Biophysics of Catheter Ablation

Allied Health Professionals Training
Workbook
Biophysics of Catheter Ablation

Instructions
Radiofrequency (RF) Ablation
Cryoablation
References
This workbook provides information about the biophysics of catheter ablation. It is designed to enhance understanding of Boston Scientific’s radiofrequency ablation and cryoablation technologies.

To use the workbook:

- Study the content and refer to the images provided.
- Review the Key Concept listed in the righthand column.
- Read the Notes to learn more.
- Complete the exercises in the Study Guide.

The concepts in this workbook build from page to page allowing you to systematically add to your knowledge. Work at your own pace. Review concepts as needed.

KEY CONCEPT

Review the key concept before going to the next page.

NOTES

Review content as needed before answering study guide questions.
Radiofrequency (RF) Ablation

RF Ablation Principles
  RF Energy Circuit
  Goals of Ablation
  Lesion Formation

Determinants of Lesion Size
  RF Power and Duration
  Tissue Temperature
  Convective Cooling
  Electrode Radius

Assessments of Lesion Efficacy
  Efficacy Markers
  Local Impedance Measurements
  Sudden Impedance Changes

Cardiac Tissue
  Tissue Characteristics
  Lesion Characteristics
After completing this module, you should be able to:

- List the components of an RF energy circuit and describe the flow of RF current through the circuit.
- Describe lesion formation in terms of resistive and conductive heating.
- Discuss the factors that determine lesion size.
- Describe the markers of lesion efficacy and discuss their limitations.
- Describe how the characteristics of endocardial tissue affect lesion formation.
Radiofrequency (RF) ablation is the delivery of RF energy (heat) to destroy the cells responsible for initiating an arrhythmia. RF ablation requires an RF energy circuit.

- An RF energy circuit consists of an RF generator, ablation electrode, indifferent electrode, and endocardial tissue. Electric current begins in the RF generator, travels to the ablation electrode via a catheter, enters endocardial tissue; then returns to the generator via the indifferent electrode to complete the energy loop.

- In unipolar RF ablation systems, alternating current passes between the electrode in contact with endocardial tissue to an indifferent electrode placed on the patient’s skin. Most ablation systems are unipolar.

- In bipolar RF ablation systems, alternating current passes between two ablation electrodes positioned on opposite sides of the myocardium. Bipolar ablation may be used for thicker tissue that cannot be successfully ablated with a unipolar system.

Radiofrequency converts electromagnetic waves into thermal energy, which is used for dielectric heating. A dielectric medium cannot conduct electric current, but can maintain an electrical field. If the electrical field is strong enough, electric force can be transmitted without conduction.

KEY CONCEPT

An RF energy circuit consists of an RF generator, ablation electrode, indifferent electrode, and endocardial tissue.

NOTES

Electrical energy is the amount of heat generated or dissipated.

Current is the flow of electrical charge in a closed circuit. Voltage is the force that causes the current to flow.

Alternating current (AC) reverses direction at regular intervals called frequencies. Frequency is measured in Hertz (Hz).
The **goal of ablation** is to form permanent electrically-inert lesions without causing collateral tissue injury.

- RF current is delivered at a high frequency (450 to 500 kHz) and low voltage (40 to 60 V) to provide **controlled thermal injury**. Figure A.

- **Irreversible thermal injury** and loss of cellular excitability occur when tissue temperature reaches about 50°C. Temperatures lower than 50°C fail to destroy unwanted cells and may result in reversible loss of cellular excitability. Figure B illustrates the effect of tissue temperature on cellular excitability.7

- Temperatures above 100°C are associated with gas formation (steam pop), tissue carbonization (char), and coagulum formation (blood clot). Excessive heating could also damage nearby structures, such as the esophagus or phrenic nerve.

- **Lesion formation** is influenced by:
  - **Power** (watts) delivered to ablation electrode
  - **Duration** (seconds) of tissue heating
  - **Stability** of the electrode in contact with tissue
  - **Characteristics** of tissue targeted for ablation
  - **Electrode cooling** via blood flow or irrigation

Successful ablation requires an adequate amount of energy delivered for an adequate amount of time with adequate electrode-tissue contact.

---

**KEY CONCEPT**

The goal of RF ablation is controlled thermal injury and the formation of permanent electrically-inert lesions.

---

**NOTES**

Resistance is the opposition to the flow of electric current in a circuit. It is measured in ohms (Ω).
Lesion formation is the result of resistive and conductive tissue heating.

- **Resistive heating** is the direct delivery of RF current from the ablation electrode to endocardial tissue. Resistive heating is rapid (7 to 10 seconds) and is absorbed by the tissue closest to the ablation electrode (1-1.5 mm). Figure A.

- **Conductive heating** is the transfer of thermal energy from surface tissue to deeper tissue layers. Heat conduction is relatively slow and is responsible for lesion width and depth.  

- Because conductive heating is delayed, tissue temperature continues to rise for a few seconds after RF energy delivery stops. This phenomenon affects lesion size and requires titration of RF power in critical areas such as the AV node.

- Generally, more RF energy (heat) is delivered to the regional blood pool than to tissue. Heat loss to blood occurs because blood has lower resistivity than tissue and because electrode-blood contact is often more stable than electrode-tissue contact.  

Some heat is lost to tissue along the current pathway and at the indifferent electrode. **Current density** is higher at the ablation electrode because the ablation electrode has a smaller surface area than the indifferent electrode. Therefore, most heating occurs at the ablation site.

**KEY CONCEPT**

Resistive heating affects the tissue closest to the ablation electrode.

Conductive heating affects the deeper tissue layers and is responsible for lesion size.

**NOTES**

Electric current in cardiac tissue is carried by ions (charged particles). Ion oscillations due to applied RF energy result in resistive heating.

Resistivity refers to the magnitude of resistance in a particular material. Since AC current follows the path of least resistance, RF energy preferentially goes to the blood pool.
Lesion size increases with higher RF power delivery if electrode-tissue contact is stable.

- Lesion growth is monoexponential - that is, the rate of lesion growth is proportional to the power delivered. More delivered power results in more resistive heating and more heat transferred to deeper tissue layers. Figure A depicts the effect of power on lesion size: 25 W of power produces a larger lesion than 7 W of power. Note that extending the duration of tissue heating does not increase lesion size indefinitely.

- The efficiency of heat transfer depends on the stability of electrode-tissue contact. Stable contact reduces heat loss to blood, catheter movement due to cardiac and respiratory motion, and the distance between the tissue and electrode. Figure B depicts the relationship between electrode distance and tissue temperature: the greater the distance, the less efficient the transfer of heat. The dotted line at 50°C represents irreversible thermal injury.

- At any given power, adequate tissue contact is necessary for consistent lesion formation. Too much contact force, however, reduces blood cooling and can lead to excessive heating. Higher power combined with high contact force increases the risk of gas formation (steam pop).

**KEY CONCEPT**

Lesion size increases with higher RF power if electrode-tissue contact is stable.

Lesion growth is monoexponential proportional to the power delivered.

**NOTES**

Tactile feedback, EGM characteristics, and fluoro or ultrasound imaging are used to assess electrode-tissue contact.

New technologies include contact force sensing catheters to help optimize electrode-tissue contact.
Determinants of Lesion Size

Tissue Temperature

**Tissue temperature** depends on the power level, electrode-tissue contact, and electrode cooling by blood flow and irrigation.

- Figure A illustrates the linear relationship between tissue temperature and power level. At the same electrode position, the temperature rise at 25 W is 2.5 times higher than that at 10 W.

- A sensor (thermistor or thermocouple) located in the ablation electrode provides an *indirect measure* of tissue temperature - indirect because the electrode is heated by the heated tissue it touches.

- The sensor underestimates the surface tissue temperature because of electrode cooling by regional blood flow. For irrigated ablation, the sensor is completely non-reflective of the maximum tissue temperature (hot spot), which typically occurs a few millimeters beneath the endocardial surface.

*Both electrode cooling by blood and variations in electrode-tissue contact affect the sometimes large temperature differences between electrode and tissue.*

---

**KEY CONCEPT**

Tissue temperature depends on the power level, electrode-tissue contact, and electrode cooling by blood flow and irrigation.

The maximum tissue temperature typically occurs a few mm beneath the endocardial surface.

---

**NOTES**

Tissue temperature may rise at a low RF power setting in the presence of good electrode-tissue contact and low blood flow.

---

Figure A: Tissue temperature rise
Lesion size varies with **convective cooling**.

- **Passive convective cooling** is achieved by the blood flowing near the ablation electrode. *Low blood flow* causes the electrode to reach the target tissue temperature at a lower RF power level. *High blood flow* increases heat loss to blood and requires more RF power to reach the target tissue temperature. Figure A.

- **Active convective cooling** is achieved with electrode irrigation - either by flushing sterile saline through openings in the ablation electrodes or circulating fluid within the electrodes. **Electrode irrigation** permits delivery of larger amounts of RF power for a longer duration to create deeper lesions. Irrigated ablation also reduces the risk of coagulum formation by washing away the proteins that form clots.

- The **opposing effects** of tissue heating and convective cooling are varied. Cooling *with* increased RF power results in deeper lesions. Cooling *without* increased RF power results in greater heat loss and smaller lesions. Cooling via irrigation may reduce coagulum formation, but limits the usefulness of temperature feedback.²,⁸

*Ablation success requires continuous monitoring of multiple parameters. No single factor determines ablation success.*⁵

---

**KEY CONCEPT**

Lesion size varies with passive and active convective cooling.

Passive cooling is achieved by the regional blood flow. Active cooling is achieved with electrode irrigation.

---

**NOTES**

*Lesion size varies with convective cooling.*

*The opposing effects of tissue heating and convective cooling are varied.*

*Ablation success requires continuous monitoring of multiple parameters. No single factor determines ablation success.*

---

*Figure A: Passive convective cooling*

*Figure B: Active convective cooling*
Determinants of Lesion Size

With stable tissue contact and the same delivered power, lesions formed with a large electrode are always smaller than lesions formed with a small electrode.\(^3\)

- The surface area of an 8 mm electrode is twice that of a 4 mm electrode. Tissue impedance at the interface with blood and tissue is 90-100 Ω for an 8 mm electrode and 100-120 Ω for a 4 mm electrode.

- As illustrated in Figure A, tissue impedance through the rest of the patient is 45 Ω, so the ratio of interface impedance to patient impedance is lower for the 8 mm electrode than the 4 mm electrode.

- With stable tissue contact, a 4 mm electrode delivers 4.5 W of effective power in both parallel and perpendicular orientations. An 8 mm electrode delivers 1.8 W of effective power in a perpendicular orientation and 4.0 W in a parallel orientation. Thus, an 8 mm electrode may require 1.5 to 5 times more power than a 4 mm electrode to achieve the same tissue temperature. A larger electrode reduces the efficiency of heat transfer to tissue. Also, heat transfer is more variable with a larger electrode because there is greater variability in tissue contact.

Figure A: Effective power delivery for 4 mm vs 8 mm electrodes\(^3\)

KEY CONCEPT

With the same total power, lesions formed with a large electrode are always smaller than lesions formed with a small electrode.

NOTES

Impedance is a measure of all resistances to current flow in an AC circuit. It is measured in ohms (Ω).
EGM amplitude, loss of pacing, and impedance measurements are used as markers of lesion efficacy.

- An **decrease in EGM amplitude** at the site of ablation or the **loss of pacing capture** are non-specific markers of ablation success. These markers are not always reliable because they are difficult to quantify in real time. Catheter positioning and electrode-tissue contact affect EGM amplitude and morphology. Loss of pace excitability does not guarantee permanent conduction block.

- Heating reduces tissue resistivity and causes **impedance** to drop steadily during ablation.\(^1\)\(^,\)\(^8\) Clinicians typically monitor RF generator impedance (GI) and adjust ablation parameters as needed to achieve an adequate impedance drop. A **GI impedance drop > 10 \(\Omega\)** from baseline is associated with effective cell death and is considered a reliable marker of lesion efficacy.\(^1\)\(^,\)\(^8\) The **baseline impedance** depends on tissue type and electrode-tissue contact.

- The RF generator measures **transthoracic** impedance between the ablation and indifferent electrodes. GI is an imprecise measure, however, because of variations across muscle, lung, and bone.\(^2\)

**KEY CONCEPT**

Markers of lesion efficacy:
- EGM amplitude decrease
- Loss of pacing capture
- Generator impedance drop > 10 \(\Omega\) from baseline

**NOTES**

The recovery of conduction after ablation success may be due to reversible thermal injury or edema in the tissue near the lesion.

\(^{1-8}\)

*No thermal lesion occurs without a drop in impedance and the extent of the drop depends on tissue temperature and the amount of tissue heated.*\(^5\)
Local Impedance Measurements

Measurements of **local impedance (LI)** at the catheter tip have been used to assess electrode-tissue contact and may provide a real-time indicator of lesion efficacy.²,⁶,⁸

- Local impedance (LI) is a **direct measure** of the resistive load of tissue and blood on the ablation electrode. *Higher baseline LI* is associated with greater electrode-tissue contact and an indication the target LI drop is achievable.² *Lower baseline LI* is associated with less electrode-tissue contact and greater electrode-blood contact.² Figure A.

- Studies show that LI in high voltage (healthy) tissue is higher than LI in low voltage (unhealthy) tissue. The impedance of healthy tissue ranges from 115 Ω to 225 Ω (voltage ≥ 3.0 mV). The impedance of unhealthy tissue ranges from 60 Ω to 115 Ω (voltage ≤ 1.5 mV). *Thus, lower baseline LI* is more likely in scarred or chronically ablated tissue.⁶

- **A LI drop correlates with increasing temperature and greater lesion depth.⁶** Figure B. Studies show that baseline LI is a better predictor of impedance drops than GI.⁵,⁶

*The magnitude of LI drop, even in short RF ablations, is a reliable measure of lesion formation.*¹¹
An impedance drop followed by a **sudden impedance rise** indicates coagulation formation or steam pop.\(^5\)

- **Coagulum formation** is more likely when the tissue temperature rises above 70° C. Coagulum usually adheres to the catheter tip and can cause a sudden rise in impedance. If the coagulum adheres to the tissue, impedance and temperature may not be affected. Therefore the absence of an impedance rise does not guarantee the absence of a blood clot.

- Temperatures above 110° C can lead to evaporation and the formation of a gas bubble that expands and eventually explodes, producing an **audible steam pop**. The steam pop occurs because the temperature rises *too fast* and the steam cannot diffuse smoothly through the tissue. **Steam pop lesions** are associated with a sudden rise in impedance (up to 10 Ω) and a sudden drop in temperature.

*A combination of carefully monitored ablation parameters is the most efficient strategy for preventing the adverse effects of ablation.*\(^5\)

**KEY CONCEPT**

An impedance drop followed by a sudden impedance rise is indicative of coagulum formation or steam pop.

**NOTES**

Steam pop occurs in only about 0.1% to 1.5% of RF ablation procedures, but its consequences are serious. They include embolic stroke, cardiac perforation, and ventricular septal defect.\(^5\)
The **characteristics of the tissue** targeted for ablation affect the stability of electrode-tissue contact and the response of the tissue to heating.

- It may be more difficult to achieve stable electrode-tissue coupling on a *smooth endocardial surface* (right or left atrial wall), which may in turn decrease lesion size.
- Efficient heat transfer is more likely in *trabeculated tissue or ventricular pockets*, which increases the risk of excessive tissue heating.
- The *tricuspid and mitral valves* have a high volume of regional blood flow which increases passive cooling and may decrease lesion size.
- Perforation from steam pop is more likely in *thin tissue* (atrial wall, RVOT) than thick tissue (ventricular wall).
- RF ablation in scarred tissue results in irregular tissue injury.$^{13}$

**KEY CONCEPT**

The characteristics of the tissue targeted for ablation affect the stability of electrode-tissue contact and the response of the tissue to heating.

**NOTES**

- Right atrium
  - Healthy
  - Smooth atrial tissue (SA)
  - Thin walled
  - Pectinate
  - CTI pouch

- Left atrium
  - Smooth zones
  - Pectinate ridges-hard to heat
  - Posterior wall 4-6 mm
  - Some areas 2 mm
  - PV sleeve enclosed structure

- Ventricular tissue
  - Thick tissue
  - Structures (leaflets, cordae
  - Pockets
  - Scar, infarct

- VALVE PLANES
  - Firmer tissue
Ablated cardiac tissue responds to injury in the same way as other tissue

- An **RF lesion** is pale because of the breakdown of myocyte proteins and loss of red pigment. The center of the lesion is dessicated (dry) and is surrounded by hemorrhage and inflammation. Within a few months the lesion becomes fibrotic with inflammation infiltrates and significant volume contraction. The lesion is surrounded by healthy tissue with no transition zone. Figure A.

**KEY CONCEPT**

An RF lesion is pale because of the breakdown of myocyte proteins. Over time, the lesion becomes fibrotic and is surrounded by healthy tissue with no transition zone.
Catheter Cryoablation

Cryoablation

Basic Principles
Lesion Formation
Lesion Characteristics
After completing this module, you should be able to:

- Define cryoablation. Describe how cryoablation is used to form a lesion.
- Discuss the advantages of cryoablation relative to RF ablation.
- Describe the characteristics of a cryoablation lesion.
Cryoablation is the use of extreme cold to destroy the cardiac cells responsible for initiating an arrhythmia. It may be achieved with a focal or balloon catheter.

- Cryoablation involves **freezing and thawing** using a compressed refrigerant - usually nitrous oxide (N\textsubscript{2}O). Liquid N\textsubscript{2}O is delivered under pressure to a small chamber at the catheter tip. Upon entering the chamber, the N\textsubscript{2}O expands and evaporates to form a gas - a process called the **Joule-Thomson effect**. The catheter adheres to endocardial tissue and extracts heat from the tissue at the catheter interface.

- Freezing causes cellular dehydration followed by extracellular ice formation. Thawing induces cell membrane rupture and ischemic reperfusion injury.* The result is the obliteration of blood vessels, cell death, and the formation of electrically inert lesions.

- Optimum **lesion formation** depends on maintaining contact of the ablation catheter with endocardial tissue at **about -40°C** for at least two minutes and **slow thaw times** to ensure cell death. The cryoablation system provides feedback about the N\textsubscript{2}O flow rate, pressure, temperature, cooling time, and thawing time to guide ablation.

*Reperfusion is caused by the return of the blood supply to tissue that has been deprived of oxygen.

Balloon cryoablation catheter

**KEY CONCEPT**

Cryoablation involves periods of freezing and thawing to destroy the cardiac cells responsible for initiating an arrhythmia.

**NOTES**

Cryoablation is typically guided by CT or MRI.
Cryoablation provides several advantages over RF ablation.

- Freezing causes the catheter or balloon to firmly **adhere** to the endocardial tissue. **Cryoadhesion** results in greater catheter stability and permits precise lesion formation with less risk of collateral damage. Cryoadhesion facilitates ablation at sites in which catheter stability is difficult to maintain. It permits safe ablation during an arrhythmia or programmed stimulation because there is less risk of catheter dislodgment due to cardiac and respiratory motion.¹²

- If tissue is cooled to a milder temperature for a brief duration (e.g., -30°C for 30-60 seconds), cell damage is **reversible** and conduction usually recovers when the tissue is re-warmed. Clinicians may use the period of reversible tissue injury to assess the clinical effects of ablation before forming a durable lesion - called **cryomapping**.

- Cryoablation lesions have a smaller surface area than RF lesions. The figure depicts the differences: the depths of the cryolesion and RF lesion are comparable, but the cryolesion has a smaller surface area and smaller volume.

---

**KEY CONCEPT**

Cryoablation advantages:

- Catheter adherence to freezing tissue provides catheter stability
- Period of reversibility if clinical effects are not as expected.
- Smaller effective lesions compared to RF.

**NOTES**

Studies show that cryoablation is associated with less patient discomfort than RF ablation so there may be less need for anesthetics.¹²

A disadvantage: cryoablation takes longer than RF ablation.¹²
Cryoablation results in a **discrete homogenous lesion** clearly separated from normal myocardial tissue.

- The structural integrity of the lesion is preserved because collagen fibers are less susceptible to destruction by extreme cold and because the tissue is protected by the heating effects of the coronary blood flow. This may reduce the risk of complications such as perforation or esophageal injury.\textsuperscript{12}
- Cryoablation is associated with minimal endothelial surface disruption and less platelet and coagulation cascade activation. Studies show that thrombus formation is less likely with cryoablation than RF ablation.\textsuperscript{12}
- Cryolesions may be less arrhythmogenic than RF lesions because of the distinct border between ablated and healthy tissue.

**KEY CONCEPT**

Cryoablation results in a discrete homogenous lesion clearly separated from normal myocardial tissue.

**NOTES**


