AC Measurements and Simulations of Hepatic Radiofrequency Ablation

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Supporting Information

Technical notes of equipment

The features of the radiofrequency ablation (RFA) system developed by the Biomedical Technology and Device Research Laboratories at the Industrial Technology Research Institute include the following:

- **RF generator:**
  - Maximum output power of 200 W; maximum output current of 2 A;
  - Embedded algorithm for continuous monitoring of output impedance, voltage, and current to automatically adjust the RF energy output;
  - Continuous monitoring of probe tip temperature with a thermocouple implemented within the RFA probe;
  - Internal water cooling for the RFA probe;
  - Touchscreen LCD panel for user-friendly display and operations.

- **Electrode:**
  - Straight electrodes of various sizes (17-gauge or 18-gauge) and active lengths (1, 2, 3, or 4 cm) for liver tumor ablations or thyroid gland lesion ablations.

Verification experiments of phase measurements

To verify that the experimental setup as shown in Fig. 1(B) can accurately resolve the phase difference between RF voltage and current, the following accuracy validation measurements were performed. Exactly the same setup for the RF ablation experiments was used to measure three types of loads in place of bovine liver: (1) a resistor, (2) a resistor and a capacitor connected in parallel, and (3) a resistor and an
inductor connected in series. After the phase difference was resolved by the experimental setup, the same load was measured with a precision impedance analyzer (Microtest 6632) for the phase angle of impedance at the same frequency of 480 kHz. Each resistor, capacitor, and inductor was measured for its value of resistance, capacitance, and inductance, respectively, with the same precision impedance analyzer.

The phase difference in the experimental setup was measured as the phase of RF current relative to the phase of RF voltage, which corresponded to the expressions of RF voltage $V_0 \cos \omega t$ and RF current $I_0 \cos(\omega t + \phi)$, where $\phi$ is the phase difference. The results of the phase accuracy experiments are listed in Table S1. It can be observed that the phase angles of impedance measured with the precision impedance analyzer are quite close to the theoretical values, and the small deviation is due to the parasitic elements of the devices under test. The phase difference measured with the experimental setup not only agreed very well with the counterpart from the precision impedance analyzer, but also remained quite stable with a fluctuation of $\pm 1^\circ$ or smaller. Therefore, the setup as shown in Fig. 1(B) provided sufficient accuracy of phase measurements to support the experimental conclusions.

Table S1. Experimental results of phase accuracy measurements.

| Load: a resistor | Load # | $R$ (Ω) | $\phi$ (°), theoretical calculation | $\phi$ (°), precision impedance analyzer | $\phi$ (°), experimental setup |
|------------------|--------|---------|-------------------------------------|-----------------------------------------|-------------------------------|
| 1                | 49.5   | 0       | 3.1                                 | ~3.0                                    |
| 2                | 100.3  | 0       | 3.6                                 | ~5.6                                    |
| 3                | 150.2  | 0       | 3.1                                 | ~3.2                                    |

| Load: a resistor and a capacitor connected in parallel | Load # | $R$ (Ω) | $C$ (nF) | $\phi$ (°), theoretical calculation | $\phi$ (°), precision impedance analyzer | $\phi$ (°), experimental setup |
|--------------------------------------------------------|--------|---------|-------------------------------------|-----------------------------------------|-------------------------------|
| 1                                                      | 101.1  | 0.329   | 5.7                                 | 6.4                                    | ~7.2                          |
| 2                                                      | 150.3  | 0.980   | 23.9                                | 24.6                                   | ~22.3                         |
| 3                                                      | 152.3  | 2.47    | 48.6                                | 47.9                                   | ~48.1                         |
| 4                                                      | 299.4  | 2.79    | 68.3                                | 69.2                                   | ~70.5                         |

| Load: a resistor and an inductor connected in series | Load # | $R$ (Ω) | $L$ (μH) | $\phi$ (°), theoretical calculation | $\phi$ (°), precision impedance analyzer | $\phi$ (°), experimental setup |
|-----------------------------------------------------|--------|---------|-------------------------------------|-----------------------------------------|-------------------------------|
| 1                                                    | 101.1  | 2.7     | -4.6                                | -6.5                                    | ~7.2                          |