Development and Optimization of In-Situ Local Tumor Ablation and Recycling System for Consistent Heating and Clinical Translation

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Significance & Hypothesis/Techniques:

In limb salvage surgery (LSS), endoprostheses are associated with mechanical complications, and structural allografts are constrained by graft incorporation failure and limited availability. While conventional recycled autograft techniques offer advantages such as anatomical compatibility and cost-effectiveness, they are limited by infection risk due to extracorporeal handling, as well as delayed union or nonunion. Even pedicled frozen autografts carry a risk of local recurrence, possibly due to incomplete tumor eradication, and microwave-based techniques may lead to tumor cell contamination of the surgical field and limit retrieval of tumor specimens. Thus, we devised in-situ local tumor ablation and recycling (ISTAR), based on an adaptation of the pedicled autograft approach to prevent osteotomy site complications, enable reliable hyperthermic tumor ablation, reduce bacterial contamination through intraoperative application, and allow safe procurement of tumor tissue for pathological evaluation, thereby facilitating integrated tumor-bearing bone recycling.

Innovation:

The ISTAR heating chamber is designed to prevent bacterial and tumor contamination and facilitate tumor tissue collection. A radiofrequency-based approach controls electromagnetic field distribution, enabling non-invasive heating without catheter or antenna insertion. This allows energy to be delivered over a wider area in a single application, supporting tumor ablation at pasteurization temperatures.

Approach (Materials & Methods):

A bovine metatarsal bone model was reconstructed using 3D scanning data. The ISTAR system was designed using a 2.4 GHz-based approach. Heating performance was simulated based on the specific absorption rate (SAR) using Ansys HFSS and ICEPAK to guide heating chamber design electromagnetic energy application. Five configurations — electrode, antenna, single-waveguide, mode-stirring cavity, and dual-port waveguide systems — were comparatively analyzed (Fig. 1), and the most suitable configuration was selected for experimental validation. Temperature was measured using 22 fiber-optic sensors, of which 20 were inserted into cortical bone at 1.5 cm intervals in four directions (anterior, posterior, left, and right), with five sensors in each direction, while the remaining two monitored ambient temperature (Fig. 2).

Result:

The proportions of bone surface area within the target temperature range (65–75 °C) were 23.04% for the antenna system, 20.88% for the electrode system, 45.01% for the single-waveguide system, and 24.66% for the mode-stirring cavity system. In most configurations, heating was primarily localized in the distal part of the bone model. In the dual-port waveguide system, 26.45% of the bone area was heated to the target temperature, but the area remained confined to regions adjacent to the ports. The single-waveguide configuration was selected for experimental validation in seven specimens. The median temperatures were as follows (distal to proximal): anterior (65, 68, 75, 73, 65 °C), left (65, 72, 68, 66, 70 °C), right (75, 74, 75, 70, 72 °C), and posterior (70, 78, 79, 73, 68 °C) (Fig. 3).

Discussion & Impact:

Our findings demonstrate that a relatively uniform heating pattern can be achieved with ISTAR; however, temperature variability persists. Ongoing efforts, including refinement of the rotatable chamber system and incorporation of non-contact temperature measurement with real-time feedback, aim to improve spatial temperature distribution and facilitate clinical translation. Ultimately, ISTAR may reduce complications associated with LSS while enabling effective integration of oncologic treatment and bone reconstruction.

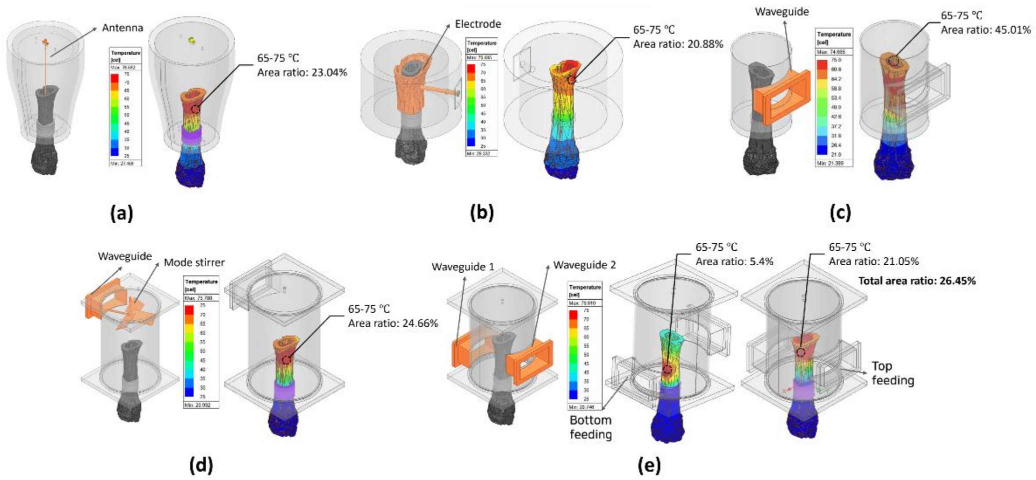

Fig. 1. Five RF chamber configurations: (a) antenna, (b) electrode, (c) single-waveguide, (d) mode-stirring cavity, and (e) dual-port waveguide systems

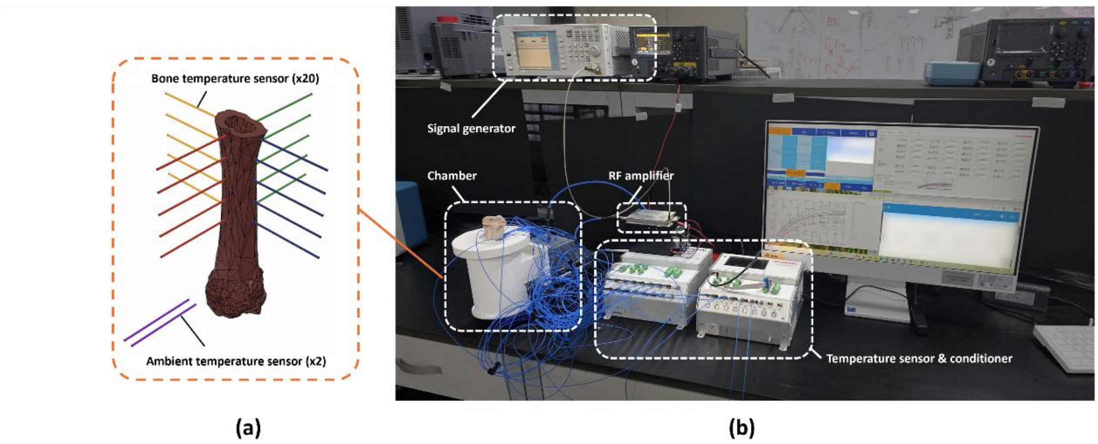

Fig. 2. (a) Placement of temperature sensors and (b) experimental setup for temperature measurement

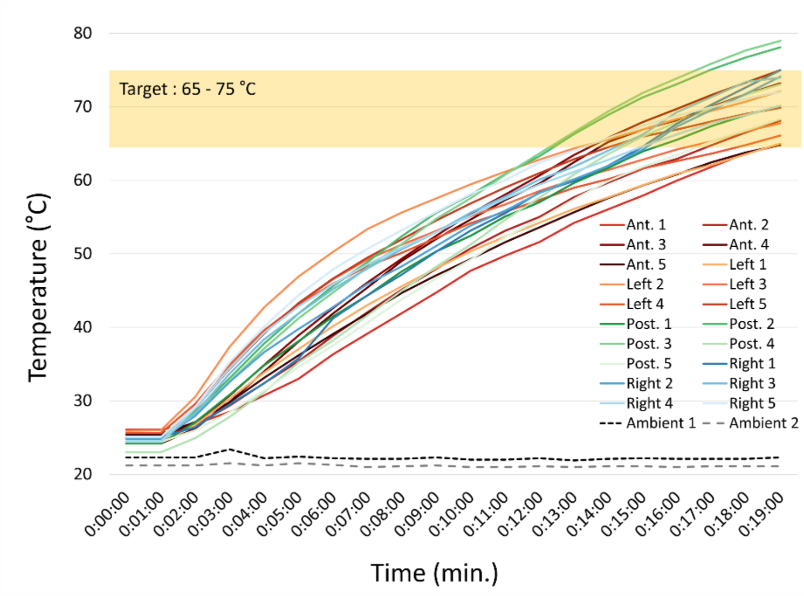

Fig. 3. Temporal temperature profiles