Real-time VR Simulation of Laparoscopic Cholecystectomy based on Parallel Position-based Dynamics in GPU

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Presenter: Peng Yu

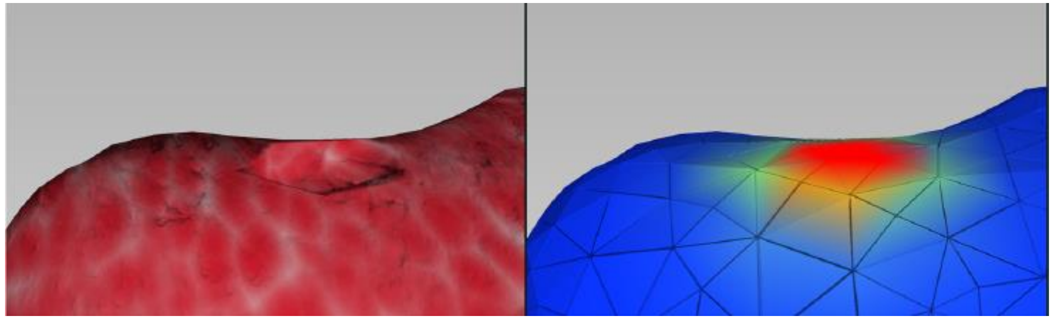
Contents

1. Research background and motivation

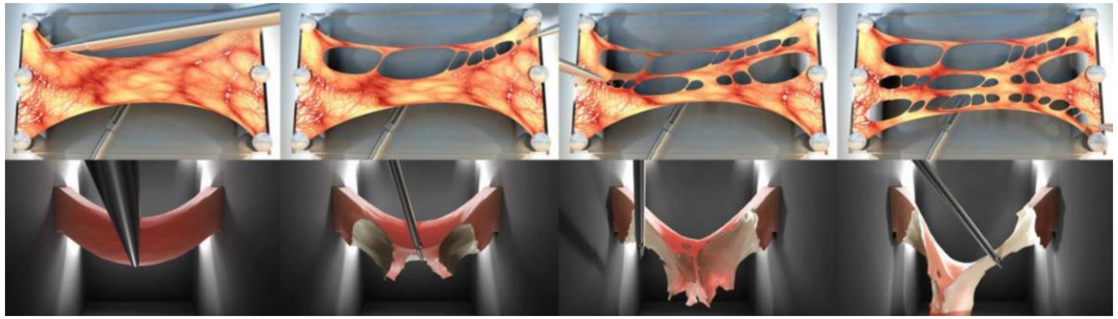
- 90% cholecystectomy is laparoscopic surgery.
- Minimally invasive, fast recovery, widely accepted.
- Long training process & high surgery skill required.
- The VR surgery simulator could simulate cholecystectomy laparoscopic surgery in terms of visual effects, auditory sense and haptic feedback.
- The tissue deformation and electrocautery is a key component of virtual laparoscopic surgery

2. Related work

- Soft tissue deformation methods
  - Mass-spring system
  - Finite Element method
  - Position based dynamics
- Soft tissue electric burning simulation



Lu et al. IJMRCAS. 2014

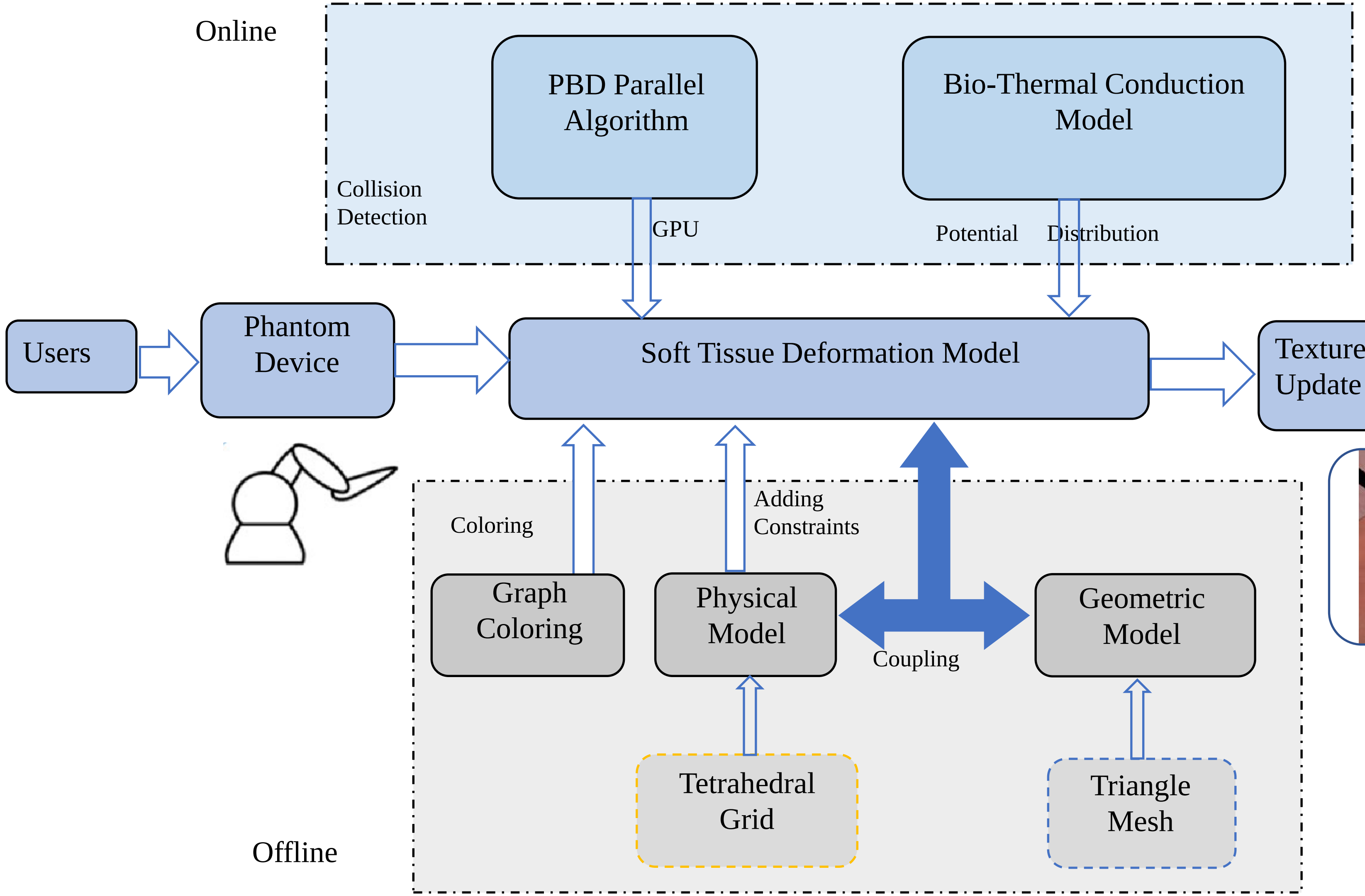


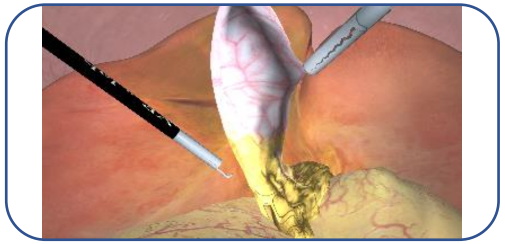
Qian et al. CAVW. 2016

3. Contributions

- Soft tissue deformation based on graph coloring algorithm of Gauss-Seidel solver on GPU.
- A bio-thermal conduction model for fat tissue burning.
- A Laparoscopic cholecystectomy simulator based on VR.

4. System overview





5. PBD model based on graph coloring algorithm

Algorithm 1 Parallel PBD Deformation Based on Graph Coloring

Input: At time t, the input are the vertex position $\mathbf{x}_i^t$, velocity $\mathbf{v}_i^t$, Reciprocal of quality $w_i = 1/m_i$, an external force vector $\mathbf{f}$, time step Δt and constraints set C of the tetrahedral model.

Output: At time t, updated position $\mathbf{x}_i^{t+1}$, and velocity $\mathbf{v}_i^{t+1}$.

$i \leftarrow 0$

Graph coloring the tetrahedral model. Constraints set $C = (C_1, C_2, \cdots, C_k)$ is Graph coloring asses, in which each constraint set has its (= $1, \cdot, N), \forall c[C_i] \in c$. For $\forall (C_j, C_m) \in C_i, C_j$ and C_m no sharing point.

loop

for all Vertices i **do**

$\mathbf{v}_i \leftarrow \mathbf{v}_i + \Delta t w_i \mathbf{f}_{ext}(\mathbf{x}_i)$

end for

dampVelocities $(\mathbf{v}_1, \cdots, \mathbf{v}_n)$

for all Vertices i **do**

while solverIterations $<$ MaxIters **do**

for all Constraint $C_i \in C$ **do**

for all Constraint $C_{i\,j} \in C_i$ **do**

projectConstraints($\mathbf{x}_i$) in parallel on GPU

end for

end for

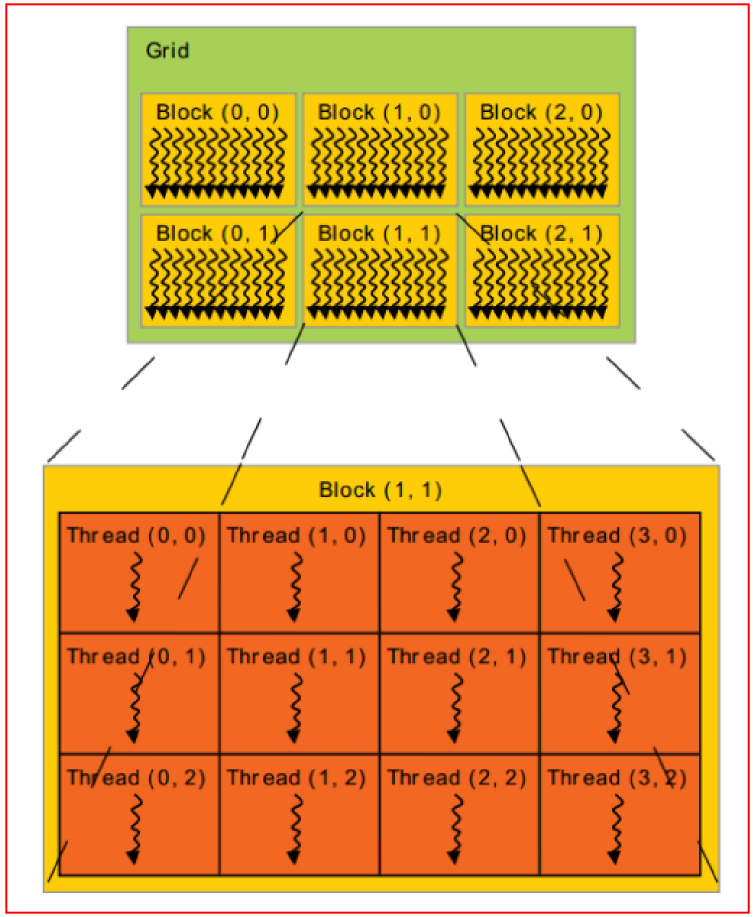
end while

$\mathbf{v}_i^{t+1} \leftarrow (\mathbf{x}_i - \mathbf{x}_i^t)/\Delta t$

$\mathbf{x}_i \leftarrow \mathbf{x}_i$

end for

end loop



5. PBD model based on graph coloring algorithm

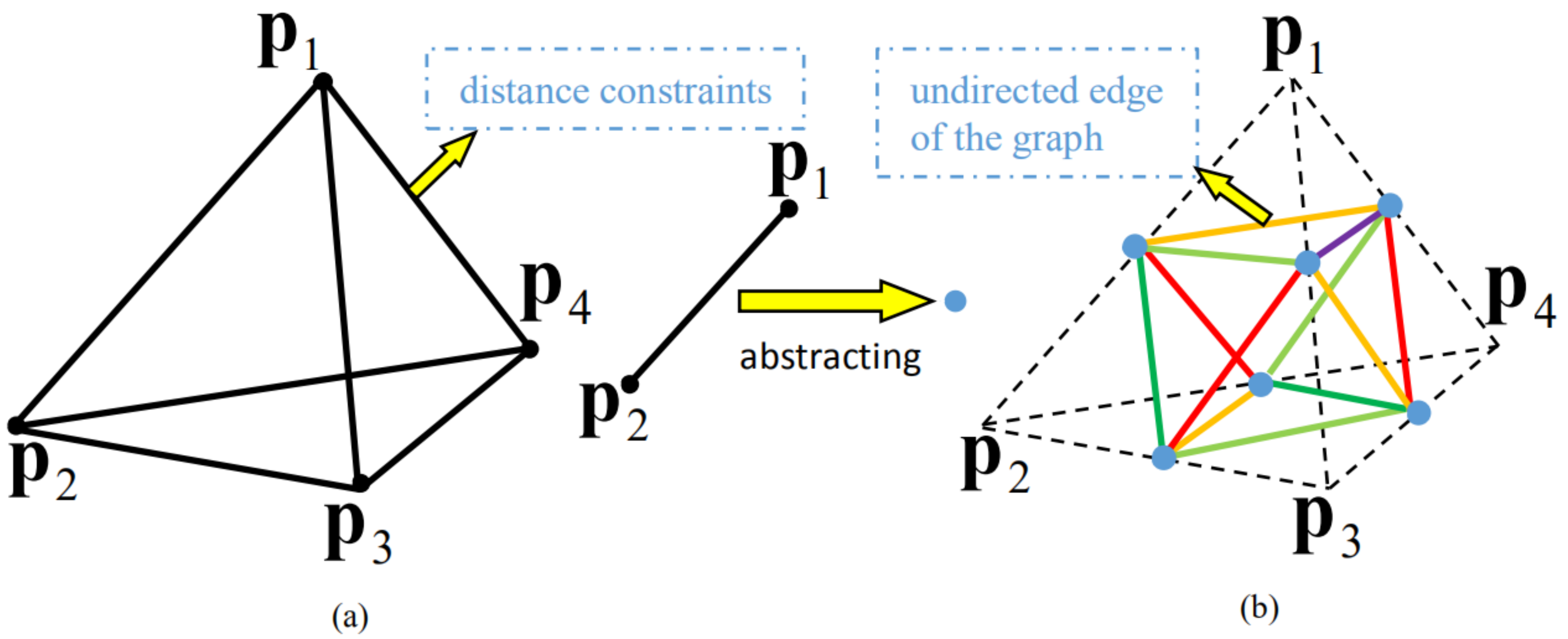


Fig. 3: The graph coloring of distance constraints. (a) Each edge in the tetrahedron is a distance constraint, which can be treated as node in graph; (b) Abstracting the constraints with a shared vertex into two nodes, which are connected by an undirected edge. Two connected undirected edges means these constraints has a shared vertex, so they should be set with different color.

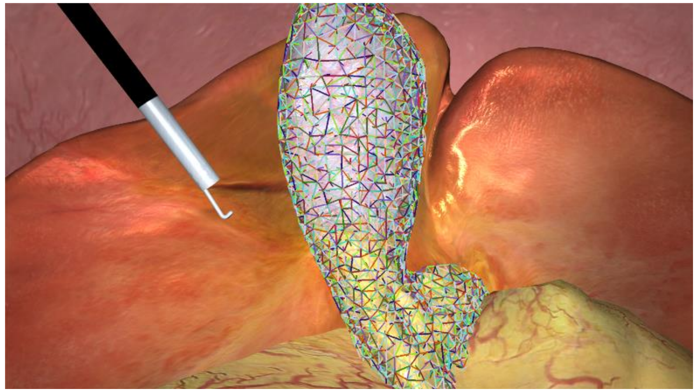
5. PBD model based on graph coloring algorithm

Algorithm 2 The Random Dyeing Disc Graph Coloring

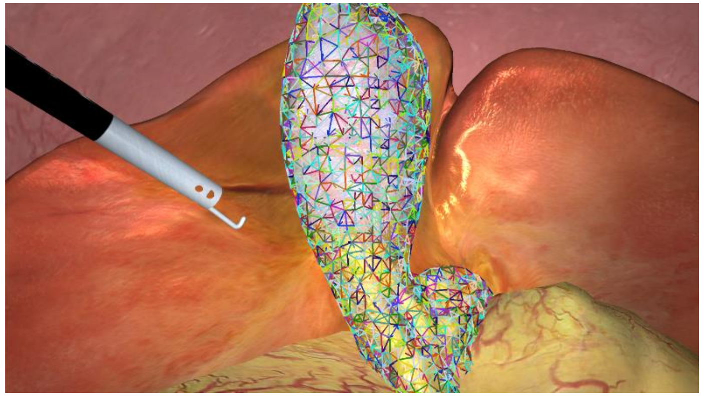
Input: Undirected graph $G = (C, E), C = (C_i, i = 1, \cdots, k)$ is the set of constraints to be dyed.

Output: Coloring results $c = (c[C_i], i = 1, \cdots, k)$ for constraints set C.

$M \leftarrow C$
for all Constraint $C_i \in M$ **do**
    $R_v \leftarrow \{0, 1, \cdot, \Delta c/s\}$
end for
while $M \neq \emptyset$ **do**
    for all Constraint $C_i \in M$ **do**
        $c[C_i] \leftarrow$ random color in R_v
    end for
    $I \leftarrow \emptyset$
    for all Constraint $C_i \in M$ **do**
        $S \leftarrow$ colors of all the neighbors of C_i
        if $c[C_i] \notin S$ **then**
            $I \leftarrow I \cup c[C_i]$
            $c[C_i] \leftarrow$ random color in R_v
            delete $c[C_i]$ from dyeing disc of neighbors of C_i
        end if
        $M \leftarrow M - I$
    end for
    for all Constraint $C_i \in M$ **do**
        if $R_v = 0$ **then**
            $R_v \leftarrow R_v \cup \{|R_v| + 1\}$
        end if
    end for
end while



(a)



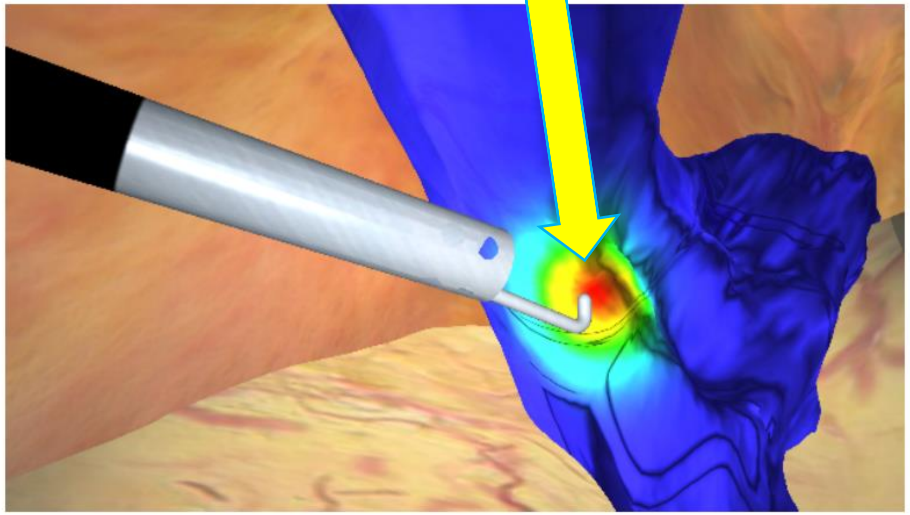
(b)

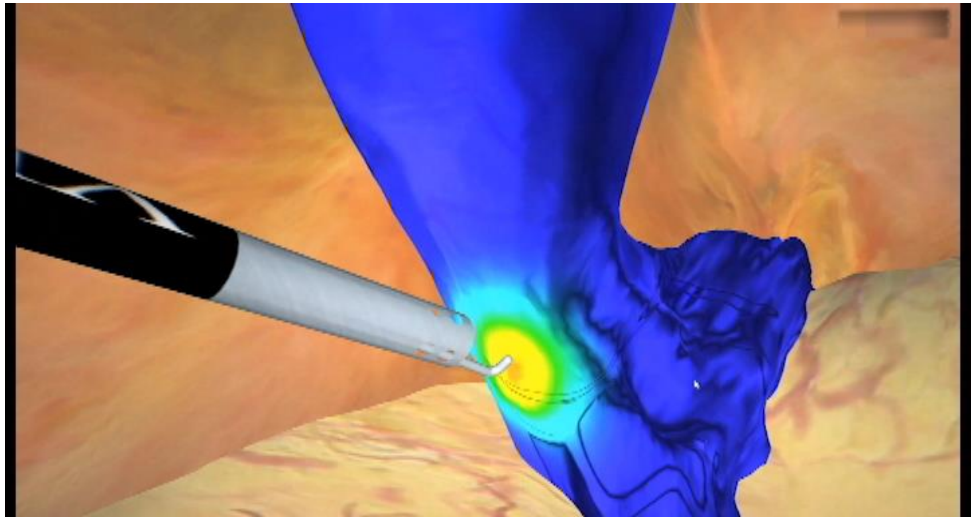
The coloring results of gallbladder model by random dyeing disc algorithm.
(a) Distance constraints; (b) Volume constraints.

6. The simulation of electrocautery

The surface bio-heat transfer equation can be expressed as:

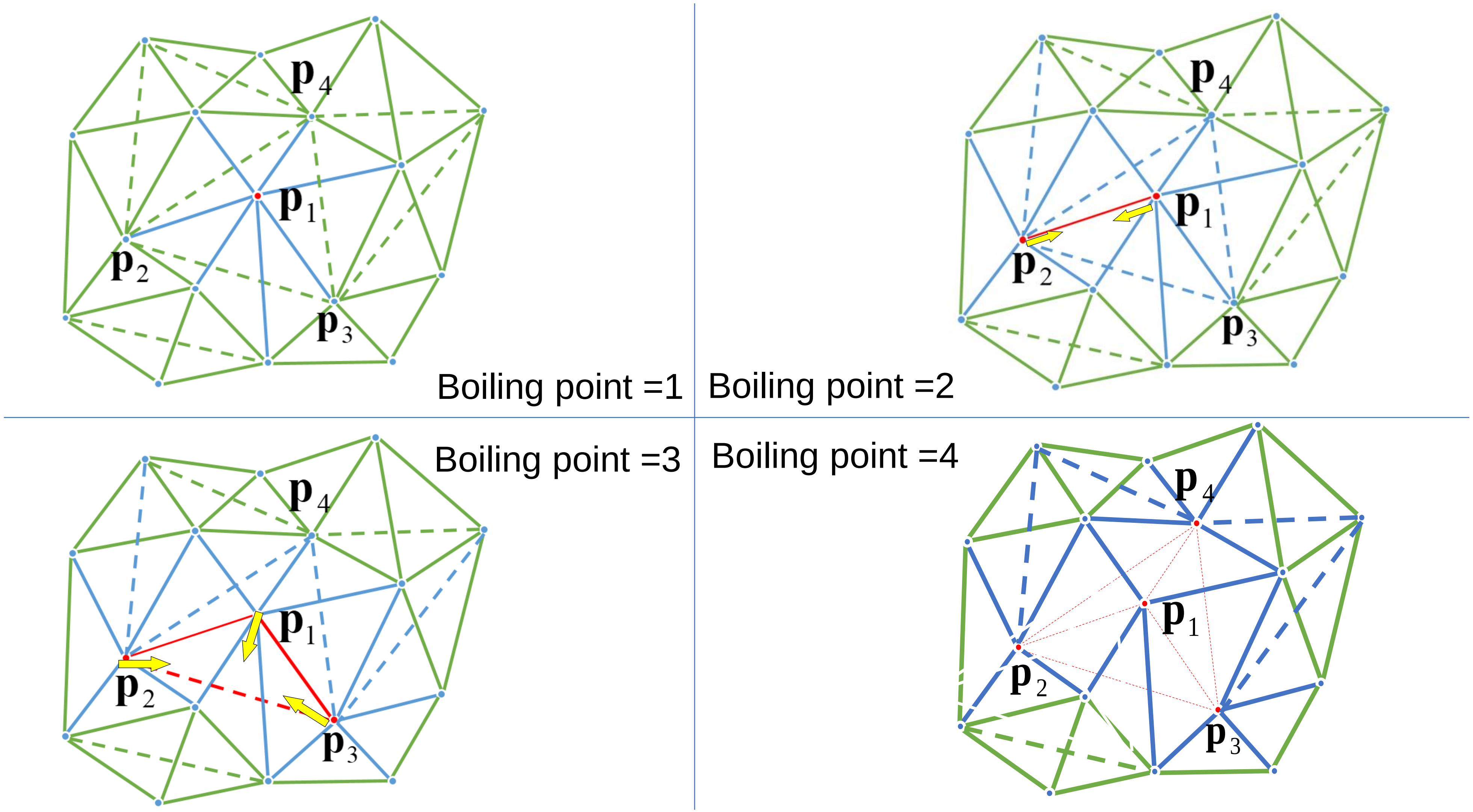
$$\rho c \frac{\partial T}{\partial t} = k\nabla^2 T + \omega_b c_b (T - T_\alpha) + q_s + q_{hook},$$



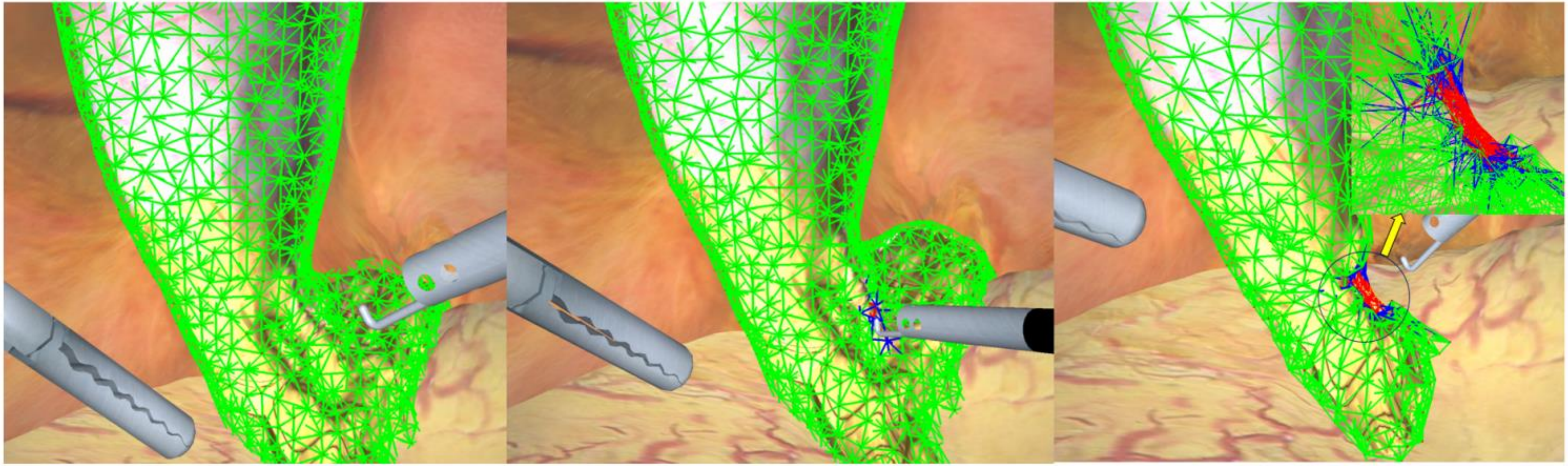


Temperature distribution of bioth-ermal conduction electrocautery model.

6. The simulation of electrocautery



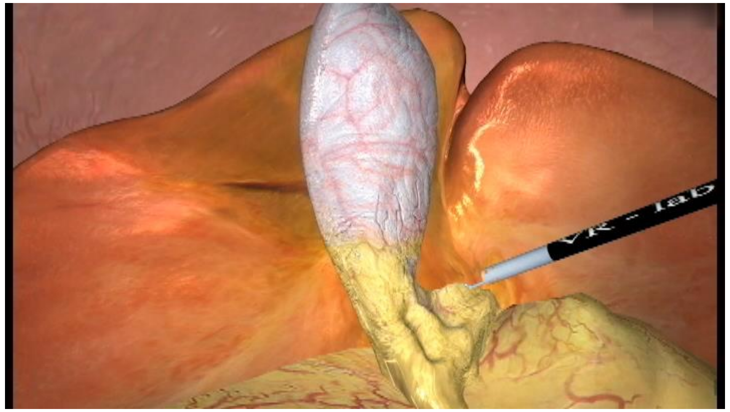
6. The simulation of electrocautery

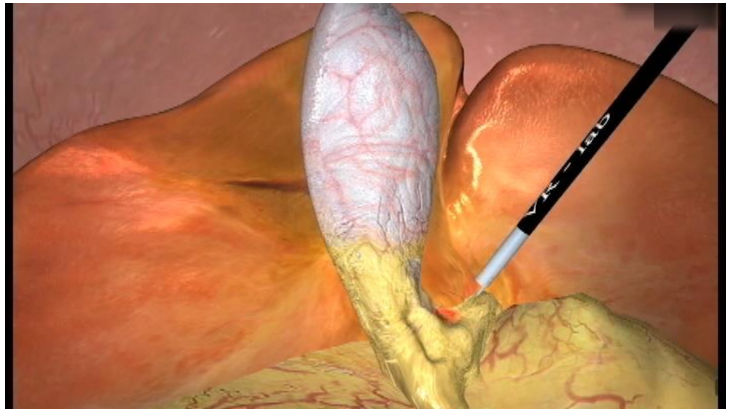


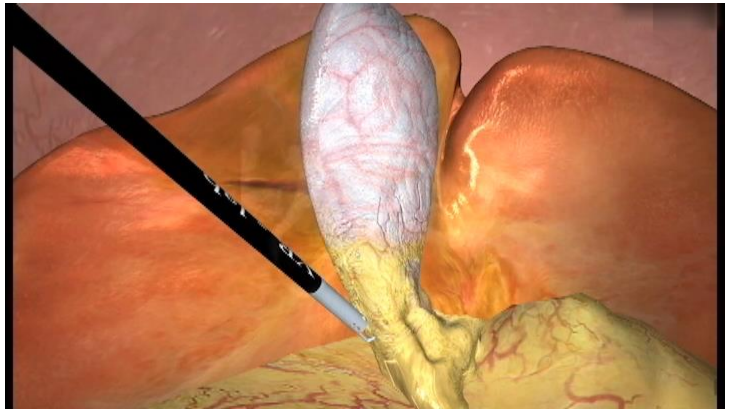
The topology change of fat tissue mesh during electrocautery.

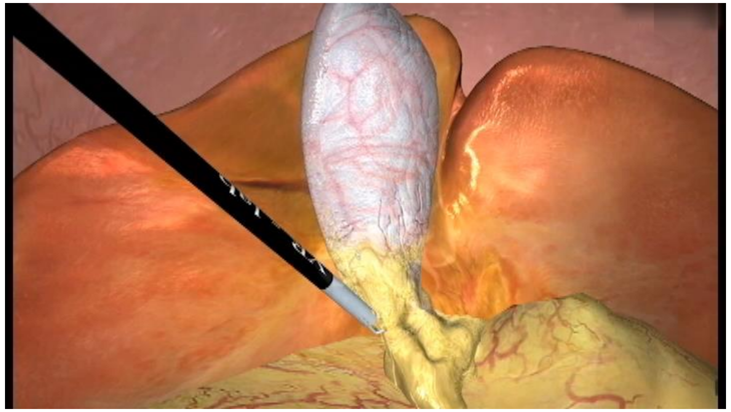
7. Experiments and comparison

The simulation of fat tissue electrocautery



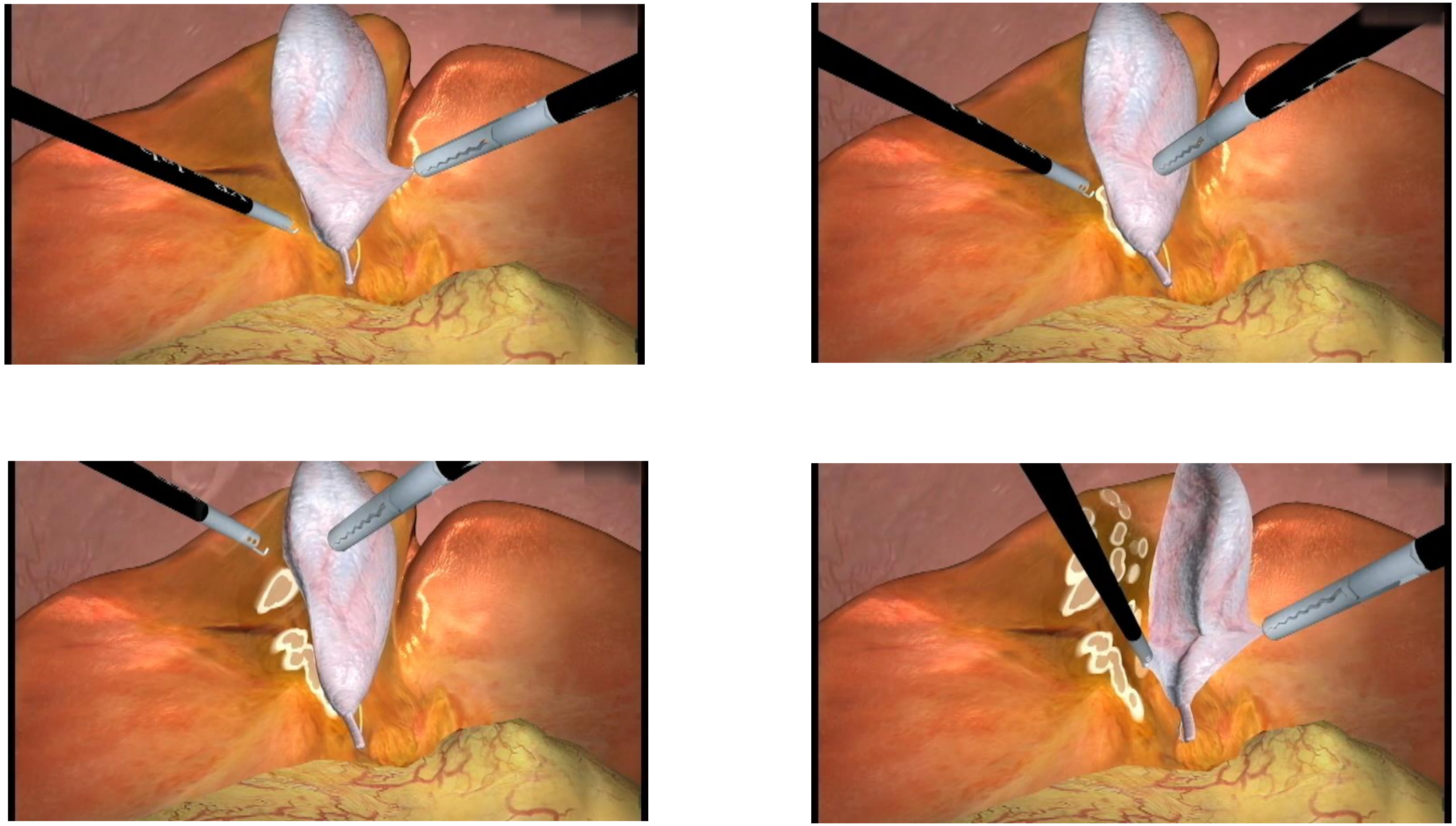




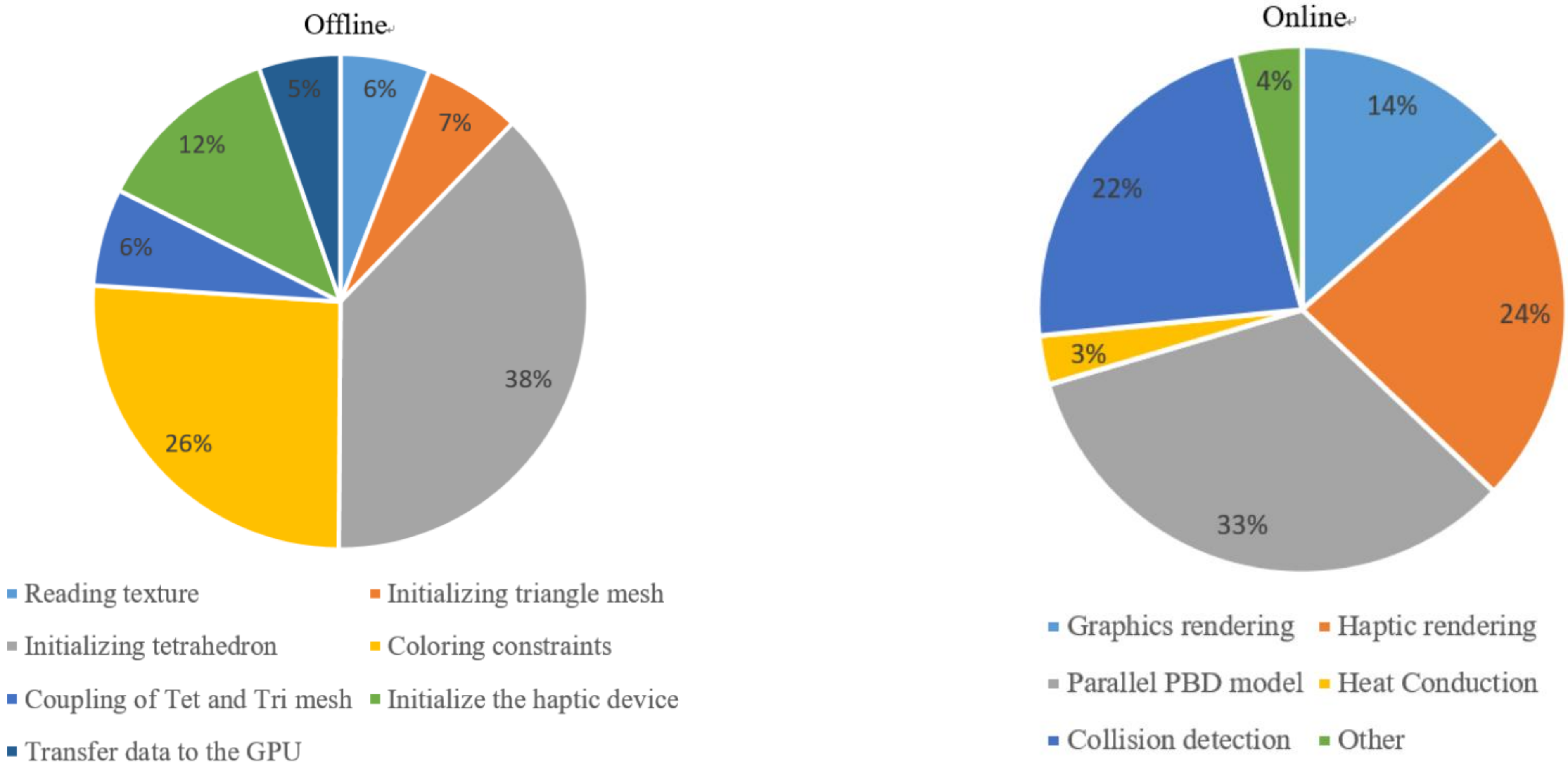


7. Experiments and comparison

The simulation of hepatobiliary separation

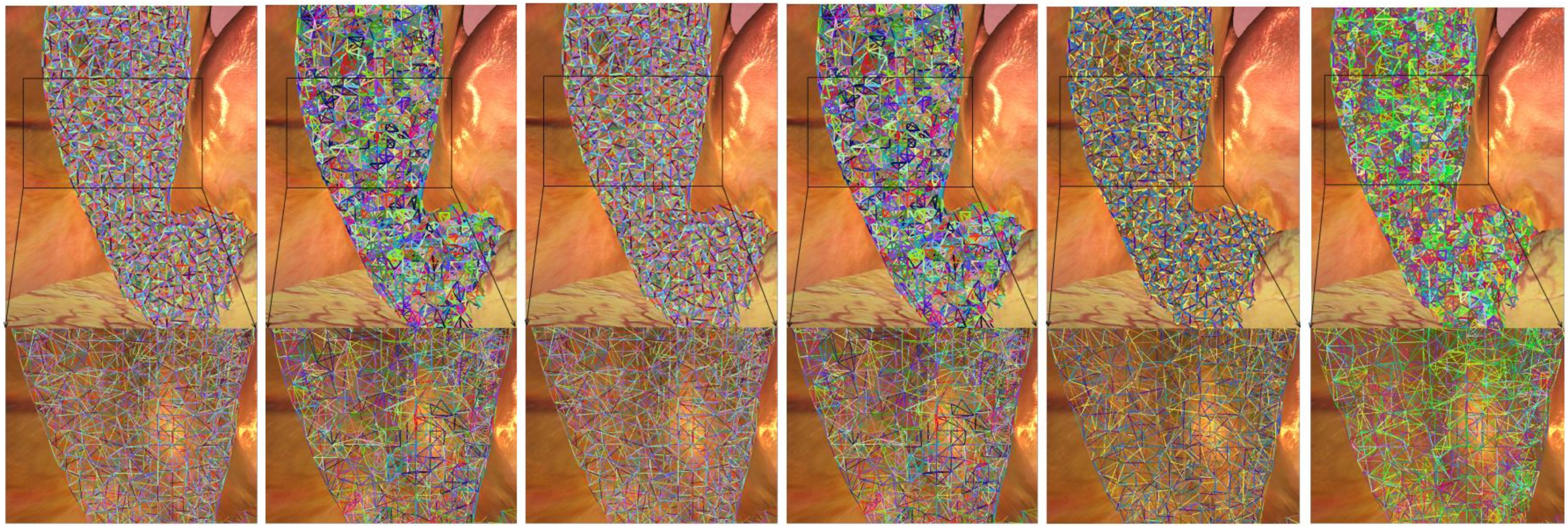


7. Experiments and comparison



(a) (b)

7. Experiments and comparison



(a) (b) (c) (d) (e) (f)

7. Experiments and comparison

Vertices	Links	Tets	Calculate parallel PBD on GPU		Calculate PBD on CPU
			Time cost per step (ms)	Colors	Time cost per step (ms)
3966	21076	13125	14.31-14.42	40	16.38-17.41
6823	32256	22650	12.20-12.35	32	28.51-29.10
10608	56503	35056	14.49-14.57	36	45.79-47.36
12481	66366	41144	16.36-16.47	40	54.81-55.65
20869	110459	68338	21.65-22.16	39	111.51-116.38

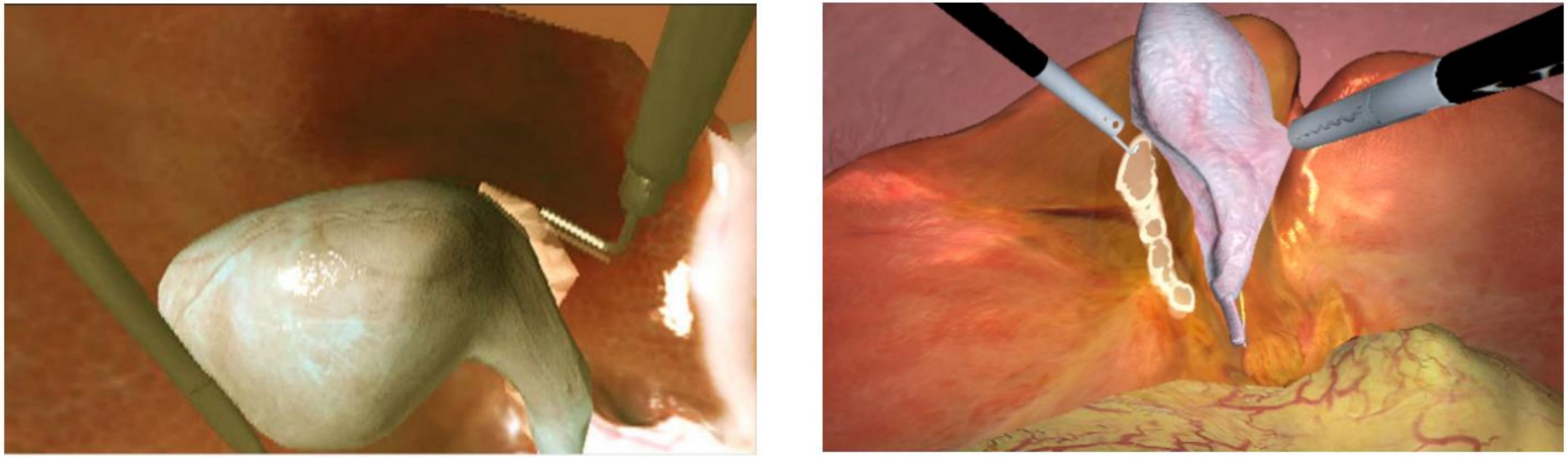
Table 3: Comparison of parallel PBD and ordinary PBD simulation results for gallbladder model (0.2ms time step, 30 iterations, Random dyeing disc algorithm).

7. Experiments and comparison

	Kim et al.			Ours		
No. of tetrahedra (Liver)	518	5024	10615	5176	12876	19729
No. of tetrahedra (Gallbladder)	108	470	817	519	883	22611
Avg. Speed (HZ)	29.3	12.4	7.3	84.75	82.64	57.44

Table 4: Comparison of data size and computational efficiency with respect to the work of Kim et al [3].

7. Experiments and comparison



(a) (b)

Fig. 13: Comparison of simulation visual performance with the work of Kim et al [3]. (a) The screenshot in [3]; (b) The screenshot of our simulator.

8. Validation

	1	2	3	4	5	6	7	8	9	10
Mean	7.3	8.1	7.0	6.9	7.8	7.8	7.4	6.5	6.4	8.0
SD	0.27	0.62	0.36	1.22	0.82	0.62	0.62	0.45	0.49	0.56

Table 5: Statistics of the questionnaire.

9. Conclusion

- We used the random dyeing disc algorithm implemented on GPU to accelerate the deformation model and obtain a better computation performance.

- We introduced a physical model based on bio-heat conduction in the fat tissue electrocautery.

- Our simulator can separate the liver and gallbladder with a hybrid multi-model connection model.

9. Conclusion

- Due to the intrinsic shortcoming of PBD method, the stiffness of the organ model is sensitive to the number of iterations and the step size.
- Phantom Omni only supports single point force feedback, a trainee merely grab a point or a few points in local area when grabbing the soft tissue.
- We can develop the evaluation system, which can afford a reminder when operation error happens and deliver the score report after the training is completed.

Thank You