Two-Phase Protocol for Dupuytren's Contracture Management: Cord Thermal Weakening & Release (CTWR) with Adjuvant Radiotherapy (CTWR-AR)

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Abstract
This paper proposes a **two-phase integrated treatment protocol** for Dupuytren's contracture that combines **Cord Thermal Weakening & Release (CTWR)** — a targeted, ultrasound-guided heating technique to mechanically neutralize contractile cords — with **Adjuvant Radiotherapy (CTWR-AR)** — a post-release low-dose radiotherapy protocol to suppress myofibroblast activity and reduce recurrence risk. CTWR offers precise, immediate, single-session cord release without the immune or spread risks of enzyme injection, while CTWR-AR adds biological control of disease progression. A detailed procedural description for each phase is presented, followed by a comparative review of CTWR against standard collagenase injection.

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1. Background & Rationale
Dupuytren's contracture is a chronic fibroproliferative disorder of the palmar fascia involving abnormal myofibroblast activity and collagen deposition. Cords shorten over time, causing finger flexion deformity. Current treatments — surgery, percutaneous needle fasciotomy, collagenase injection (CCH), and early-stage radiotherapy — each have limitations:

- **Surgery**: Effective but invasive; long recovery; recurrence 20–50%.
- **CCH injection**: Minimally invasive but costly; recurrence up to 50% in 3–5 years; risk of skin tears, tendon rupture, allergic reaction.
- **Early-stage radiotherapy**: Effective in preventing progression, but rarely used once contracture is established.

The proposed two-phase approach is designed to:

1. **Mechanically eliminate contracture** in any stage by precision heating and rupture (CTWR).
2. **Biologically suppress residual fibroblast activity** to prevent recurrence (CTWR-AR).

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2. Phase 1: Cord Thermal Weakening & Release (CTWR) Protocol
Purpose
To selectively weaken Dupuytren's cord collagen by controlled heating to ~65–70 °C for 5–10 s at depth, immediately followed by mechanical manipulation to rupture the cord with minimal collateral injury.

Patient Selection

- Moderate to severe contracture with well-defined cords.
- Exclude patients with:
    - Local infection over the treatment site.
    - Severely compromised skin quality over the cord.
    - Severe neuropathy or ischemia of the hand.

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3. Equipment Options
Heating Probes / Energy Sources — must allow *precise, localized heating* at target depth:

1. **Radiofrequency (RF) probe** — monopolar or bipolar; built-in thermocouple for real-time temperature control.
2. **Microwave ablation antenna** — rapid collagen heating; often water-cooled to protect skin.

3. **Diode laser fiber** (1470 nm, 200–400 µm) — tuned to collagen absorption; can be introduced via fine needle.
4. **High-Intensity Focused Ultrasound (HIFU)** — *experimental*; non-contact heating limited by hand anatomy and bone shadowing.

Guidance: High-frequency linear ultrasound (12–18 MHz) for precise cord targeting and safety. Portable MSK ultrasound units are widely available and **not excessively expensive**, often costing less than a high-end laptop.

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4. Targeting & Guidance

Ultrasound guidance means the operator visualizes the cord and the probe tip in *real time* on the screen:

- Cord: appears as a bright, fibrous band.
- Probe tip: visible as a bright dot/line.
- Guidance allows precise positioning within or alongside the cord, avoiding nerves, vessels, and tendons.

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5. Pre-Procedure Preparation

1. **Anesthesia**: Local infiltration or digital nerve block without epinephrine.
2. **Cord tensioning**: Gentle extension via splint or assistant to make cord taut.
3. **Sterile prep**: Antiseptic solution; sterile gel/probe cover for ultrasound.

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6. Heating Phase

Goal: Achieve irreversible collagen denaturation at ~65–70 °C for 5–10 s in the cord's core.

Steps:

1. **Cord localization**: Trace entire cord on ultrasound; choose thickest, tightest segment for heating.
2. **Entry planning**: Select site for straight access while avoiding critical structures.
3. **Local anesthesia**: Infiltrate just above cord.
4. **Device insertion under ultrasound**: Advance probe/fiber to cord midpoint; tip visualized continuously.
5. **Tissue separation if needed**: Hydrodissect with saline if nerve/vessel proximity is <3 mm.
6. **Controlled heating**:
   - RF: 65–70 °C for 5–10 s.
   - Microwave: low-power pulse ~5 s.
   - Laser: short pulses totaling 5–8 s.
   - Thermometry used if available; otherwise follow calibrated power-time curves.
7. **Monitoring**: Watch for cord shrinkage, echotexture change; stop if sharp radiating pain occurs.
8. **Probe removal**: Under ultrasound, confirm no bleeding or tissue irregularity.

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7. Immediate Manipulation Phase

- Immediately extend treated finger(s) to rupture the now-brittle cord.
- If rupture is incomplete, repeat heating at remaining segment(s).

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8. Post-Procedure Care

- Light dressing for 24 h.
- Begin gentle motion exercises within 1–2 days.
- **Optional**: Proceed to CTWR-AR within 1–2 weeks for recurrence prevention.

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9. Safety Measures

- Maintain ≥3 mm clearance from neurovascular structures.
- Avoid skin temp >45 °C; stop if deep pain persists after heating.

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10. Documentation & Monitoring

- Record pre/post joint angles.
- Document device type, power, duration, temperature.
- Follow-ups: 1 week, 1 month, 3 months, 1 year.

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3. Phase 2: Adjuvant Radiotherapy After CTWR (CTWR-AR)

Purpose

To destroy residual active fibroblasts/myofibroblasts in the treated fascia, reducing recurrence risk.

Indications

- Completed CTWR with full or partial rupture.
- High-risk for recurrence (multiple nodules, early onset, aggressive history).

Timing

Start **7–14 days** after CTWR — inflammation subsides but fibroblasts remain in radiosensitive phase.

Radiation Modality

- **Orthovoltage X-rays** (120–150 kV) — standard in Europe.
- **Electron beams** (3–6 MeV) — depth-tuned to fascia.

Field Definition

- CTWR-treated zone plus 1–2 cm margin.
- Shield non-target fingers/wrist.

Dose & Fractionation

- **Total**: 30 Gy in two identical series.
- **Series 1**: 5 × 3 Gy (Mon–Fri).
- **Interval**: 6–12 weeks.
- **Series 2**: Repeat 5 × 3 Gy.

Procedure Steps

1. **Consultation**: Review CTWR outcomes, skin status, explain RT goals.
2. **Simulation & Planning**: Hand positioned flat, immobilized in thermoplastic mold; field defined with lead cutouts or electron applicator.
3. **Delivery**: Orthovoltage: 1–2 min/session; Electron beam: 2–3 min/session.
4. **Between series**: Maintain gentle stretching; monitor acute reactions.

Biological Effects

- DNA damage → loss of fibroblast replication.
- Cytokine modulation → reduced inflammation.
- Fibroblast senescence → stable, non-contractile cells.

Side Effects

- **Acute**: Mild redness, dryness, itching.
- **Late**: Hypopigmentation, skin thinning, telangiectasia.
- **Rare**: Secondary skin cancer (<0.5% lifetime risk in older adults).

Monitoring

- Weekly during treatment.
- At 6 weeks, 6 months, 1 year, then annually ×5 years.

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4. Comparative Review: CTWR vs Collagenase Injection (CCH)

Precision & Control

- **CTWR**: Direct ultrasound visualization and heating confined to cord.
- **CCH**: Palpation-based injection; enzyme spread less controllable.

Single-Session Efficiency

- **CTWR**: Cord weakened and ruptured same day.
- **CCH**: Requires return visit 1–2 days later.

Risk Profile

- **CTWR**: No immune reactions; minimal swelling.
- **CCH**: Allergic reaction risk; frequent swelling/bruising; rare tendon rupture.

Cost

- **CTWR**: Capital device + low-cost disposables.
- **CCH**: Proprietary enzyme ~$3–4k/vial in US.

Recurrence Prevention Integration

- **CTWR**: CTWR-AR planned seamlessly from Phase 1 ultrasound mapping.
- **CCH**: Radiotherapy possible but requires separate mapping.

Summary Table:

Feature	**CTWR**	**CCH**
Mechanism	Collagen denaturation & rupture	Collagen enzymatic cleavage & rupture
Guidance	Ultrasound, precise	Mostly palpation
Time to rupture	Immediate	1–2 days
Sessions	One	Two
Immune risk	None	Present
Swelling/bruising	Minimal	Common
Cost per treatment	Low consumable	High drug cost
Recurrence control	Integrates with CTWR-AR	Needs separate planning

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5. Potential Impact

The CTWR + CTWR-AR protocol could:

- Provide precise, controllable release in all stages.
- Minimize systemic risk and skin/tendon injury.
- Reduce recurrence via combined mechanical and biological control.
- Offer cost-efficient long-term management.

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6. Next Steps

1. **Bench & cadaver testing** — validate heating parameters, safety margins.
2. **Pilot clinical trial** — compare CTWR-AR vs CCH in moderate/severe cases.
3. **RCT** — evaluate recurrence rates, function, patient satisfaction.

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.

A.8 — Calculation Framework (No In-Probe Sensors)

Perpendicular insertion; point or short-segment heating; single/multi-burst control

A.8.1 Purpose

Provide a **sensor-free** method to choose **heating times and burst patterns** that bring the **cord core** to **collagen-denaturation temperature** (≈ 65–70 °C) while keeping the **cord surface** and adjacent tissues **below a safe temperature**—so that the cord becomes **maximally weakened exactly at the intended site**, making the subsequent **mechanical rupture** easy and localized.

A.8.2 Core Assumptions

- The probe crosses the cord **through its thickness** (perpendicular to cord axis).
- The **active heated length** inside the cord equals the **ultrasound-measured through-thickness** d (meters), unless using a **point-heat tip**, in which case the heated volume is set by the tip radius r_{eff}.
- Adjacent tissue protection is paramount; we select **short bursts** to confine heating.

A.8.3 Safety Targets

- **Cord surface temperature limit** (to protect skin, nerves, tendon):
  - **Target**: $T_{\mathrm{surf,max}} \leq 45^{\circ}\mathrm{C}$ for multi-second exposures.
  - **Brief spikes** up to ~**48 °C** for **<1 s** may be acceptable, but **avoid** if near neurovascular structures.
- **Cord core temperature target** (to denature collagen & kill local myofibroblasts):
  - $T_{\mathrm{core,target}} \approx 68^{\circ}\mathrm{C}$ (choose 65–70 °C window).
- **Clinical goal**: create a **localized "weak link"** (max mechanical contrast: low strength at the target, preserved strength around it) to guide rupture precisely at that site.

> Rationale: peripheral nerves and skin develop heat injury with sustained exposures > 43–45 °C; tendons are more heat-tolerant than nerves but still should not be heated above ~45 °C for multiple seconds.

A.8.4 Material Parameters (Cord / Palmar Fascia)

Use these for planning (adjust if better local data are available):

- Thermal conductivity $k \approx 0.45\ \mathrm{W\cdotp m^{-1}\cdotp K^{-1}}$
- Density $\rho \approx 1100\ \mathrm{kg\cdotp m^{-3}}$

- Specific heat $c_p \approx 3600$ J\cdotpkg^{-1}\cdotpK^{-1}
- Thermal diffusivity $\alpha = \frac{k}{\rho c_p} \approx 1.14 \times 10^{-7}\ \mathrm{m^2/s}$
- Initial temperature $T_0 \approx 37^\circ\mathrm{C}$
- Required rise at the core $\Delta T_{\text{core}} = T_{\text{core,target}} - T_0 \approx 31\ \mathrm{K}$

Device variables

- Probe power delivered to tissue P (watts)
- Coupling efficiency $\eta \in [0.60,\ 0.85]$ (contact, conduction loss, micro-motion)

A.8.5 Heating Modes

We support two **perpendicular** delivery modes:

(A) Point-heat (tip)

- Effective heated volume approximated by a **sphere** radius r_{eff} (e.g., 0.4–0.8 mm depending on tip geometry and contact).
- Volume $V_{\text{sphere}} = \frac{4}{3}\pi r_{\text{eff}}^3$.
- Best when the cord is **thin** or close to sensitive structures; enables **tiny, precise weak points**.

(B) Short mid-section heater

- Active heated **segment length** L_h is confined to $L_h \le d$ (equal to measured through-thickness).
- Volume $V_{\text{cyl}} = \frac{\pi d^2}{4} L_h$ (use $L_h = d$ for full-thickness short-segment).
- Best for **moderate-thick** cords where a **full-thickness ellipsoidal/cylindrical "notch"** is desired in one activation.

> Never set $L_h > d$ inside the cord; if your device's minimal active length exceeds d,
> use **point-heat** or **micro-stepped bursts** (very small in/out movements with short pulses) to synthesize an internal ellipsoid **without spilling outside the cord**.

A.8.6 Core Temperature Time (Energy-Balance)

For a targeted volume V, the energy to raise the core from T_0 to $T_{\text{core,target}}$ is:

$$Q_{\text{req}} = \rho\, V\, c_p\, \Delta T_{\text{core}}.$$

With coupling efficiency η, the **heating time** is:

$$t_{\text{heat}} = \frac{Q_{\text{req}}}{P\,\eta} = \frac{\rho\, c_p\, \Delta T_{\text{core}}}{P\,\eta} V.$$

Plug-in volumes:

- **Point**: $V = V_{\text{sphere}} = \frac{4}{3}\pi r_{\text{eff}}^3$.
- **Short segment**: $V = V_{\text{cyl}} = \frac{\pi d^2}{4} L_h$ with $L_h \le d$ (use $L_h = d$ for a conservative full-thickness "notch").

Key scalings

- Point: $t_{\text{heat}} \propto r_{\text{eff}}^3$
- Short segment: $t_{\text{heat}} \propto d^2 L_h$ (and if $L_h = d$, $t_{\text{heat}} \propto d^3$)
- In both: $t_{\text{heat}} \propto 1/P$, $t_{\text{heat}} \propto 1/\eta$

A.8.7 Surface Safety Check (Keep $T_{\text{surf}} \le 45^\circ\text{C}$)

Let R be the **cord radius** $R = d/2$. During a **short burst**, heat diffusion distance is

$$\delta(t) = \sqrt{4\alpha t}\,.$$

For **center heating**, a conservative estimate for the **fraction** of the core temperature rise that reaches the surface after time t is

$$A(t) \;\approx\; \exp\!\left(-\frac{R^2}{4\alpha t}\right).$$

Thus an **upper-bound estimate** for surface rise is

$$\Delta T_{\text{surf}}(t) \;\lesssim\; A(t)\,\Delta T_{\text{core}}.$$

Safety rule: ensure

$$T_0 + \Delta T_{\text{surf}}(t) \;\le\; T_{\text{surf,max}} \quad (\text{use } 45^\circ\text{C}).$$

If not satisfied: split t_{heat} into n **bursts** (each $t_b = t_{\text{heat}}/n$) with **1–2 s pauses**; recompute $A(t_b)$ until the inequality holds. (More, shorter bursts reduce surface heating while still reaching core target cumulatively.)

A.8.8 Worked Examples (3 W, $\eta = 0.75$, $T_0 \to 37^\circ\text{C}$, $T_{\text{core,target}} \to 68^\circ\text{C}$)

Example 1 — Short segment, full-thickness notch

- $d = 3$ mm → $R = 1.5$ mm; $L_h = d = 3$ mm
- $V = \frac{\pi d^2}{4} L_h = \frac{\pi (0.003)^2}{4} \cdot 0.003 = 2.12 \times 10^{-8}\ \text{m}^3$
- $Q_{\text{req}} = \rho V c_p \Delta T_{\text{core}} = 2.60\ \text{J}$

- $t_{\text{heat}} = \dfrac{2.60}{3 \cdot 0.75} = 1.16\ \text{s}$
- Surface check: $\delta = \sqrt{4\alpha t} = 0.73\,\text{mm}$, $A = \exp[-R^2/(4\alpha t)] \approx 0.014$.
  $\Delta T_{\text{surf}} \approx 0.014 \times 31 \approx 0.44°\text{C} \Rightarrow T_{\text{surf}} \approx 37.4°\text{C}$ → **well below 45 °C**.
- **Plan**: one **1.2 s** burst; manipulate immediately.

Example 2 — Lower power, same cord

- Set $P = 1\,\text{W}$ (same $d = 3\,\text{mm}$, $\eta = 0.75$): t_{heat} triples → **3.48 s**.
- Surface check: $\delta = 1.26\,\text{mm}$; $A \approx 0.24$; $\Delta T_{\text{surf}} \approx 7.5°\text{C} \Rightarrow T_{\text{surf}} \approx 44.5°\text{C}$ (borderline).
- **Plan**: split into **2 bursts** of **1.75 s** with 1–2 s pause. Recompute A per burst (smaller), which lowers T_{surf} safely below 45 °C.

Example 3 — Point-heat tip

- $r_{\text{eff}} = 0.5\,\text{mm}$ → $V = \dfrac{4}{3}\pi r^3 = 5.24 \times 10^{-10}\ \text{m}^3$
- $Q_{\text{req}} \approx 0.064\ \text{J}$ → $t_{\text{heat}} = \dfrac{0.064}{3 \cdot 0.75} \approx 0.029\ \text{s}$.
- **Plan**: **very short pulse(s)**; typically deliver **multiple 30–50 ms bursts** at slightly different micro-positions to sculpt a tiny ellipsoidal weak point, then manipulate.

A.8.9 Burst Strategy (Space–Time Optimization)

- **Default burst**: 0.5–2.0 s (power and geometry dependent).
- **Inter-burst pause**: 1–2 s to limit radial diffusion (keeps surface cool).
- **Duty cycle**: adjust to keep $T_{\text{surf}} \le 45°\text{C}$ by the A-factor check above.
- **Micro-stepping** (optional): for short-segment mode, you may **advance/retract the probe by 0.2–0.5 mm** between bursts to shape a **local ellipsoid** while staying inside the cord.

A.8.10 Quick-Reference Table (Short-Segment, $L_h = d$; 3 W, $\eta = 0.75$)

Using $t_{\text{heat}} = \dfrac{\rho c_p \Delta T_{\text{core}}}{P\,\eta}\,\dfrac{\pi d^3}{4}$:

d (mm)	t_{heat} (s)	Surface note (single burst)
2.0	0.34	Very safe
2.5	0.67	Very safe
3.0	1.16	Very safe
3.5	1.84	Safe

d (mm)	t_{heat} (s)	Surface note (single burst)
4.0	2.74	Usually safe; consider 2 bursts if low power

Scaling

- New P: multiply times by $3/P_{\text{new}}$.
- New η: multiply by $\eta_{\text{old}}/\eta_{\text{new}}$.
- New ΔT_{core}: multiply by $\Delta T_{\text{new}}/31$.

A.8.11 Medical Integration & Guardrails

1. **Adjacency protection**: keep **≥ 3 mm** from neurovascular bundles or **hydrodissect**; use **external skin cooling** if the cord lies very superficial.
2. **Keep it short**: favor **short bursts** and **fractionation** over long, continuous heats—the surface stays cooler while the core still accumulates dose.
3. **Aim for contrast**: the goal is **maximum local weakening** (low tensile strength) **at the target site** while preserving surrounding fascia strength—so the rupture happens **exactly there** with minimal force.
4. **Post-heat manipulation**: manipulate **immediately** after the final burst while the cord is brittle.
5. **Cumulative cap**: keep **cumulative heat time per site ≤ 5 s** (typical cases need far less) before moving or re-targeting.

A.8.12 Step-By-Step Optimization Protocol

1. **Measure** d (through-thickness) with ultrasound at the intended site.
2. **Select mode**:
   - **Point-tip** for micro-precision or very thin/sensitive locations.
   - **Short segment** with $L_h = d$ for a full-thickness notch.
3. **Compute** t_{heat} from the formulas with your **actual** P and η.
4. **Surface check**: compute $\delta = \sqrt{4\alpha t_{\text{heat}}}$ and $A = \exp[-R^2/(4\alpha t_{\text{heat}})]$; verify $T_0 + A\,\Delta T_{\text{core}} \leq 45^\circ\text{C}$.
   - If not: split into **2–4 bursts**; re-check until safe.
5. **Deliver** the planned burst(s); **micro-step** 0.2–0.5 mm between bursts as needed to shape the weak zone.
6. **Manipulate** immediately to rupture; document $d, P, \eta, t_{\text{heat}}$, burst plan, and outcomes.

Bottom line: With **perpendicular insertion**, **point-or short-segment bursts**, and a **45 °C surface limit**, this sensor-free framework lets you compute **short, safe, and effective** heating schedules that create a **precisely localized weak point**—making cord rupture **predictable and easy** while protecting adjacent tissues.