Appendix A: Probe Heat Delivery Optimization for Cord Thermal Weakening

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A.1 Purpose and Scope

This appendix addresses the **thermal engineering aspects** of the heating probe used in **Cord Thermal Weakening & Release (CTWR)**, focusing on the precise delivery of heat to the target cord segment while minimizing collateral damage.

We analyze **heat release modes**, **time-dependent power modulation**, and **3D heating geometry** for optimal weakening of the Dupuytren's cord.

A.2 Heat Release Modes

Two main strategies exist for releasing heat from a probe inserted into the cord:

1. **Point Release (Localized Heated Tip)**
    - Heat is released primarily at the distal end of the probe.
    - Advantage: Creates a small, highly localized thermal zone for **precise cord weakening**.
    - Limitation: A single heated point weakens only a small cross-section of the cord; multiple placements may be required for full rupture.
    - Best for: **Thin cords**, or where adjacent anatomy (nerve, vessel) is very close.
2. **Linear Release (Segmented or Continuous Heated Element)**
    - Heat is generated along a section of the probe shaft, creating an **elongated thermal zone**.
    - Advantage: Weakens a longer segment of cord in one application, potentially allowing rupture with less force.
    - Limitation: Requires more careful control to avoid heating beyond cord margins.
    - Best for: **Thicker cords** or where the cord runs deep enough to allow elongated heating without nerve proximity risk.

A.3 Primary Objectives of Heating

1. **Achieve Sufficient Thermal Damage**
    - Target temperature: **65–70 °C** in cord core for **5–10 seconds**.
    - Effect: Collagen denaturation → loss of tensile strength → brittleness.
    - Outcome: Cord is mechanically weak and easily fractured during manipulation.
2. **Minimize Collateral Heating**
    - Adjacent tissues (skin, tendon, nerve, vessel) must stay **below 45 °C** to avoid functional damage.
    - Requires precise **spatial control** (where heat is released) and **temporal control** (how long it is released).

A.4 Thermal Analysis and Control Strategies

A.4.1 Spatial Control: Optimizing Heat Distribution

- **Radial Heat Gradient**: The highest temperature should be at the cord center, with steep drop-off toward surrounding tissue.
- **Probe Surface Engineering**:
    - **Segmented heating elements** allow activation of only those segments fully within the cord.
    - **Directional heating coatings** (e.g., thermal insulation on one side) can shield adjacent sensitive tissue.
- **Insertion Angle**: Perpendicular insertion reduces length of heat path through non-target tissue.

A.4.2 Temporal Control: Time-Dependent Power Modulation

- Heat transfer into tissue is **time-dependent**; excess exposure causes unintended spread.
- **Stepwise heating**: Short bursts with brief pauses allow heat to equilibrate in the target region without excessive conduction outward.
- **Ramp-up profiles**: Gradually increasing power prevents overheating of probe surface before cord interior reaches target temperature.

A.5 3D Geometry of Heated Region

Assume **perpendicular probe insertion** through the cord. The goal is to determine the heated volume shape that results in maximum mechanical weakening with minimal energy and risk.

A.5.1 3D Heat Transfer Modeling Considerations

- **Cord cross-section**: Elliptical or ribbon-like rather than perfectly round.
- **Heated region geometries** tested in simulation:
    1. **Spherical zone** — produced by point tip heating; ideal for focused weakening.
    2. **Cylindrical zone** — produced by linear heating elements; good for long, narrow cords.
    3. **Elliptical flattened zone** — may match cord anatomy better and maximize collagen denaturation in functional axis.

A.5.2 Optimal Geometry

- For most cords, an **elongated ellipsoid oriented along cord fibers** provides the greatest loss of tensile strength for minimal volume heated.
- This shape can be approximated in practice by:
    - Short, linear heated segment matching cord width.
    - Activation time tuned to cord thickness and probe-tissue thermal conductivity.

A.6 Practical Recommendations (Revised)

1. **Probe Design**:
    - Modular heating zones (switchable segments).
    - **No embedded thermocouples** — instead, temperature is **back-calculated** using:
        - Known **cord tissue thermal properties** (thermal conductivity, specific heat).
        - Measured **cord geometry** from pre-procedure ultrasound.
        - Set **heat release rate** and spatial distribution along probe.
    - This calculation yields an **estimated time-to-target temperature** in the cord's core, guiding the optimal heating duration for each case.
    - Calibration curves can be established experimentally in ex vivo cords and tissue phantoms.
2. **Energy Control Software**:
    - Integrate pre-calculated heating time profiles for different cord sizes and insertion depths.
    - Allow operator to adjust based on patient-specific ultrasound measurements.
3. **Procedural Adjustment**:
    - If cord is very close to skin, prefer point heating + multiple passes.
    - If cord is deep and thick, use linear heating in one or two activations.

A.7 Conclusion

Optimizing **probe geometry** and **heat release control** in both space and time — guided by **calculated temperature profiles** rather than in-probe sensors — ensures that cord collagen reaches denaturation temperature quickly and safely. Pre-procedure ultrasound measurement of cord size and depth allows tailored heating durations for each patient. This calculated, model-based approach minimizes complexity of the probe while maintaining precision in energy delivery, achieving effective cord weakening with minimal collateral injury.