HIGH-FREQUENCY SURGERY

EE 471 – F2016

Prof. Yasser Mostafa Kadah

Basics

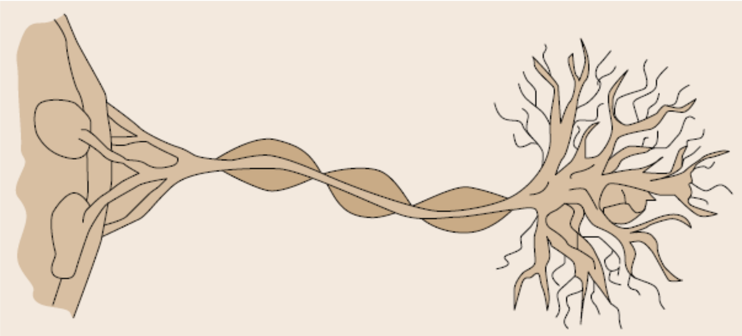
- High-frequency (HF) surgery can be defined as application of electrical energy in surgery for effecting thermally induced change or destruction of tissue cells with aim of hemostasis (stopping bleeding), cutting tissue, or sealing it
- In HF surgery, high-frequency alternating current (preferably 0.3–4 MHz) is delivered by special applicators (or active electrodes) to tissue to be treated, where thermal tissue interaction takes place due to electrical resistance of tissue
- HF surgery devices have many synonymous names
  - HF surgery – RF surgery – radiosurgery – electrosurgery – cautery – electrocautery – diathermy – endothermy – transthermy – electrotomy
- Today, HF surgery has become indispensable tool for all surgical disciplines for inpatient or outpatient care

Bioelectrical and Biothermal Effects: Electrolytic Effect

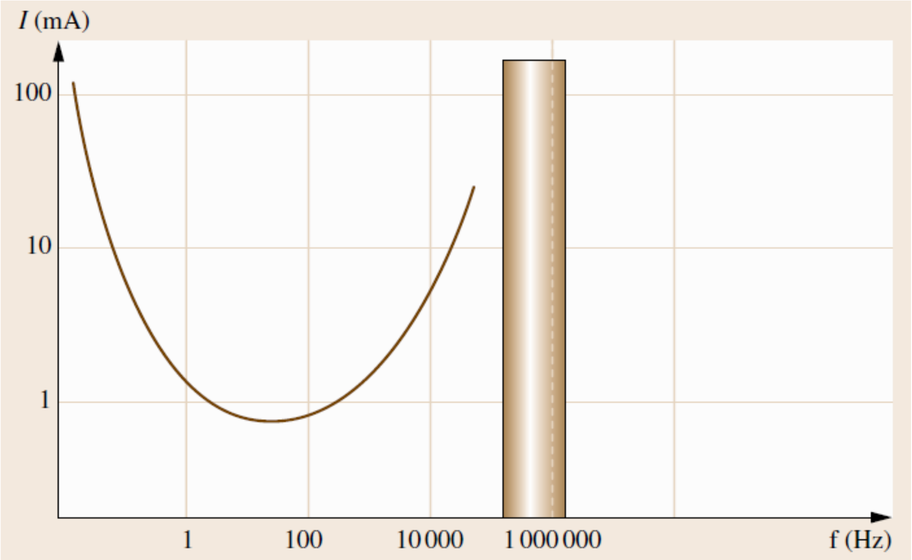
- When electric current flows through biological tissue, bioelectrical and biothermal effects occur, depending on the type of current, current intensity, and frequency
- With DC and low-frequency AC currents, electrolytic effect dominates where ion migration takes place in tissue
  - Positively charged ions travel to the negative pole (cathode) and negatively charged ions to the positive pole (anode)
- Effect is used in medicine in ionophoresis for transporting certain drugs into the body
- In HF surgery this effect is undesirable as tissue's cytochemical content can become damaged

Bioelectrical and Biothermal Effects: Faradic Effect

- When AC currents with frequency of up to 20 kHz flow through biological tissue, faradic effect occurs
  - Currents stimulate nerves and muscle cells, leading to muscle contraction
  - Stimulus effect peaks at frequencies between 10 and 100 Hz
- In HF surgery, this effect is undesirable as muscle contractions are painful, and possibly even dangerous for patient, and problem for surgeon



Nernst law of electrical nerve stimulus threshold



Bioelectrical and Biothermal Effects: Thermal Effect

- With HF alternating currents, both electrolytic and faradic effects are largely prevented in biological tissue, and thus thermal effect dominates
  - Frequency of alternating current is then at least 300 kHz
- This desired thermal effect is mainly used for two different applications: cutting and coagulation
- Amount of heat created in tissue mainly depends on specific resistance of tissue, current density, and duration of exposure
  - Thermal effect is achieved through conversion of electrical energy into thermal energy: heat $Q = I^2 R t = V^2 t / R$ (J)

Heat Equations of Coagulation

- HF power P_{coag} required for coagulation can be calculated by using both the heat quantity Q_{coag} and the coagulation time t_{coag}

$$P_{coag} = \frac{Q_{coag}}{t_{coag}} \quad (W)$$

- Heat quantity Q_{coag} depends on mass m_{coag} of tissue to be coagulated, specific heat capacity c_{coag}, and temperature difference Δt_{coag} within the coagulum (≈ 37 ◦C to 60–100 ◦C) between start and end of coagulation period

$$Q_{coag} = m_{coag} c \Delta t_{coag} \quad (W\,s)$$

- Depending on coagulation technique used, additional quantity of heat Q_{env} also must be taken into account to represent unintentional dissipation of heat in surrounding current-carrying tissues
  - Q_{env} is negligibly small for bipolar coagulation in comparison with Q_{coag}
  - Q_{env} can at times be very large relative to Q_{coag} in monopolar coagulation
  - Q_{env} always poses risk of undesired secondary effects to take into account
  - Explains higher power value in monopolar coagulation compared to bipolar

Heat Equations of Coagulation

- Heat created within active electrode during coagulation is Q_{AE}
  - Temperature of active electrode should not rise during coagulation
    - Creates layer of coagulum that can stick to active electrode
  - If active electrode directly contacts coagulum, unavoidably heated
- Heat balance equation:

$$Q_{\mathrm{tot}} = Q_{\mathrm{coag}} + Q_{\mathrm{env}} + Q_{\mathrm{AE}} \quad (\mathrm{W\,s})$$

  - Q_{coag}: heat quantity required for coagulation
  - Q_{AE}: heat quantity for active electrode
  - Q_{env}: unintended surrounding heat quantity
  - Q_{tot}: total heat quantity

Heat Equations of Cutting

- HF power P_S required for cutting can similarly be calculated by using both heat quantity Q_S and the cutting duration t_S as:

$$P_S = \frac{Q_S}{t_S} \quad (\mathrm{W})$$

- When cutting, tissue volume proportional to length, average depth, and width of cut is heated so strongly that its water content vaporizes
  - Heat quantity required for vaporizing water content in tissue (Q_S) consists of heat quantity Q_{100} to heat tissue fluid from 37 to 100 ◦C plus heat quantity Q_D to evaporate boiling tissue fluid

$$Q_S = Q_{100} + Q_D \quad (\mathrm{W\,s})$$

- Heat balance equation:

$$Q_{tot} = Q_S + Q_U + Q_{AE} \quad (\mathrm{W})$$

  - Heat quantity Q_U for unavoidable heating of tissue not involved in cutting and heat quantity for unavoidable heating of active electrode Q_{AE}

Current Density Effect

- Current density *J* plays key role in HF surgery
  - Only if current density is sufficiently high (normal: 1–6 A/cm^2) can desired cutting or coagulation effect be achieved
- Current density decreases quadratically with distance r

$$J \propto \frac{I}{r^2} \quad (\mathrm{A/cm^2}) \quad \Rightarrow \quad \Delta t \propto \frac{I}{r^4} \quad (\mathrm{K})$$

  - Temperature increase decreases quadratically with distance r

Electrical Model of Biological Tissue

- Biological tissue mainly behaves like ohmic resistor
  - Specific resistance in muscle tissue and well-vascularized tissue is low
  - Specific resistance in tissues with little fluid content such as bones, cartilage, and fat have high specific resistance: low current flow

Tissue	Specific resistance ρ (Ωcm)
Blood	160–300
Muscle, kidney	160–260
Spleen	270–300
Heart	200–230
Liver	200–380
Brain	670–700
Lung	160–1000
Fat	1600–3300

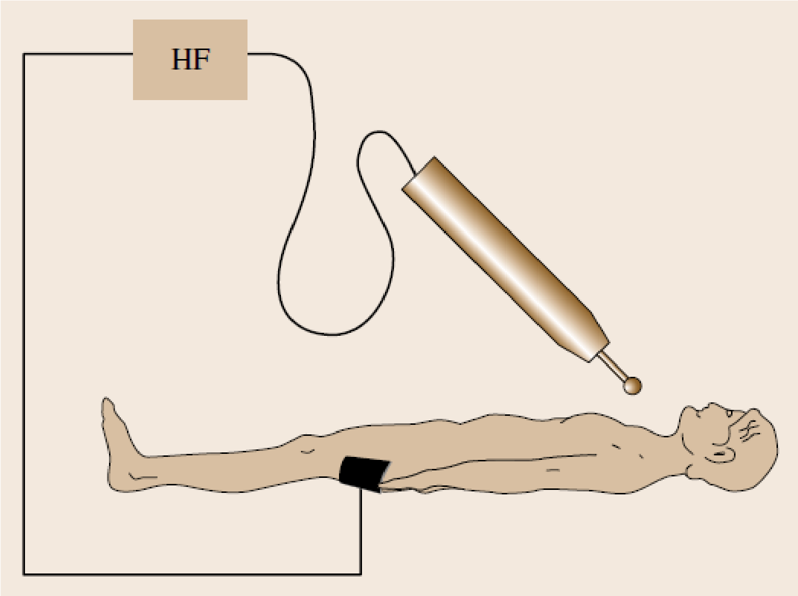
Thermal Tissue Damage

- Regardless of method used to heat tissue (HF current, laser, IR coagulator, ultrasound, ferrum candens, etc.), thermal effects can be classified qualitatively as follows:

Temperature	Tissue reaction
Up to ca. 40 °C	No significant cell changes
From ca. 40 °C	Reversible cell damage (depending on the duration of exposure)
From ca. 49 °C	Irreversible cell damage
From ca. 60–65 °C	Coagulation: Collagens are transformed into glucose, the tissue containing collagen shrinks and produces a hemostasis of the bleeding vessels
From ca. 90–100 °C	Dehydration/desiccation (drying out): Transition of intracellular and extracellular fluids to the vaporous state. Glucose can produce a sticking effect due to dehydration; the coagulum shrinks
From ca. 200 °C	Carbonization: The tissue carbonizes as in a 4th degree burn; unpleasant smell of the burnt tissue; the healing process can be impaired
Several hundred °C	Vaporization (evaporation of the tissue): Emission of plume and gases

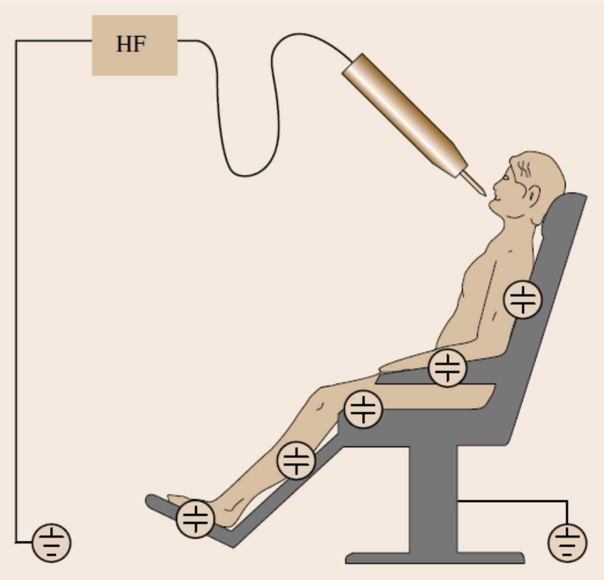
Monopolar Application Technique

- Active and neutral electrodes must be connected to HF surgical device with physical effects produced at active electrode
  - Neutral electrode covers far greater skin contact surface area to ensure that current density (current per unit area) remains relatively low
  - Active electrode has small contact area to produce high current density
- Neutral electrode also called:
  - Plate electrode
  - Passive return electrode
  - Dispersive electrode
  - Indifferent electrode
  - (incorrectly) grounding electrode



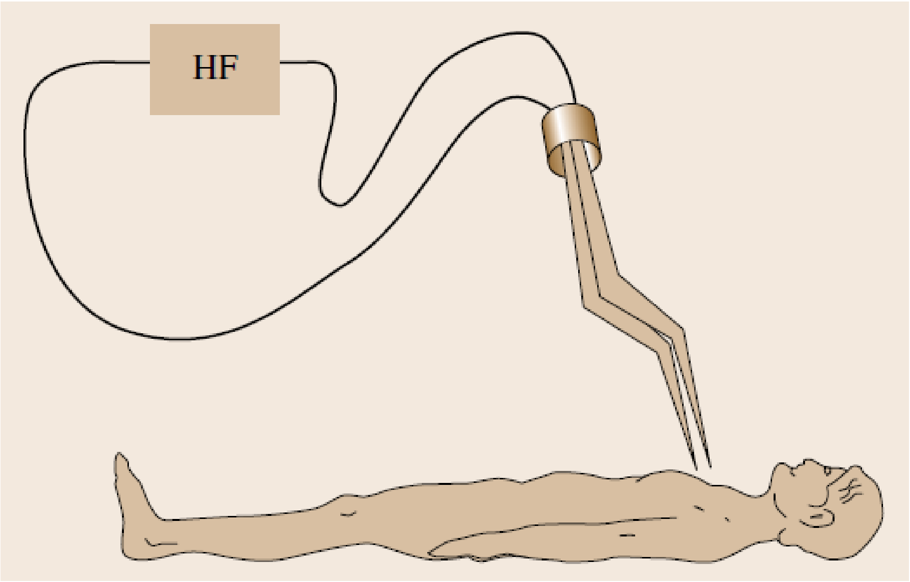
Monoterminal Application Technique

- Circuit is closed via the patient's body capacitive contact to ground
  - Special form of monopolar mode with no neutral electrode
  - Increase in electromagnetic interference with other devices
- Technique safe only for small working currents, hence only suitable for minor surgical interventions, e.g., dentistry and dermatology
  - Only units with maximum HF output power of 50W should be used
  - Higher output power could cause severe patient burns



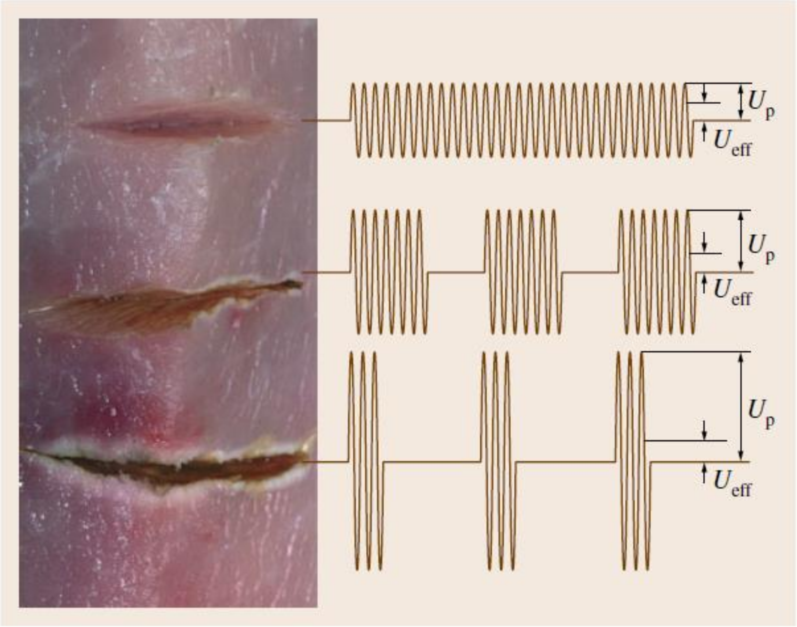
Bipolar Application Technique

- Both electrodes (active and neutral) in single instrument
  - Current flows into tissue via one electrode and back via the other (no neutral electrode)
- Advantages compared to monopolar technique:
  - Current only flows through tissue held between two electrodes where thermal effect is intended
  - Danger of patient burns by touching conductive objects during operation is negligible
  - Reduced influence on cardiac pacemakers
  - Lower interference with other devices
  - No stray currents



Types of Current and Their Application

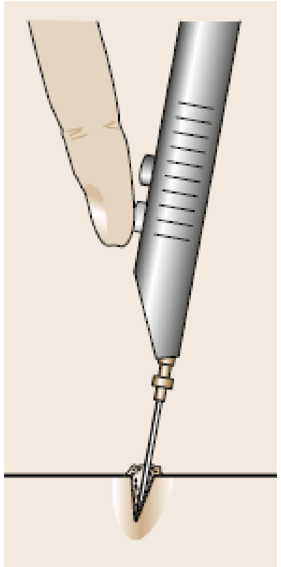
- HF current effect determined by time, voltage, and modulation



	Output Voltage Range Open Circuit, $V_{peak\text{-}peak}$, V	Output Power Range, W	Frequency, kHz	Crest Factor $\left(\frac{V_{peak}}{V_{rms}}\right)$	Duty Cycle
Monopolar modes					
Cut	200–5000	1–400	300–1750	1.4–2.1	100%
Blend	1500–5800	1–300	300–1750	2.1–6.0	25–80%
Desiccate	400–6500	1–200	240–800	3.5–6.0	50–100%
Fulgurate/spray	6000–12000	1–200	300–800	6.0–20.0	10–70%
Bipolar mode					
Coagulate/desiccate	200–1000	1–70	300–1050	1.6–12.0	25–100%

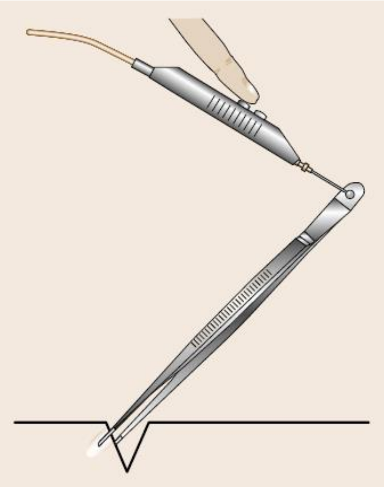
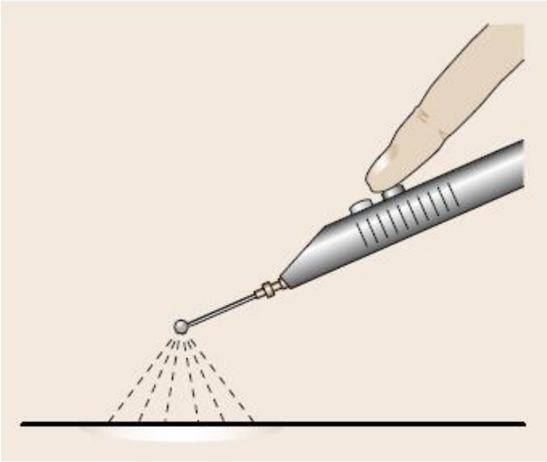
Cutting Currents

- Tissue cutting only possible using HF current if voltage between active electrode and tissue is sufficiently high to generate electric sparks
  - Distance small enough and minimum voltage of ≈ 200 V exceeded
- Quality of cutting depends on:
  - Size and shape of cutting electrode
    - great difference between large-blade electrode or microneedle
  - Type of cut and cutting speed
  - Whether cutting is superficial or deep, incision speed is fast or slow
  - Tissue properties
    - Tissues with low electrical resistance (muscles, vessels), output voltage may breaks down – tissues with high electrical resistance (fat), effect is less
- Variants of cutting currents include Controlled, fractionated and Argon-assisted cutting



Coagulation Currents

- Aim of coagulation is to denature tissue using HF current, or to constrict vessels to an extent where bleeding stops
  - Coagulation effect mainly depends on level and form of output voltage, the current density in tissue, tissue resistance, form and size of active electrode, and application time
  - To coagulate biological tissue, temperature of ≈ 70 ◦C is required
  - At higher temperatures, glucose within coagulate dehydrates and tissue can stick to active electrode, and if higher carbonization of tissue result


Example: Spray Coagulation (Fulgaration)

- Spray coagulation uses very high pulsed and strongly modulated output voltages of several thousand volts (up to 8 kV) used (crest factor up to 20)
- If user approaches tissue with small-area electrode (needle electrode) under spray voltage, air between tip and tissue is ionized at distance of 3–4 mm from tissue
  - Via ionized air in electric field, spark discharges to tissue, followed by fur spark discharges spraying energy to tissue surface and coagulating relatively large tissue area
- With ball electrode, weaker electric field at same distance
  - Increases as distance gets smaller and ionization of air with accompanying spark discharge only present at closer distance with ball electrode

$$\text{Electric field strength } E = \frac{\text{Voltage } U \ \ (\text{kV})}{\text{Distance } l \ \ (\text{mm})}$$

Typical Output Characteristics

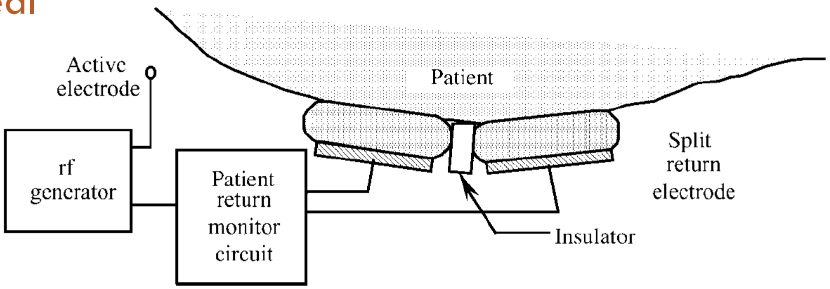
	Output Voltage Range Open Circuit, $V_{peak\text{-}peak}$, V	Output Power Range, W	Frequency, kHz	Crest Factor $\left(\frac{V_{peak}}{V_{rms}}\right)$	Duty Cycle
Monopolar modes					
Cut	200–5000	1–400	300–1750	1.4–2.1	100%
Blend	1500–5800	1–300	300–1750	2.1–6.0	25–80%
Desiccate	400–6500	1–200	240–800	3.5–6.0	50–100%
Fulgurate/spray	6000–12000	1–200	300–800	6.0–20.0	10–70%
Bipolar mode					
Coagulate/desiccate	200–1000	1–70	300–1050	1.6–12.0	25–100%

Typical Power Settings

Power-Level Range	Procedures
Low power	
<30 W cut	Neurosurgery
<30 W coag	Dermatology
	Plastic surgery
	Oral surgery
	Laparoscopic sterilization
	Vasectomy
Medium power	
30 W–150 W cut	General surgery
30 W–70 W coag	Laparotomies
	Head and neck surgery (ENT)
	Major orthopedic surgery
	Major vascular surgery
	Routine thoracic surgery
	Polypectomy
High power	
>150 W cut	Transurethral resection procedures (TURPs)
>70 W coag	Thoracotomies
	Ablative cancer surgery
	Mastectomies

Neutral Electrode (NE)

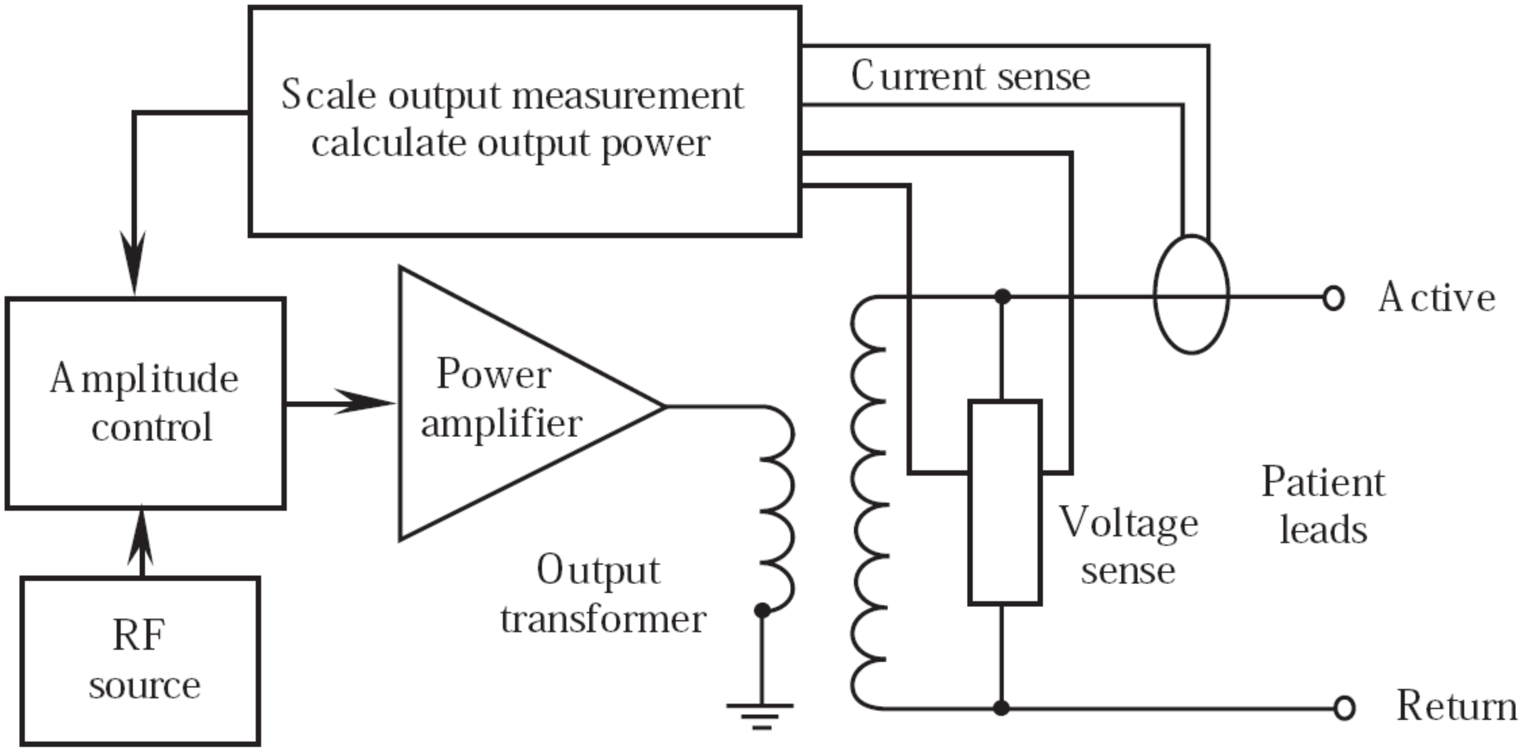
- In monopolar mode, thermal effect required exclusively at active electrode with no thermal reaction underneath (NE)
  - To prevent patient burns, potential heating in NE application area must be kept below 6 ◦C
  - Correct attachment of NE to make absolutely sure it does not detach during operation
  - Advanced systems offer NE monitoring technology that keeps proper NE attachment under constant control and disarms monopolar HF energy delivery if problem detected
- Original assumption that return flow of current from deep tissue layers was equally distributed across the surface of the neutral electrode was not correct
  - Current distribution shows distinct current concentration at edges of NE (edge effect).
  - Effect caused by layered structure of skin with dermis offering good conductivity over poorly conducting fat tissue layer
  - If rectangular NE used, edge closest to target site offer least resistance: form hot spot
  - Electrode as round as possible is therefore ideal



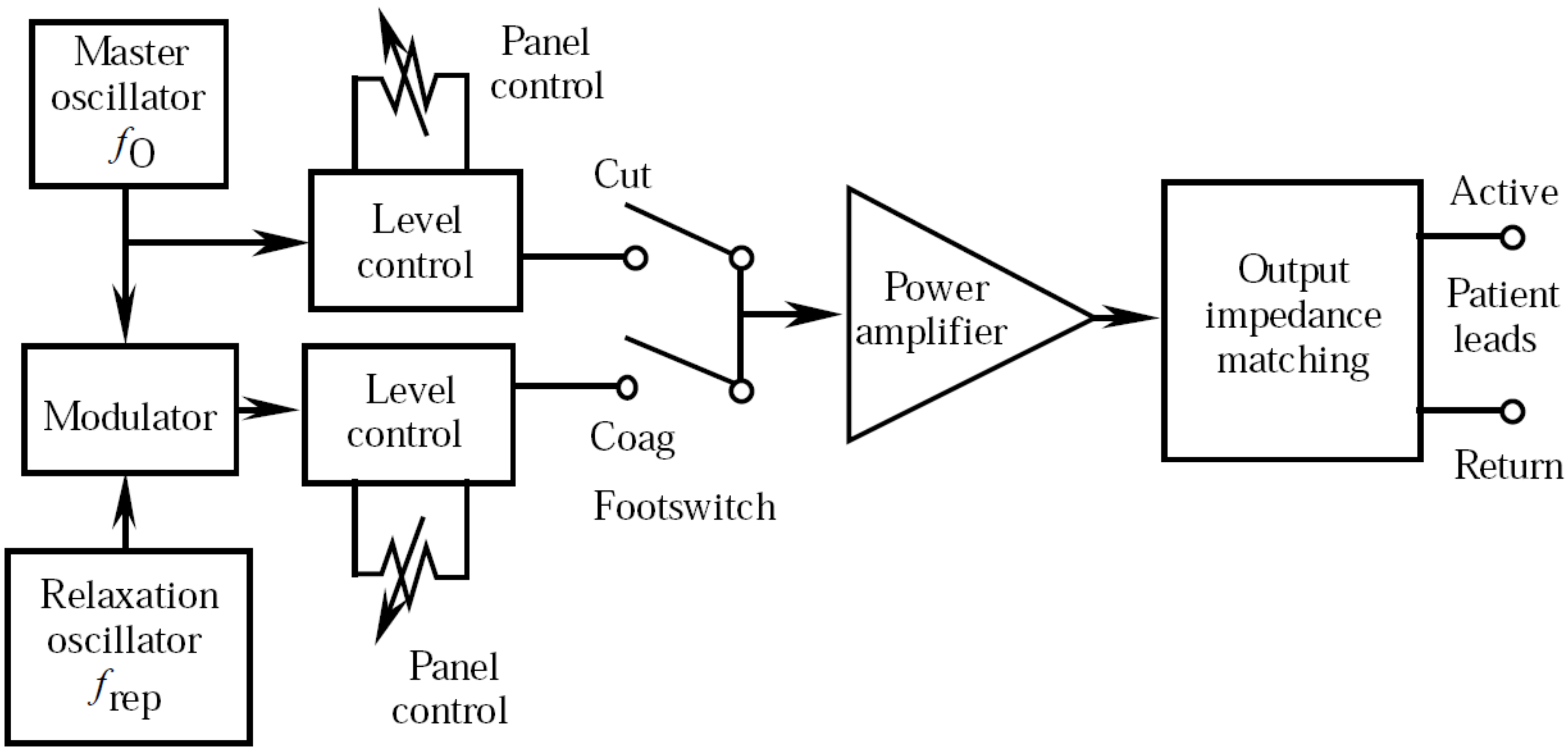
Rules for Neutral Electrode Application

- Ensure good tissue contact (e.g., shaving hair for proper contact)
- Keep fluids away from the NE area, as these can adversely affect both adhesion and electrical properties of NE
- Do not reuse disposable (single-use) NE
- NE must not be trimmed or reduced in size
- Additional contact gel should never be applied to the NE
- Bony or uneven surfaces, implant sites, places with thick layers of fat (such as abdomen or buttocks), and scarred tissue are unsuitable for NE application
- Use contact quality monitor that requires exclusive use of split NEs

HF Surgery Device Design Example

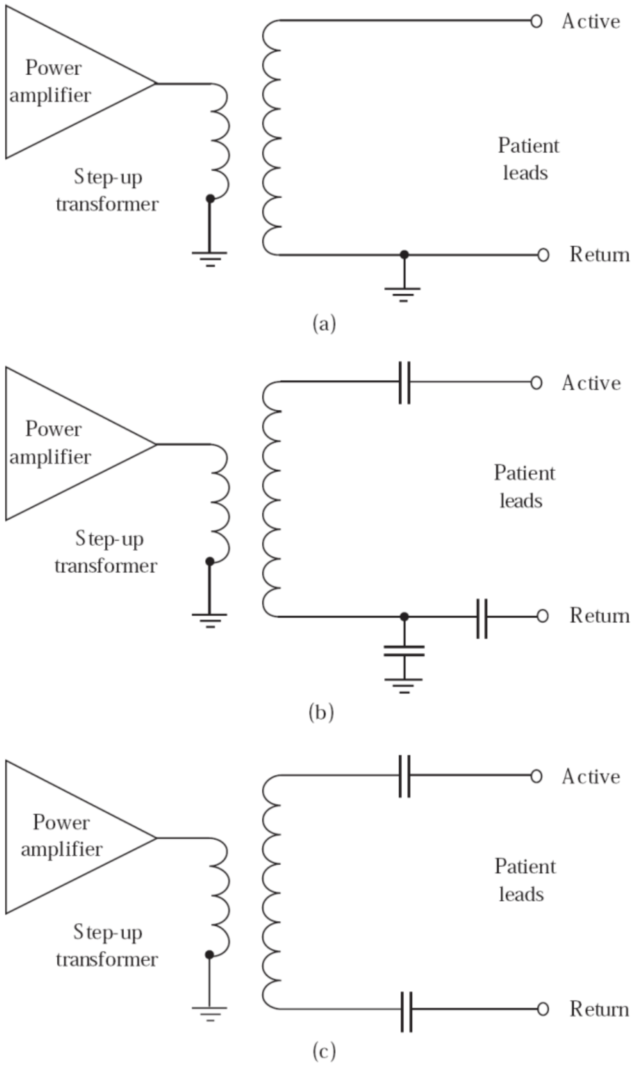


HF Surgery Device Design Example



Lead Isolation

- Several possible strategies
  - Grounded
  - Referred to ground
  - Isolated
- No isolation system is ideal



Reading Assignment

- Read Chapter 34 of *Springer Handbook of Medical Technology*