Carbon Fiber in Ablation Applicators: Structure, Function, and Clinical Applications

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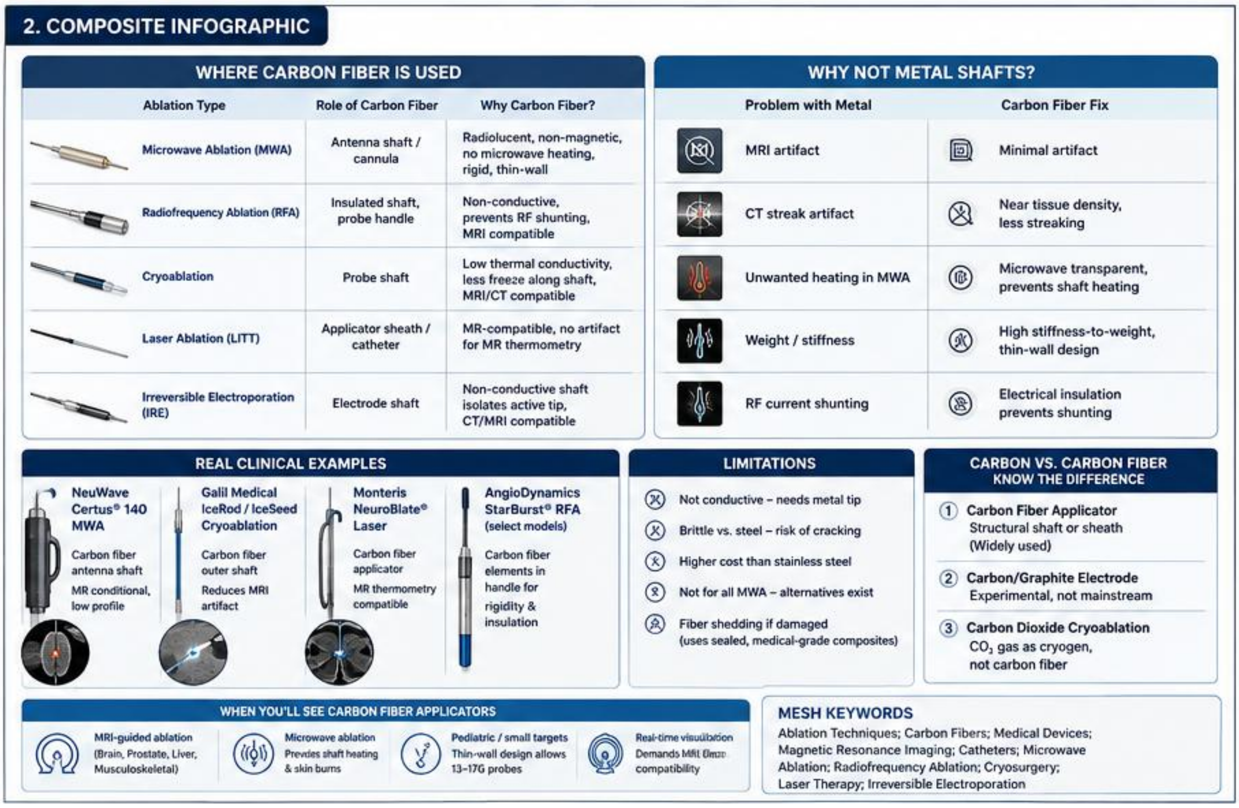
***Abstract*—Advances in image-guided tumor ablation have increased the demand for applicator materials that combine mechanical strength, imaging compatibility, and procedural safety. Carbon fiber has emerged as an important structural material in several ablation platforms, particularly those designed for magnetic resonance imaging (MRI)-guided interventions and microwave-based therapies. Unlike metallic components that actively deliver energy, carbon fiber typically serves as the shaft, sheath, or supporting structure of the applicator. Its low imaging artifact, favorable stiffness-to-weight ratio, and resistance to unwanted electromagnetic interactions make it particularly attractive in modern ablation systems. This review summarizes the role of carbon fiber across various ablation modalities, discusses its advantages and limitations, and highlights representative commercial applications.**

Graphical abstract



I. Introduction

Percutaneous ablation techniques—including radiofrequency ablation (RFA), microwave ablation (MWA), cryoablation, laser interstitial thermal therapy (LITT), and irreversible electroporation (IRE)—have become established treatments for a wide range of oncologic and non-oncologic conditions. As procedural precision has improved, increasing emphasis has been placed on applicator design and material selection.

Historically, stainless steel and titanium dominated probe construction because of their strength and manufacturability. However, these materials introduce imaging artifacts, may interact with electromagnetic fields, and can contribute to unintended energy deposition. Carbon fiber composites provide an alternative structural material that addresses many of these limitations while maintaining sufficient mechanical rigidity for percutaneous access.

Importantly, carbon fiber is rarely the active ablative component. Instead, it functions as a structural element that supports the delivery of energy through metallic electrodes, microwave antennas, cryogenic channels, or laser fibers.

II. Role of Carbon Fiber Across Ablation Modalities

The utilization of carbon fiber varies according to the ablation technology employed.

Ablation Type	Role of Carbon Fiber	Rationale
Microwave Ablation (MWA)	Antenna shaft or cannula	Radiolucent, non-magnetic, resistant to microwave-induced heating, high rigidity with thin walls
Radiofrequency Ablation (RFA)	Insulated shaft, applicator body, handle	Electrically insulating, prevents current shunting, MRI compatibility
Cryoablation	Probe shaft and structural housing	Reduced thermal conduction along shaft, minimized imaging artifacts
Laser Ablation (LITT)	Applicator sheath and catheter system	MRI compatibility and reduced interference with MR thermometry
Irreversible Electroporation (IRE)	Electrode shaft insulation	Isolates active metallic electrode while preserving imaging visibility

A common misconception is that carbon fiber serves as the energy-delivering element. In clinical devices, the actual ablative action is performed by metallic electrodes, microwave radiators, cryogenic chambers, or laser fibers. Carbon fiber primarily acts as the delivery platform.

III. Why Carbon Fiber Instead of Metal?

Several engineering challenges arise when conventional metallic shafts are used in image-guided ablation systems.

Imaging Considerations

Metallic probes generate significant susceptibility artifacts on MRI and beam-hardening artifacts on CT. These distortions may obscure tumors, treatment margins, or evolving ablation zones.

Table 2. Imaging and Procedural Advantages of Carbon Fiber

Challenge with Metallic Shafts	Advantage of Carbon Fiber

MRI susceptibility artifact	Minimal artifact allows accurate visualization
CT streak artifact	Reduced beam hardening and streaking
Obscuration of treatment margins	Improved visualization of ablation zone
Distortion of MR thermometry	Enhanced temperature monitoring accuracy

The ability to perform accurate real-time MRI monitoring is among the strongest drivers for carbon fiber adoption.

Electromagnetic Considerations

In microwave ablation systems, conductive metallic shafts can couple with the microwave field and produce unwanted heating away from the target tissue. This may result in skin burns, shaft heating, or altered energy deposition patterns.

Table 3. Electromagnetic Benefits

Issue	Carbon Fiber Benefit
Microwave coupling of metallic shafts	Reduced unintended energy absorption
Entry-site heating	Lower risk of thermal injury
Electromagnetic interference	Improved procedural stability
RF current shunting	Better insulation in RFA and IRE systems

Mechanical Properties

Carbon fiber composites possess a high stiffness-to-weight ratio, enabling long, slender probes with adequate rigidity.

Table 4. Mechanical Advantages

Property	Clinical Benefit

High stiffness	Precise targeting
Low weight	Easier manipulation
Thin-wall construction	Smaller puncture tract
Corrosion resistance	Long-term device durability
Fatigue resistance	Improved structural performance

These characteristics are especially important in MRI-guided procedures where access paths may be long and workspace constraints significant.

IV. Clinical Applications

MRI-Guided Ablation

MRI-guided interventions represent the most important application of carbon fiber-based applicators. Real-time visualization of thermal or cryogenic treatment effects requires minimal imaging artifact.

Clinical examples include:

Brain laser interstitial thermal therapy
Prostate ablation
Liver tumor ablation
Musculoskeletal tumor treatment
Pediatric interventions

The ability to visualize the evolving treatment zone in real time significantly improves procedural accuracy.

Microwave Ablation

In microwave systems, carbon fiber shafts help minimize unwanted shaft heating while preserving applicator rigidity.

Potential benefits include:

- Reduced skin burns at the puncture site
- More predictable energy deposition
- Improved compatibility with advanced imaging environments
- Smaller gauge access systems

Cryoablation

Cryoablation probes benefit from carbon fiber's relatively low thermal conductivity compared with metals.

Advantages include:

- Reduced proximal freezing
- Better preservation of shaft temperature
- Less artifact during MRI monitoring of ice-ball formation
- Improved visualization of treatment margins

Laser Interstitial Thermal Therapy (LITT)

Laser ablation depends heavily on MRI thermometry for treatment monitoring.

Carbon fiber applicators support:

- Accurate thermal mapping
- Minimal image distortion
- Stable positioning of laser fibers
- Improved treatment planning and execution

V. Commercial Examples

Several commercial systems have incorporated carbon fiber components into their applicator designs.

Table 5. Representative Clinical Systems

Device/System	Ablation Type	Carbon Fiber Component	Clinical Purpose
NeuWave Certus 140	Microwave Ablation	Antenna shaft	MRI compatibility and reduced shaft heating
IceRod / IceSeed platforms	Cryoablation	Outer shaft components	Reduced MRI artifact
NeuroBlate	Laser Ablation	Laser applicator housing	MR thermometry compatibility
StarBurst (selected generations)	Radiofrequency Ablation	Structural handle elements	Insulation and rigidity

These examples illustrate how carbon fiber serves predominantly structural rather than therapeutic functions.

VI. Limitations of Carbon Fiber

Despite its advantages, carbon fiber is not universally suitable.

Table 6. Limitations

Limitation	Clinical Implication
Limited electrical conductivity	Cannot replace metallic RF electrodes
Brittleness under excessive bending	Risk of shaft damage
Higher manufacturing cost	Increased device expense
Complex fabrication	More demanding production processes
Potential fiber shedding if damaged	Requires sealed medical-grade composite construction

Consequently, many manufacturers continue to employ alternative materials such as ceramics, polyether ether ketone (PEEK), or specialized polymer composites depending on procedural requirements.

VII. Carbon Fiber Versus Carbon Electrodes

The terms “carbon fiber” and “carbon electrode” are frequently confused.

Table 7. Important Distinctions

Term	Description	Clinical Status
Carbon Fiber Applicator	Structural shaft or sheath	Widely used
Carbon/Graphite Electrode	Energy-delivering electrode	Mostly experimental
Carbon Dioxide Cryoablation	Uses CO_2 gas as cryogen	Separate technology

While experimental carbon-based electrodes have demonstrated MRI compatibility, metallic electrodes remain the clinical standard for most thermal and electroporation procedures.

VIII. Future Directions

As MRI-guided interventions become increasingly prevalent, demand for imaging-compatible materials will continue to grow. Future developments may include:

- Hybrid carbon fiber–ceramic applicators
- Embedded fiber-optic sensing systems
- Advanced composite materials with tailored electromagnetic properties
- Fully MRI-compatible ablation platforms
- Robotic image-guided ablation systems utilizing carbon fiber instrumentation

Such innovations may further enhance procedural precision while minimizing imaging interference.

IX. Conclusion

Carbon fiber has become an important structural material in modern ablation technology. Although it does not typically participate directly in energy delivery, it provides critical advantages in MRI compatibility, reduced imaging artifact, mechanical rigidity, and resistance to unwanted electromagnetic interactions. Its greatest value is observed in MRI-guided laser ablation, cryoablation, and advanced microwave systems where visualization and procedural accuracy are paramount. As image-guided therapies continue to evolve, carbon fiber composites are likely to play an increasingly important role in next-generation ablation applicators.

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