Paper Review:

GPU-Based Real-Time Approximation of the Ablation Zone for Radiofrequency Ablation

Project 14: Needle Localization In CT-Guided Tumor Ablation

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Project Summary

- **Clinical Problem:** Minimally-invasive tumor ablation procedures

- **Goals:** Develop an algorithm to localize and identify the orientation of the ablation needle in CT images and predict the ablation zone

- **Technical Approach:**
  - Develop a 3D-segmentation algorithm of ablation needles using connected component analysis and PCA
  - Generate a real-time approximation of the ablation zone using an ellipsoid model

Provided by Drs. Xu, Sheng and Wood, Bradford

Paper Overview and Relevance

GPU-Based Real-Time Approximation of the Ablation Zone for Radiofrequency Ablation

C. Rieder, T. Kroeger, C. Schumann and H. K. Hahn

- The paper presents a novel approach to **model the ablation zone** while taking into account the **heat-sink effects** commonly caused by large **blood vessels** near the tumor site.

- The model is developed by approximating complex **numerical simulations** and **graphics hardware**, aiming to support the **ablation procedure planning process**.

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Medical Background

Radiofrequency Ablation: ablation needle → radiofrequency electrodes → high-frequency electric field → heats up a targeted area in the tumor → induces coagulative necroses.

Ablation Zone Approximation: [Wood et al.]

- Technical specification of the ablation needle (applicator)
- Location of the applicator
- Tissue thermal and electrical properties (specific heat, thermal and electrical conductivity)
- **Heatsink effects** from vessel occlusion
- Intervention of other procedure (eg. hydrodissection)

→ Ablation treatment plan is very **patient-specific** & accurate approximation of the ablation zone is **extremely complex**
→ **Clinical Problem: Under-ablation and over-ablation**
→ Needs a better way to approximate the ablation zone and guide physician to achieve accurate electrode placement

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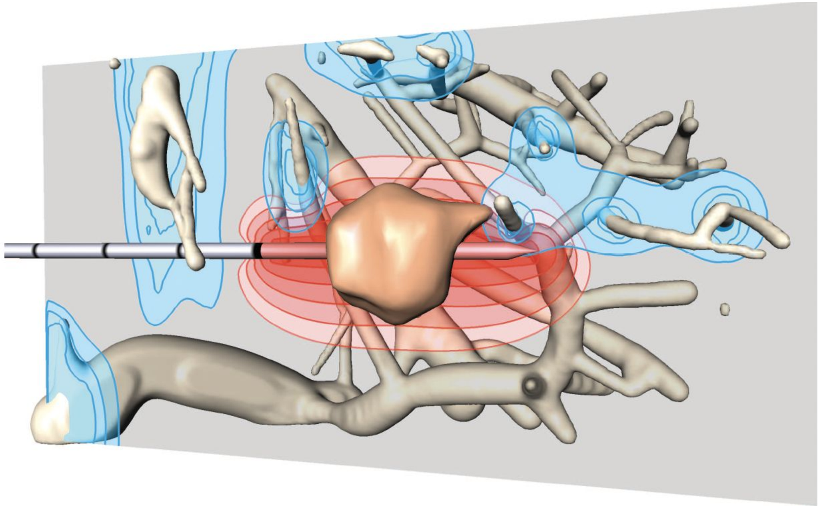
Main Points

- Proposal of a model based on weighted distance fields to approximate the ablation zone, incorporating heat-sink effects of the blood vessels.
- Integration of the approximation model into a clinical software assistant.
- Assessment of the value of the method by comparing the results with complex numerical simulations.



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Mathematical Model: Homogeneous tissue

Electric conductivity (dependent on T)

Electric potential

Quasi-static electric potential $\nabla \cdot (\sigma \nabla \phi) = 0$

Bioheat transfer equation $\rho c \partial_t T - \nabla \cdot (\lambda \nabla T) + \overbrace{\nu (T - T_{\text{body}})}^{\text{Invisible heatsink}} = q.$

Density

Specific heat

Thermal conductivity

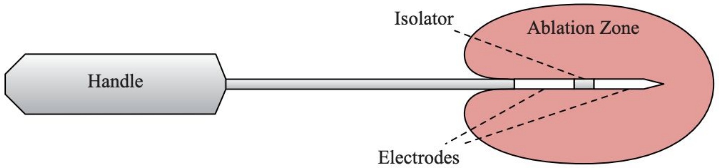
Relative blood flow rate

Heat source induced by electric current

$$q(\boldsymbol{x}) = \alpha p(\boldsymbol{x})$$

$$p(\boldsymbol{x}) = \sigma |\nabla \phi(\boldsymbol{x})|^2$$

Initial condition $T(t, \boldsymbol{x}) = T_{\text{body}} \quad t = 0.$



Boundary Conditions

- At the electrodes
- At the electrical isolator
- At large blood vessels

The coupled system is discretized using **finite elements** in space and a **backward Euler scheme** in time [*Kröger et al.*]

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Mathematical Model: Homogeneous tissue

Approximate tissue damage (Arrhenius law)

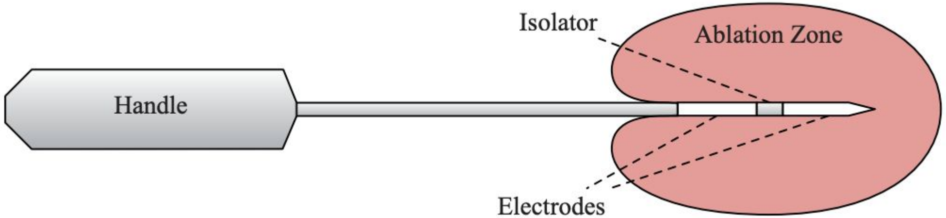
Tissue parameters

$$D(t,\boldsymbol{x}) = \int_0^t A \exp\left(\frac{-E}{RT(s,\boldsymbol{x})}\right) \mathrm{d}s$$

Necrosis Mask → Estimate Ablation Zone

$$I_{\text{sim}} = \{\boldsymbol{x} \in \Omega : D(t_{\max},\boldsymbol{x}) \geq 1\}$$

Ablation duration



Large Computation Domain Ω

The numerical approach utilizes **finite elements analysis**
→ **Long runtime**

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Mathematical Model

Weighted Distance Field Approximation

Weighted Distance Transform

sampling points

electrodes

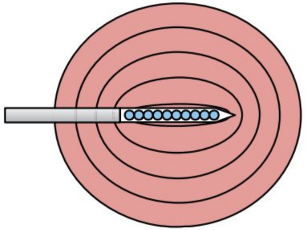
$$\tilde{f}(\boldsymbol{x}) = \left(\sum_{i=1}^{m} \sum_{j=1}^{n} \frac{1}{m \cdot |\boldsymbol{x} - \boldsymbol{s}_{ij}|^{\alpha}} \right)^{-1/\alpha}$$

Ablation Zone Approximation

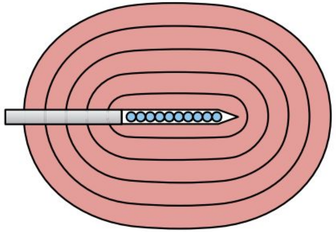
$$I_{\text{zone}}(d, \alpha) = \{\boldsymbol{x} \in \Omega : f(\boldsymbol{x}) \leq d\}.$$

Influence the size (isocurves)

Influence the shape



Small **α**



Large **α**

For any given ablation applicator and given ablation parameters (varying electrode lengths, ablation time, and generator power), solve the optimization problem for **d** and **α**

$$|(I_{\text{sim}} \setminus I_{\text{zone}}(d, \alpha)) \cup (I_{\text{zone}}(d, \alpha) \setminus I_{\text{sim}})| \overset{!}{\rightarrow} \min$$

→ Minimize volumetric difference between I_{sim} and I_{zone}

→ Create a database for all ablation parameters to look up for **d** and **α**

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Mathematical Approach: Heatsink Effects

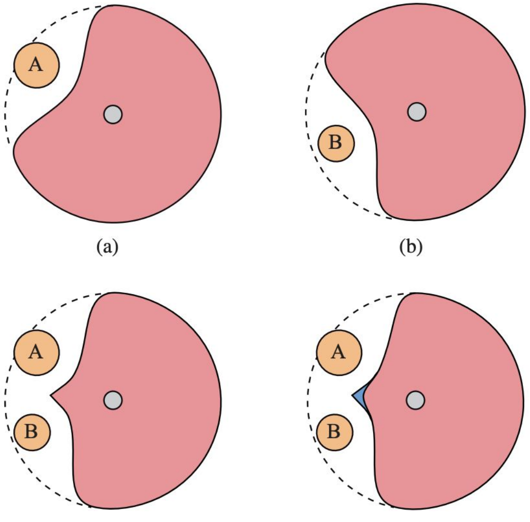
Thermal Equilibrium of the Vasculature

$$-\nabla \cdot (\lambda \nabla T) + \nu (T - T_{\text{body}}) = q$$

Normalized steady-state temperature

$$g(\boldsymbol{x}) = 1 - \frac{T(\boldsymbol{x}) - T_{\text{body}}}{T_{\text{warm}} - T_{\text{body}}}$$

$$T_{\text{warm}} := T_{\text{body}} + q/\nu$$



(a) (b)

(c) (d)

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Mathematical Approach

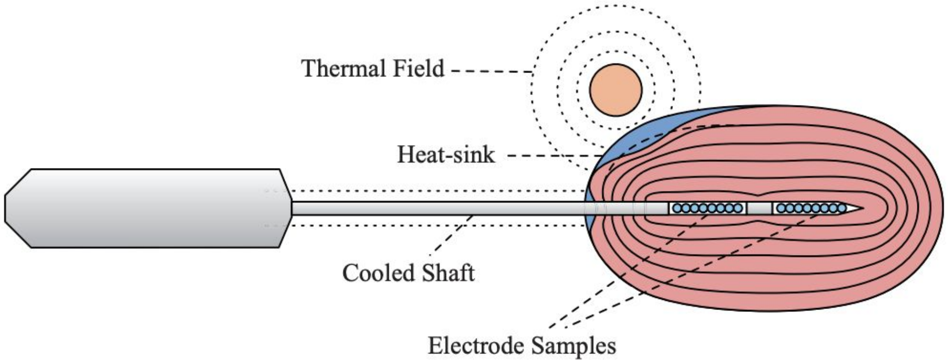
Deformed ablation zone: Combining f(x) ~ ablation needle and g(x) ~ cooling effects

$$I = \left\{ \boldsymbol{x} \in I_{\text{zone}} : \arcsin\left(\tfrac{1}{d} f(\boldsymbol{x})\right) + \arcsin(g_{\text{v}}(\boldsymbol{x})) + \arcsin(g_{\text{a}}(\boldsymbol{x})) \le \tfrac{\pi}{2} \right\}$$

arcsin() was selected as the best transition function

Vessel cooling

Internal cooling of the applicator (if applicable)



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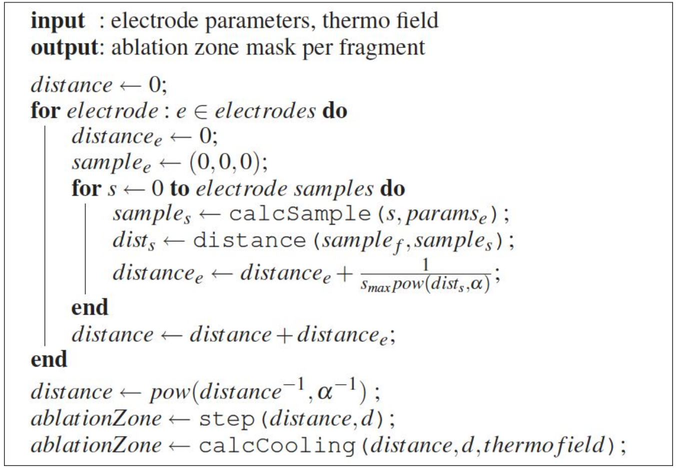
Algorithm Application

Preprocessing: Semi-automatic

- Tumor segmentation (morphology based region-growing) ~ 1-3 seconds
- Segmenting vessels in ROI (Bayesian vessel extraction algorithm) ~ < 2 seconds
- Calculate thermal equilibrium of vasculature (g(x)) ~ < 5 seconds

Calculate Ablation Zone: Modular Shader Framework

- Calculate Weighted distance field per fragment (f(x))
- Combine with thermal field (g(x)) to find ablation zone (I)



```
input  : electrode parameters, thermo field
output: ablation zone mask per fragment
$distance \leftarrow 0$;
for $electrode : e \in electrodes$ do
    $distance_e \leftarrow 0$;
    $sample_e \leftarrow (0,0,0)$;
    for $s \leftarrow 0$ to $electrode\ samples$ do
        $sample_s \leftarrow$ calcSample($s, params_e$);
        $dist_s \leftarrow$ distance($sample_f, sample_s$);
        $distance_e \leftarrow distance_e + \frac{1}{s_{max} pow(dist_s, \alpha)}$;
    end
    $distance \leftarrow distance + distance_e$;
end
$distance \leftarrow pow(distance^{-1}, \alpha^{-1})$;
$ablationZone \leftarrow$ step($distance, d$);
$ablationZone \leftarrow$ calcCooling($distance, d, thermofield$);
```

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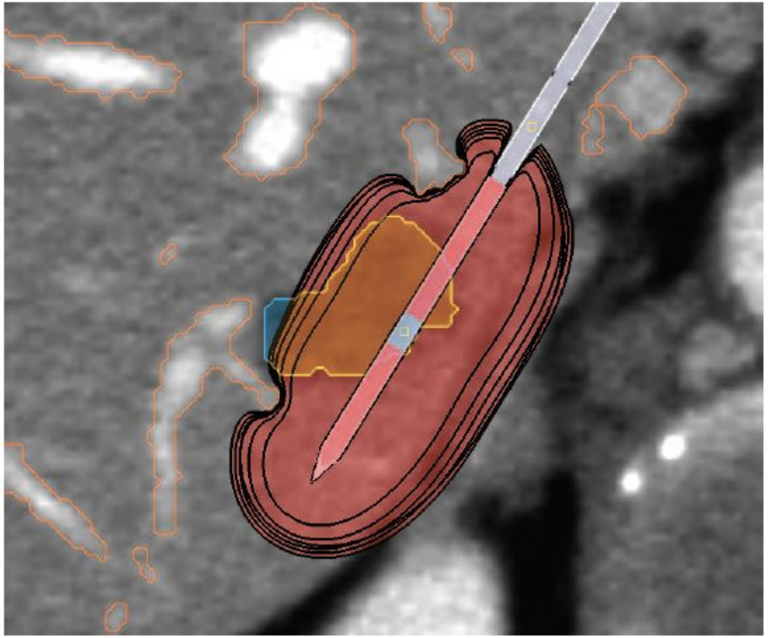
Result Visualization



2D: Multi-parameter isoline visualization of 1, 2, 4, 8, and 16 minutes of ablation progress

3D: Volume rendered with boundary and silhouette enhancement

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Evaluation

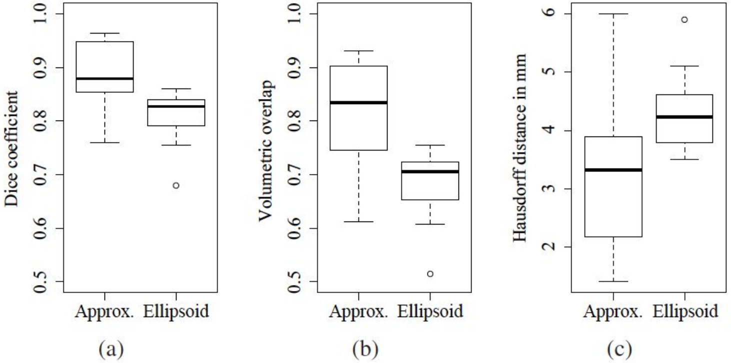

Fig. 11. (a) represents the averaged Dice coefficients from 10 simulation masks with corresponding approximation and ellipsoid masks, respectively. (b) shows the averaged volumetric overlap and (c) the Hausdorf distances in millimeter.

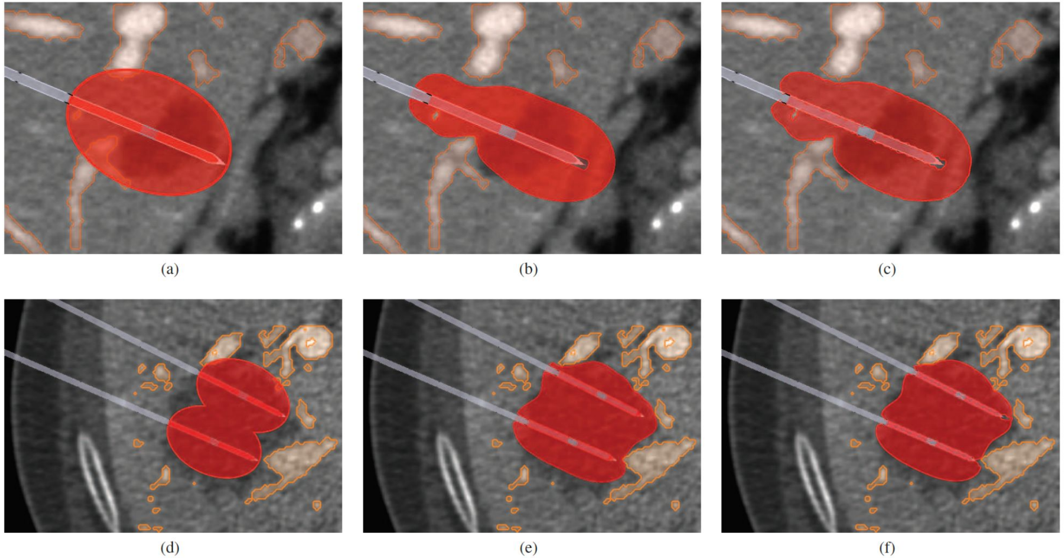

Fig. 12. Comparison of three methods estimating the ablation zone of bipolar RF applicators. In (a,d), the ablation zone is represented as simple ellipsoid. Heat-sink effects are not taken into account. Images (b,e) show the presented approximated ablation zone incorporating the cooling blood flow, and in (c,f) the coagulation mask of the numerical simulation is shown.

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Critiques

Strengths

- Rigorous, detailed and patient-specific algorithm
- Quite successfully address the heatsink effects
- Powerful visualization: more realistic approximated ablation zone
- Useful method for planning RFA
- Support medical training and help inexperienced radiologists interactively plan procedure.

Limitations

- Computationally heavy (required a GPU and can take up to several hours running time)
- Requires a lot of inputs and semiautomatic preprocessing
- The comparison between the algorithm and the ellipsoid model (Dice score, volume overlap, Hausdorff distance) did not achieve statistical significance.
- Virtual ablation needles
- Not adaptable for intraop

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Future Work

- Conduct a user study with medical experts to evaluate the clinical value using real patient data

- Integrate the approximation model into an automatic path proposal method for RF applicator placement

- Research methods to improve algorithm efficiency

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References

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Thank you

Questions?