories within the same case. Lower scores indicated lower relative procedural risk. Final clinical decision-making remained entirely at the discretion of the operator, with the quantitative evaluation serving as decision-support information rather than automated guidance. Accordingly, the score should be interpreted primarily as a structured within-case ranking tool for comparing candidate trajectories rather than as an absolute estimate of procedural risk.