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Review

Revolutionizing Patient Care: A Comprehensive Review of Recent Advances in Flexible Printed Heaters for Wearable Medical Applications

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Abstract: Recent developments in flexible printed heaters (FPHs) for wearable thermal applications, driven by the advancement of printed electronics, show great promise in revolutionizing patient care through the development of wearable flexible heaters for medical applications. Wearable heaters with high thermal stability, heat uniformity, safety, flexibility, comfort, biocompatibility, biodegradability, recyclability, and power efficiency are desirable for standalone medical thermotherapy applications. This paper reviews recent advancements in the design of FPHs for wearable thermal applications. Materials used in the FPHs, fabrication methods, design considerations, temperature control mechanisms, medical applications, and performance analysis of specific FPHs are all thoroughly discussed. Materials used in FPHs, such as conductive and substrate materials, receive special attention along with the heater design parameters. Additionally, the paper addresses the challenges and future directions for the advancement of FPHs in wearable medical applications.

Keywords: flexible printed heaters; conductive material; substrate material; heater design; wearable medical applications

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1. Introduction

The use of heat for medical purposes has a long history, dating back to ancient civilizations. In ancient Rome, sandbathing was employed to treat conditions such as asthma, arthritis, chronic pain, and congestion in the breast or abdomen [1]. Similarly, the Egyptians utilized hot sand to relieve joint pain and obesity. Hippocrates famously used ceramic bowls filled with hot water to relieve congestion [2,3].

Today, heat is commonly used in hospitals, nursing homes, and at home to address various medical needs, including pain relief, warming patients with low body temperature, facilitating intravenous (IV) line insertion, and providing comfort and relaxation [3,4]. As a non-pharmacological treatment method, heat therapy involves the application of external heat to a specific body area to increase tissue temperature, thereby alleviating symptoms associated with various conditions [2,5,6]. For instance, heat therapy is commonly used to treat low back pain [7], musculoskeletal pain [8], and malignant tumors [9]. Additionally, heat therapy plays a crucial role in the management of neonatal hypothermia [10], defined as having a core body temperature below 36.5 °C, which significantly contributes to neonatal mortality [11,12].

The primary goal of heat therapy is to expand blood capillaries and enhance blood flow to the affected area, thus promoting healing by delivering essential nutrients and oxygen to the tissues [2]. Heat therapy can be administered in dry or moist forms. Dry heat therapy uses sources such as electric heating pads, hot packs, heating lamps, and ovens, while moist heat therapy employs methods like sitz baths, hot water baths, chemical packs, and moist heating pads [3,13]. However, there have been numerous reports of burn injuries resulting from improper heat application on patients' skin [14–17]. For instance, severe burn injuries have been documented in patients in Asia due to heat application for the treatment of diabetic neuropathy [14].

A traditional electric heating pad, which is made of a wire heating element insulated in fabric, can be placed close to the body for a short period of time. It is not suitable for long-term wearable applications due to safety concerns, such as the risk of burns or overheating from prolonged exposure [18,19]. Several approaches have been made by researchers to make electric heating pads suitable for human wearable applications. One prominent development in this regard is the development of wearable heaters using conductive yarns or threads integrated into textiles [20–22]. They are designed to distribute the heat more evenly, minimizing the risk of burns or discomfort associated with prolonged exposure [20]. Polymer-based conductive yarn heaters represent a significant advancement over traditional metal-based heaters, offering improved flexibility and safety. Their design allows them to conform to the body and integrate seamlessly into textiles while operating at lower temperatures, reducing the risk of burns, and improving overall comfort during use [19]. While these heaters operate at a low power supply and provide flexibility, challenges remain regarding heat uniformity, comfort, and durability after multiple washing cycles [19,23].

Recent advancements in flexible printed electronics have led to the development of printed heaters that are more flexible, comfortable, and efficient for diverse applications [23]. FPHs utilize this technology to create electrically conductive patterns on various flexible substrates. This works through the Joule heating principle, in which heat is produced when electrical current flows through a conductor [24]. In contrast to traditional wire-based heaters, which are often rigid and bulky, printed heaters are flexible, comfortable, suitable for wearable applications, customizable, cost-effective, and scalable for high-volume production [25,26]. Additionally, traditional wire-based heaters often exhibit poor heat uniformity, leading to hotspots, and are more susceptible to oxidative corrosion, resulting in shorter lifespans [26]. FPHs, on the other hand, demonstrate greater efficiency in heat delivery and consume less power due to minimal heat loss to the environment, whereas traditional wire-based heaters are less efficient in heat delivery due to heat loss associated with insulation and wire resistance [26].

For effective wearable applications, FPHs need to deliver uniform heat utilizing a portable power supply while exhibiting rapid response times, high repeatability, and biocompatibility [23]. Wearable printed heaters should prioritize low voltage for safety, high heat-transfer coefficients, and high heat-transfer efficiencies within their effective areas [27]. Achieving optimal heat conversion efficiency is significantly influenced by the choice of conductive and substrate materials, fabrication methods, and the heater's integration [28].

This paper discusses the latest developments in FPHs. Section 2 discusses the materials used in FPHs, including conductive and substrate materials. Section 3 covers fabrication methods such as screen printing, inkjet printing, and gravure printing. Section 4 focuses on FPH designs and temperature control mechanisms for safe operation. Subsequently, the performance of selected FPHs developed by various researchers is evaluated, followed by a discussion of their applications and use cases in wearable medical contexts. Finally, the challenges, solutions, and future directions for the development of FPHs in wearable medical applications are addressed.

2. Materials for Flexible Printed Heaters

FPHs work through the Joule heating or resistive heating principle. In this principle, when the current flows through the resistor, the resistor produces heat by changing the electrical energy into heat energy. The amount of heat generated is proportional to the power dissipated in the resistor [19]. The FPHs are composed of conductive materials applied onto flexible substrates, allowing for the creation of predefined heater patterns either in series, parallel, or a combination of both. Additionally, the electrodes on both ends of the heater patterns are printed using conductive material to supply electric power to the heater, as illustrated in Figure 1.

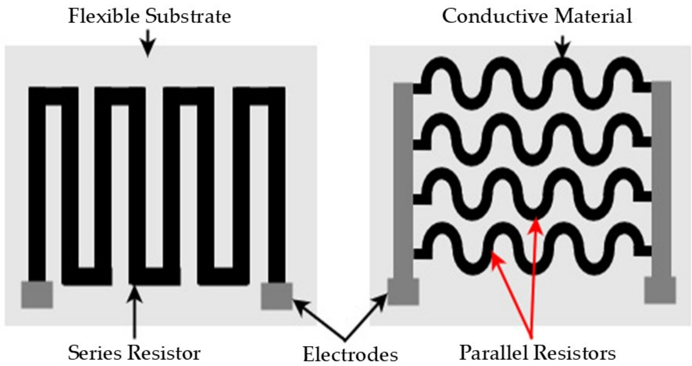

Figure 1. Illustration of FPH components using sample heater trace patterns.

2.1. Conductive Materials

Conductive materials are materials that allow the flow of current through them [29]. They also act as an electric resistor and, thus, can be used as a heating element [30]. When selecting conductive materials for FPHs, several key properties are critical. Low resistance is generally desired to minimize energy consumption [27]. High thermal conductivity is crucial for effective heat distribution, ensuring the generated heat is transferred efficiently to the intended surface or body [31]. Additionally, the heat-transfer coefficient plays a significant role in determining the effective heat transfer from the material to its surroundings [32]. A high heat-transfer coefficient enhances efficient heat dissipation, while a lower coefficient is beneficial for applications where heat retention is desired [33]. The conductive materials used for FPHs are commonly categorized as metallic, carbon-based materials, conductive polymers, and hybrid conductive materials.

2.1.1. Metallic Conductive Materials

The manufacturing of printed heaters has given considerable attention to metal-based materials because of their low sheet resistance and mechanical flexibility [34,35]. Silver is the most commonly used metal in printed heaters due to its excellent electrical conductivity (6×10^7 S/m) [5,24,36,37]. It also offers low resistance and high thermal conductivity (429 W/m.K), which makes it effective for generating heat [38]. Notable silver-based materials that are reported in the development of FPHs include silver nanoparticles (AgNPs) [39], silver nanowires (AgNWs) [40], and silver fractal dendrites (AgFDs) [41]. AgNPs are advantageous for their ease of incorporation into FPHs' formulations and their tunable properties. However, they become cytotoxic at high concentrations, and conductivity decreases when used in bulk compared with the other forms. AgNWs offer superior flexibility and conductivity, making them ideal for large-area applications. But their higher production costs and complex synthesis methods are notable drawbacks [42].

AgFDs present a promising new approach with unique branching structures that can enhance heat transfer. However, their complexity and stability in practical applications need further investigation. Generally, silver exhibits biocompatibility at low concentrations, but it can become cytotoxic at higher levels [43]. Copper also serves as a conductive material, offering good electrical (5.98×10^7 S/m) and thermal conductivity (401 W/m.K), making it suitable for heat generation. However, its susceptibility to oxidation under ambient conditions limits its use compared with silver [44]. Copper can be biocompatible when used appropriately, and copper-based biomaterials are increasingly being utilized in various medical applications [45].

2.1.2. Carbon-Based Conductive Materials

Carbon nanotubes (CNTs) and graphene are frequently used in FPHs [46,47] due to their moderate electrical conductivity, high thermal conductivity, and outstanding tensile strength and because they can be easily printed onto various substrates [48]. CNTs have thermal conductivities ranging from 2000 to 3500 W/m·K, while single-layered graphene exhibits thermal conductivities between 1600 and 4000 W/m·K [49]. Thermal conductivities for carbon-based materials are reported in ranges since the conductivities increase with temperature increments. Electrical conductivity can reach up to 10^7 S/m for pure CNTs and 10^8 S/m for pure graphene [50]. Carbon materials have exceptional biocompatibility due to their inherent chemical stability and low toxicity within biological systems [51]. Compared with CNTs, graphene is free of metallic impurities, making it a more biocompatible material [52]. While both carbon nanotubes and graphene demonstrate consistent heating capabilities in FPHs, the intricate processing and flaws in carbon-based materials hinder the FPHs' conductivity and increase the power requirements for large-area heating [44,53]. Additionally, both CNTs and graphene are costly for production, and scalability could be a challenge [52].

2.1.3. Conductive Polymers

Common conductive polymers used in FPHs include poly(3,4-ethylenedioxythiophene) (PEDOT), polyaniline (PANI), polythiophene, polypyrrole, and polyethylene dioxophene thiophene:polystyrene sulfonate. These materials are favored for certain applications due to their flexibility and good electrical conductivity [24,54]. PEDOT is widely recognized for its excellent electrical conductivity, transparency, ease of production, and stability [55]. Its flexibility allows it to be easily integrated into various substrates. PANI stands out due to its tunable conductivity and ease of synthesis [56]. However, PANI may exhibit variable biocompatibility and potential cytotoxicity under certain conditions [57]. Polythiophene is also a promising material that offers good electrical properties and processability, but its mechanical properties are less favorable compared with PEDOT. Polypyrrole is characterized by its high conductivity and ease of doping, which allows for fine-tuning of its electronic properties. However, like polythiophene, its mechanical flexibility is lower than that of PEDOT [58]. PEDOT:PSS, a combination of PEDOT and polystyrene sulfonate, combines the strengths of both materials, providing improved conductivity and mechanical properties [59].

2.1.4. Hybrid Conductive Materials

Hybrid conductive materials, which combine two or more types of conductive materials, are increasingly utilized to enhance the performance of FPHs. Such combinations leverage the strengths of each material to improve stability, homogeneous heating, mechanical integrity, and power efficiency [60,61]. Examples include silver–carbon composite inks [62] and combinations of silver nanowires (AgNWs) with polymers like PEDOT:PSS [63]. Additionally, self-regulating positive temperature coefficient (PTC) materials, such as the

Loctite ECI series, combine carbon particles, polymer binders, and wax particles to achieve effective thermal regulation [64]. Figure 2 shows the structures and illustrations of various conductive materials.

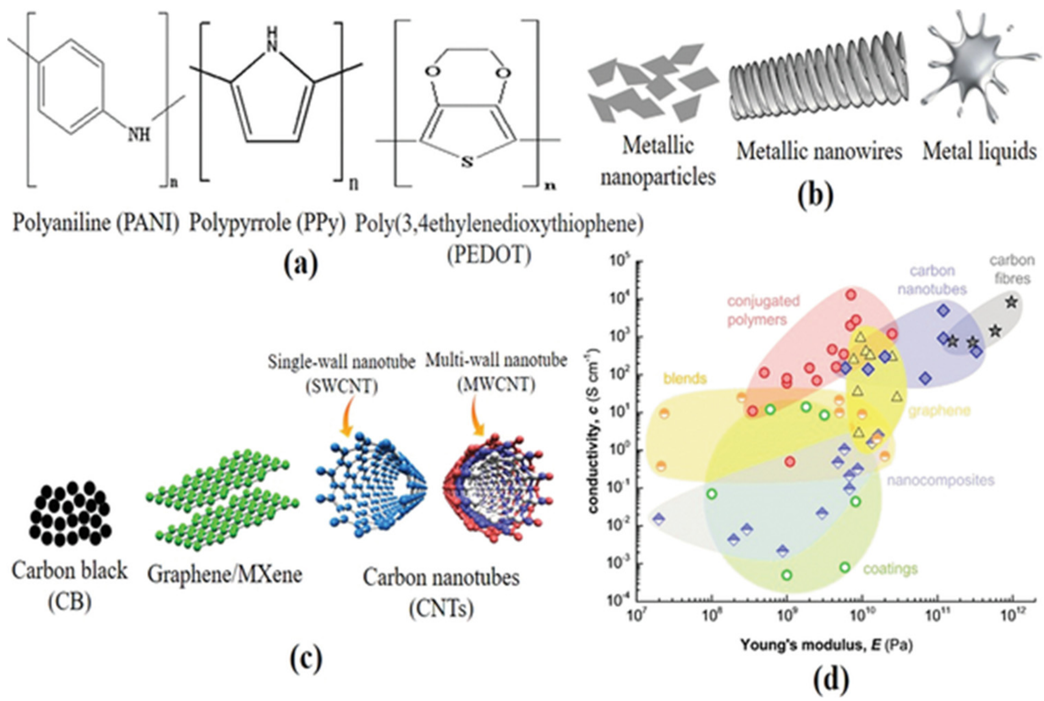

Figure 2. (**a**) Polymeric, (**b**) metallic, and (**c**) carbon-based conductive materials. (**d**) Electrical conductivity vs. Young's modulus of different electroactive fibers based on CNTs (blue diamonds), carbon fibers (gray stars), intrinsically conducting polymers (ICPs) (red circles), blends of conjugated and insulating polymers (orange/white circles), graphene (yellow triangles), nanocomposites of carbon black (CB) (blue/white diamonds), CNTs or graphene embedded in an insulating polymer matrix with (green/white circles) coatings of textile fibers with ICPs, CNTs, or graphene [65].

2.2. Substrate Materials

In printing, a substrate is a base material or a surface onto which the coating or printing is applied [66]. The substrate material is crucial in determining the flexibility, stability, and safety of FPHs [24]. For optimal performance under stretching, bending, and twisting circumstances, the right selection of flexible or stretchable substrates is essential. Common substrate types include flexible plastic films, stretchable elastomers, and textiles.

2.2.1. Flexible Plastic Films

Polyethylene Terephthalate (PET) [67,68] and Polyimide (PI) [69–71] are widely reported flexible plastic films suitable for printed heaters. PET is extensively utilized in the healthcare sector due to its biocompatibility, mechanical strength, high uniformity, and resistance to chemicals and abrasion [72]. PI exhibits excellent resistance to high temperatures, favorable dielectric properties, biocompatibility, and flexibility, making it widely used in medical applications [73].

2.2.2. Stretchable Elastomers

Thermoplastic polyurethane (TPU) [74] and polydimethylsiloxane (PDMS) [75] are notable stretchable elastomers used in FPHs. TPU possesses strong ductility, excellent biocompatibility, great hydrolysis, and abrasion resistance, making it suitable for wearable applications [76,77]. PDMS possesses excellent electrical, optical, and mechanical properties and is widely used for various biomedical applications due to its excellent biocompatibility [78,79]. It possesses a low dielectric constant and high electrical insulation properties along with good elasticity, flexibility, and resilience [80].

2.2.3. Textiles

Textile materials such as cotton, nylon, and polyester are also considered substrates [81]. However, direct deposition and patterning on textile surfaces can be challenging due to the inherent weaves, which can affect resolution, adhesion, and material permeation [81].

3. Flexible Printed Heater Fabrication Methods

The fabrication of FPHs involves the printing of conductive busbars and resistive heating elements on flexible substrates using printing technologies [82]. Printing is a top-down manufacturing technique that creates physical objects by adding specific materials layer by layer. It is pollution-free, customizable, and has a wide range of potential applications in wearable electronics [83]. The widely used printing techniques for FPHs are screen printing, inkjet printing, and role-to-role (R2R) gravure printing.

3.1. Screen Printing

Screen printing is a versatile and user-friendly technology that uses a doctor blade to extrude and transfer inks onto the substrate through a mesh screen. This process enables the formation of conductive circuits on flexible surfaces by selectively applying conductive nanoparticles [84]. The screen-printing setup comprises five essential components: screen, ink, squeegee (doctor blade), a printing table, and a substrate, as illustrated in Figure 3. Additionally, it is equipped with a control panel that allows users to operate the machine, adjusting settings like speed, pressure, and timing. A screen features a specific graphic design etched into a mesh, allowing for precise ink transfer. Conductive inks are utilized to create the desired patterns and circuits.

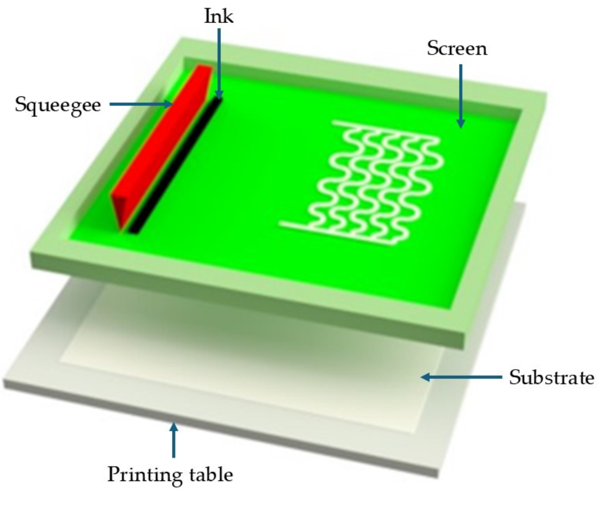

Figure 3. Schematic illustration of screen-printing components.

The squeegee is employed to push the ink through the screen and onto the substrate, which is securely positioned on the printing table during the printing process. Once printing is complete, the substrate undergoes drying or curing to ensure optimal ink adhesion. The screen is then cleaned for reuse, enhancing the efficiency of the overall process. Screen printing offers several advantages, including the ability to cover a large area, high-volume production, cost-effectiveness, and durability of prints. However, it is most suitable for simpler designs that do not require high precision or complexity [85].

3.2. Inkjet Printing

An inkjet printer is a device that creates a conductive path on a substrate by precisely ejecting selected conductive ink through a nozzle in the form of small droplets [86], as illustrated in Figure 4. The ink droplets are ejected from the nozzle by pressure pulses generated by a piezoelectric transducer. As the print head moves across the substrate, it deposits conductive ink droplets in accordance with a predetermined digital design. Following the printing process, it is essential for the conductive ink to dry or cure properly to achieve optimal electrical conductivity and durability. This fully digital printing process is known for its high deposition resolution [87] and offers greater precision compared with other printing techniques. However, inkjet printing requires careful attention to ink specifications and properties; any variations can lead to clogging issues, which may impact equipment maintenance and subsequent experimental results [85].

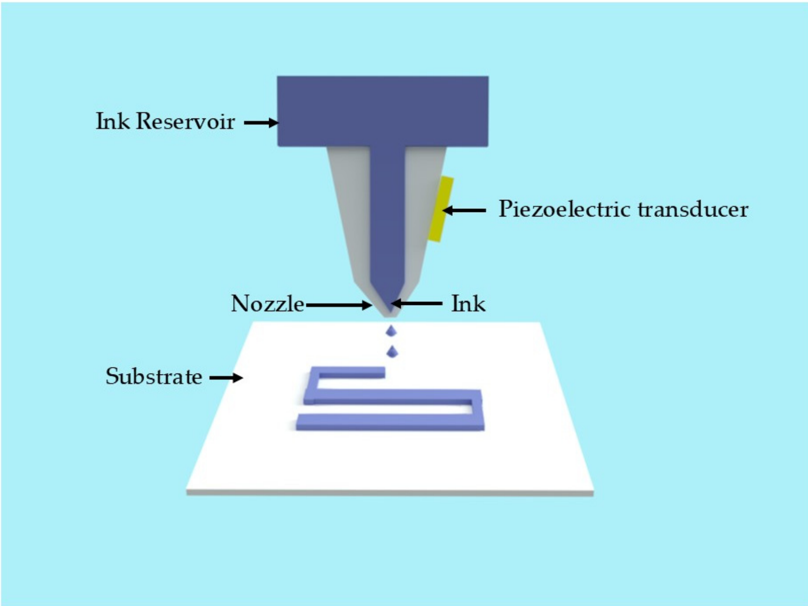

Figure 4. Schematic illustration of the main parts of an inkjet printing machine.

3.3. Role-to-Role Gravure Printing

Role-to-role (R2R) gravure printing is a widely used technique for producing high-quality printed patterns on flexible substrates, particularly in applications such as electronics and packaging [88]. This method involves transferring conductive inks to create intricate designs on a continuous roll of material.

In R2R gravure printing, the desired pattern is designed and etched onto a printing plate, which is mounted on a printing roller as illustrated in Figure 5. The process begins by coating the entire surface of the printing plate with conductive ink. A special scraping method, using a blade, removes ink from the non-patterned areas, leaving the ink only in the cavities of the plate's design.

Once the printing plate is prepared, the substrate is positioned between the printing plate and an impression roller. By applying pressure, the conductive ink is transferred from the plate to the substrate, forming the desired pattern [89]. This impression technique ensures precise and uniform ink application [85]. R2R gravure printing is suitable for a variety of paper applications and is known for its durability and resistance to wear and tear. However, it is important to note that producing the printing plate can be costly, leading to high operational expenses. Additionally, this method is not ideal for low-volume runs due to its setup and material costs [85].

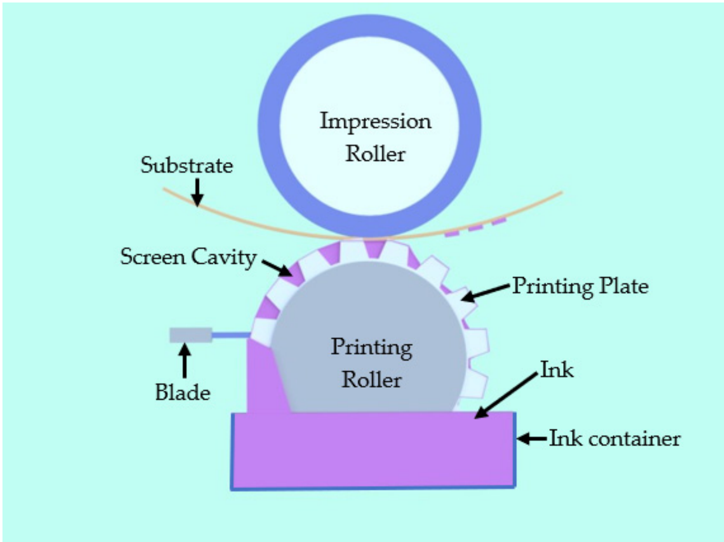

Figure 5. Schematic illustration of the main parts of a gravure printing machine.

4. Flexible Printed Heater Design and Temperature Control Mechanisms

The design of FPHs plays a crucial role in their performance, cost, and safety. Careful attention must be given to the choice of heater trace pattern and the configuration of the resistors, whether arranged in series or parallel connections, as well as the selection of heater ink in the design process. Common trace patterns include horseshoe patterns [90], rectangular meander patterns [62], and membrane heaters [91], as illustrated in Figure 6.

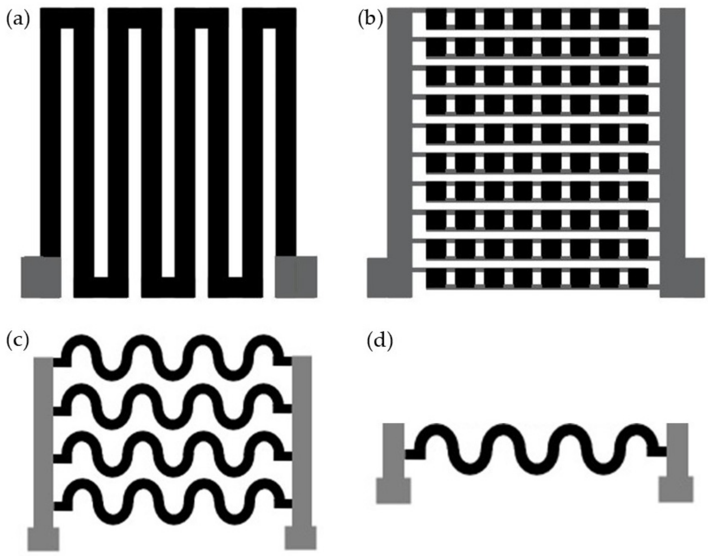

Figure 6. Sample FPH design patterns: (**a**) rectangular meander pattern heater design; (**b**) membrane pattern heater design; (**c**) horseshoe patterns in parallel; and (**d**) single-resistor horseshoe pattern.

The estimation of heater resistance is influenced by several factors, including the sheet resistance of the heater material, the length of the resistor(s), the width and thickness of the resistor trace, and the arrangement of the resistors. Hence, the resistance of the heater is given by Equation (1) [90].

$$R = Rs\frac{L}{w} \quad (1)$$

where Rs is sheet resistance in ohms per square ($\Omega/\square$), L is the length of the resistor in meters (m), and W is the width of the resistor trace in meters (m).

For the horseshoe pattern, the calculation of length involves measuring the lengths of the arcs that connect the resistor from one electrode to the other. The length of the arc is given by Equation (2) [92].

$$\text{Arc Length} = 2\pi r\left(\frac{\theta}{360}\right) \quad (2)$$

where θ is the angle covered by the arc in degrees, and r is the radius of the arc in meters (m).

Once the length of a single arc in a horseshoe resistor is calculated using Equation (2), the total arc length of a single resistor can be determined by multiplying the length of the arc by the total number of curves.

For example, consider the horseshoe pattern depicted in Figure 6c, which consists of four resistors connected in parallel. Each resistor features seven arcs (horseshoes). If the radius of each arc is 3 mm and the angle covered by the arc is 120°, the arc length can be calculated as follows:

$$\text{Arc Length} = 2\pi r\left(\frac{\theta}{360}\right) = (2 \times 3.14 \times 3\text{ mm})\left(\frac{120}{360}\right) = 6.28\text{ mm}$$

To find the total arc length of a single resistor, we multiply the arc length by the number of arcs:

$$\text{Total Arc Length} = 7 \times 6.28 = 43.96\text{ mm}$$

Thus, the total arc length for a single resistor in this configuration is 43.96 mm.

For a horseshoe pattern with multiple resistors connected in parallel (Figure 6c), the total resistor (R_T) of the heater is obtained by using Equation (3) [93].

$$R_T = \left(\frac{1}{R1} + \frac{1}{R2} + \frac{1}{R3} \cdots \frac{1}{Rn}\right)^{-1} \quad (3)$$

where $R1$, $R2$, $R3$, . . . Rn are individual resistances in ohms (Ω).

The power output (P) of the flexible heater is given by Equation (4) [94].

$$P = \frac{(V)^2}{R} \quad (4)$$

where V is the voltage applied to the heater in volts (V) and R is the total electrical resistance of the heater in ohms (Ω).

Now, using the above equations, one can estimate the temperature of the heater at different power supplies. The temperature (T) of an FPH is given by Equation (5) [94].

$$T = \left(\frac{P}{hA}\right) + T_{amb} \quad (5)$$

where P is the power output in watts (W), h is the heat-transfer coefficient of the heater material in watts per square meter per kelvin ($W/m^2 \cdot K$), A is the surface area of the printed heater pattern in square meters (m^2), and T_{amb} is the ambient temperature of the surrounding environment in kelvin (K).

The heat-transfer coefficient of the heater material is given by Equation (6).

$$h = \frac{K}{L} \quad (6)$$

where K is the thermal conductivity of the heater material in watts per meter per kelvin ($W/m \cdot K$) and L is the length of the heater in meters (m).

Taking the heater design from Figure 6c again, if the heater is printed with a heater ink with a sheet resistance of 1700 Ω/□ and thermal conductivity of 0.1 W/m·K, the calculated resistance for a single resistor with a total arc length of 43.96 mm and a width of 2 mm can be determined using Equation (1):

$$R = Rs\frac{L}{w} = (1700\ \Omega/\square)\left(\frac{43.96\ \text{mm}}{2\ \text{mm}}\right) = 37{,}366\ \Omega$$

The total resistance, considering equal values for all four resistors, is 9341.5 Ω. The power output of this heater for a 9V power supply, using Equation (4), is 8.67 mW. Using these values, the estimated equilibrium temperature, using Equation (5), is 68.35 °C.

Temperature control for FPHs can be achieved through external controllers or by designing the heaters to be self-regulating, which automatically limits the temperature to a predetermined value. There are a number of options for external controller-based temperature controls for FPHs, such as On/Off switching, proportional controllers (PCs), and proportional integral derivative (PID) controllers [95].

In the On/Off switch temperature control mechanism, the heater is activated when the temperature falls below the set point and deactivated once the temperature reaches the set point. However, this method can lead to instability, as the temperature may oscillate around the set point rather than maintaining a stable value. A proportional controller works by modulating the power supplied to the heater as the temperature reaches the set point, allowing the heater to reach the desired temperature with less energy. This method is relatively straightforward to implement and offers improved stability compared with the On/Off mechanism. However, it does have limitations, including offset errors and potential instability at higher gain settings [90,96].

A PID controller uses a closed-loop feedback mechanism to control the temperature by finely tuning three gains: proportional, integral, and derivative. This approach minimizes steady-state error and enhances overall stability, resulting in more precise temperature control. However, while it significantly reduces fluctuations, the offset from the set temperature may not always reach zero [95]. All the controller-based temperature monitoring systems rely on feedback from temperature sensors to effectively regulate the heater's temperature, ensuring accurate and responsive adjustments based on real-time data.

Another method of controlling the temperature of FPHs is by using PTC heater materials in their development. PTC materials possess a unique property that causes their resistance to increase as temperature rises. This characteristic enables the development of self-regulating heaters that automatically limit the temperature to a predetermined constant value. As the temperature increases, the heightened resistance restricts the flow of current, effectively preventing overheating and enhancing safety in various applications [82].

5. Medical Applications and Performance Analysis of Flexible Printed Heaters

5.1. Medical Applications

Printed heaters have significant potential for a variety of medical applications. FPHs intended for medical applications must meet several critical requirements to ensure safety, effectiveness, and usability. Biocompatibility, electrical insulation, thermal performance, and environmental stability are among the major requirements. Numerous studies have explored the development of FPHs tailored for healthcare. For instance, Zeng et al. [41] developed a flexible wearable heater measuring 12 cm by 5 cm employing AgFDs printed on a thin PET substrate using screen-printing technology. This device demonstrated excellent heating performance, as illustrated in Figure 7a–c.

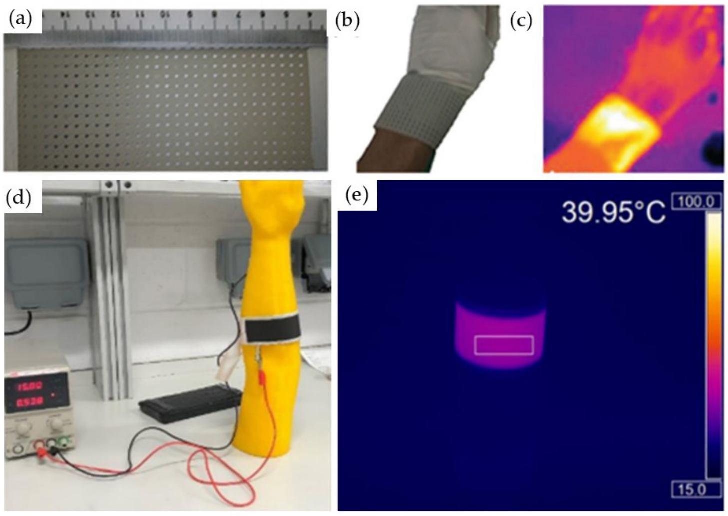

Figure 7. Photograph of a large-area FPH by Zeng et al. [41] (**a**) printed on PET substrate; (**b**) attached to the human wrist; and (**c**) a thermal image of the heater attached to the human wrist (reproduced with permission [41], Copyright 2024 Wiley). An FPH by Claypole et al. [27] (**d**) attached to a 3D prosthetic arm and (**e**) a thermal image of the heater.

Similarly, Pillai et al. [62] developed a wearable thermography device for superficial heat therapy of the wrist. This device utilized silver–carbon composite ink printed on a polyester substrate using screen printing, achieving a steady-state heating temperature of 50 °C at a power density of 55 mW/cm^2. This highlights the potential of FPHs in targeted therapeutic applications.

In another study, Claypole et al. [27] developed a flexible heater measuring 15 cm by 4 cm, utilizing a conductive ink composed of graphite nanoplatelets and carbon black, as shown in Figure 7d,e. This heater was refined and integrated into a wearable garment used by British athletes for body warming during training sessions and at the Tokyo 2021 Olympics [27,97].

Additionally, Liu et al. [23] developed a printed flexible heater based on copper–nickel rose-stem nanowires for portable thermotherapy, achieving a saturation temperature of 172.8 °C under 6 V, demonstrating the potential of FPHs in efficient thermal management applications.

Dr. S. Salaghi's oval-shaped flexible heater was the first to be used in the medical industry as a heating element for the chest, abdomen, and trunk [98]. Currently, several industrial companies are producing FPHs for various medical applications.

Butler Technologies, Inc. has developed flexible wound recovery badges and wearable heating braces designed for back pain and neck problems using TPU substrates [99]. The inherent flexibility and stretchability of the TPU substrate facilitate the seamless integration of these badges, allowing for effective heat application to promote rapid wound recovery. A flexible heater was also used in heating braces to relax muscles and relieve pain [99].

Quad Industries has also introduced smart heating garments, including flexible body warming jackets for patient warming, glove heaters for arthritis or joint pain, and heated socks [100]. These versatile heating products from Quad Industries serve multiple purposes, highlighting their significance not only in medicine but also in everyday applications. Figure 8 showcases various printed heater products developed by these companies.

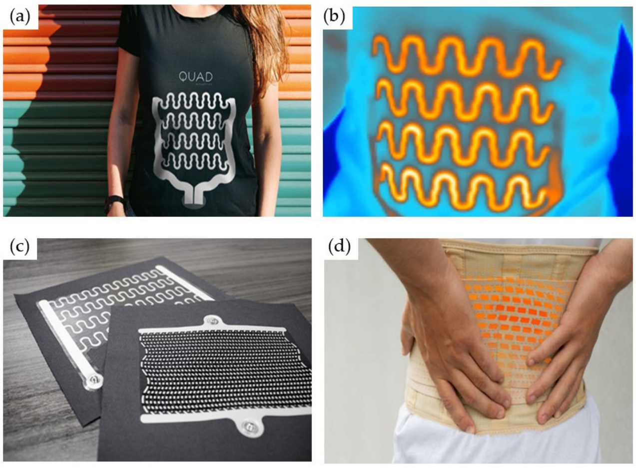

Figure 8. (**a**) Photograph of a textile-integrated FPH and (**b**) its thermal image (developed by Quad Industries [100]). (**c**) Heated wound-recovery badges and (**d**) a heating back brace (developed by Butler Technologies Inc. [99]).

5.2. Performance Analysis

FPHs made from various conductive materials, substrate materials, and designs were evaluated to assess the differences in performance metrics, including power consumption, saturation temperature, response time, and durability.

In a comparison of printed heaters of the same size (60 cm^2), Zeng et al. [41] developed heaters using AgFDs ink screen-printed on PET substrates, achieving a saturation temperature of 38.3 °C under a 5-volt power supply with a rapid response time of 35 s. In contrast, Claypole et al. [27] utilized nanocarbon ink with a silver busbar screen-printed on PET/TPU substrates, resulting in a saturation temperature of 40 °C at a 9-volt power supply but with a slower response time of 120 s. The difference in response time and power consumption can be attributed to the resistance of the conductive materials used, with nanocarbons exhibiting a higher resistance than silver fractal dendrites. This higher resistance limits the flow of current, resulting in a longer time to reach the desired temperature. In addition to this, the heater developed by Claypole et al. [27] was designed as a single-resistor heater, while the heater designed by Zeng et al. [41] has a quadrate mesh structure, which further influences the resistance variations between the two designs.

Another comparison involves heaters of the same size (25 cm^2) developed by Pillai et al. [62] using silver–carbon composite ink screen-printed on a PE substrate and by Li et al. [101], using AgNW conductive ink screen-printed on a PET substrate. The heater developed by Li et al. [101] demonstrated a slightly higher temperature of 55 °C at the expense of high power consumption and slower response time. Conversely, Pillai et al. [62] achieved a temperature of 50 °C with lower power consumption and a faster response time. Again, these performance differences can be traced back to the resistance of the conductive materials and the design patterns of the heaters. The materials with low resistance allow for more efficient current flow, which can lead to quicker heating, and less energy is required to reach the desired temperature. Pillai et al. [62] utilized a rectangular meander pattern, which generally results in higher resistance compared with the mesh design implemented by Li et al. [101].

The performance analysis of the selected FPHs is summarized in Table 1. This analysis reveals significant variations in performance metrics across the various FPHs. The choice of conductive and substrate materials should be decided based on the specific application of the wearable FPHs. For applications requiring quick response times, high saturation temperatures, and low power consumption, silver-based conductive materials could be a suitable choice. Conversely, for applications that require a low saturation temperature, carbon-based conductive materials could be more appropriate.

Table 1. Summary of performance analysis of selected FPHs.

Conductive Material	Substrate	Printing Method	Size (cm^2)	Power Supply (v)	Saturation Temperature (°C)	Response Time (s)	Power (W)	Durability	Ref.
AgFDs	PET	Screen printing	12 × 5	5	38.3	35	-	Stable after 2000 bending cycles	[41]
Silver–carbon composite ink	PE	Screen printing	5 × 5	5	50	60	0.811	Maintained excellent performance under various bending radii	[62]
Nanocarbon ink with silver busbar	PET/TPU	Screen printing	15 × 4	9	40	120	3.78	Temperature decreases with applications of nominal strains	[27]
AgNW conductive ink	PET	Screen printing	5 × 5	4	55	80	1.86	Shows stable performance	[101]
Ag NWs/ PEDOT:PSS	PET	Inkjet printing	5 × 2	6	85	30	-	Less than 20% resistance variation after 10,000 bending cycles	[102]
AgFDs	Textile	Screen printing	3 × 0.4	1	89	100	-	Workable strain range of 105%	[63]
Silver particle-based ink	TPU/PET	R2R gravure printing	9.8 × 4.3	4	78	240	6.67		[103]

6. Challenges

Several challenges must be addressed to achieve the desired outcomes from the FPHs. First, achieving high durability and reliability could be a challenge as wearable FPHs are often subjected to mechanical stresses such as stretching, twisting, and bending. Therefore, selecting appropriate conductive and substrate materials is critical [89]. The materials must be flexible, durable, and low-cost; withstand high temperatures; and exhibit excellent thermal conductivity, oxidation resistance, and electrical insulation properties for effective heat transfer and safe operation. The use of flexible and stretchable substrates is essential for achieving good print resolution and to maintain good mechanical properties under bending, stretching, or twisting conditions.

Second, minimizing power consumption presents another significant challenge, particularly for large-area heaters, which must operate using portable power sources with limited capacities, such as batteries. Designing a heater with low power requirements, selecting designs that allow for lower voltages and higher currents, and integrating efficient energy management systems are vital strategies for reducing overall power consumption.

Third, maintaining uniform heating across the entire surface of the heater is another challenge due to variations in the resistance of printed traces and the conductivity of the heating material. By optimizing resistance distribution, selecting appropriate materials, and choosing proper widths and gaps for internal and external traces, a uniform heat distribution could be achieved for FPHs [104].

Fourth, addressing the issues with sustainability such as life cycle, recyclability, and (bio)degradability of FPH materials could be a challenge. Many flexible heaters are not easily recyclable due to the combination of materials used. Developing materials that can be recycled or disposed of safely is a major hurdle. The development of biodegradable conductive polymers and materials holds promise. In addition to this, developing a strategy to recycle FPHs is crucial.

Lastly, the absence of standardized guidelines and regulatory documents for FPHs for wearable medical applications could make it challenging to bring wearable FPHs into practice in the medical field. The manufacturers and researchers must collaborate closely with regulatory bodies to address issues of safety, efficacy, and quality control. This covers factors including electrical safety, biocompatibility, and adherence to pertinent regulations and standards for medical devices.

7. Future Directions and Opportunities

Based on the review conducted, the researchers have identified some future directions and opportunities that could improve the effectiveness of wearable FPHs for medical applications.

1. Exploring novel conductive materials with excellent electrical and thermal conductivity at a self-regulating temperature close to human body temperature could increase the performance of the wearable heater and its usability for wearable medical applications. Additionally, incorporating biodegradable and recyclable materials in the development of FPHs is essential for addressing sustainability concerns.
2. Exploring the potential integration of shape memory materials and origami-inspired designs holds significant promise for enhancing the adaptability and functionality of FPHs. Shape memory materials can undergo reversible shape changes in response to temperature variations, allowing for adaptive heating solutions that conform to the body's contours for optimal contact and therapeutic effectiveness [105]. Considering a novel origami tessellation approach could also advance FPHs in terms of flexibility and comfort [106,107].

3. Incorporating vital sign monitoring sensors could advance the wearable printed heater to enable measurement of important parameters such as body temperature, oxygen saturation, respiration rate, heart rate, and others for effective medical follow-up.
4. Intelligent textiles and smart heating fabrics that integrate sensors and actuators play a vital role in advancing wearable heaters. Intelligent textiles can adapt to the wearer's body temperature and environmental conditions, providing customized heating solutions that enhance comfort. Smart heating fabrics can adjust heat levels based on the user's physiological responses, optimizing therapeutic effectiveness.
5. Multidisciplinary collaboration among researchers, healthcare professionals, industry, and regulatory bodies will enable the development of a regulatory standard for wearable printed heaters for medical applications.
6. Conducting clinical trials and validation studies to demonstrate the efficacy, safety, and cost-effectiveness of printed heaters for specific medical applications is another critical step in this process. This will facilitate the utilization of FPHs for medical applications.

8. Conclusions

The progress in flexible printed electronics has significantly contributed to the development of FPHs for various applications. Current advancements in FPHs hold great promise for revolutionizing patient care through the development of wearable heaters. By selecting appropriate conductive materials, substrate materials, and fabrication methods, it is possible to develop FPHs that are comfortable, flexible, safe, and efficient for medical applications.

Metal-based conductive materials, such as silver-based inks or pastes, offer excellent electrical and thermal conductivity, making them suitable for applications that require high temperatures and low power consumption. In contrast, carbon-based materials, while consuming more power, provide high resistance and good tensile strength, making them suitable for low-temperature applications. The choice of substrate also plays a critical role, as it depends on the temperature applied and the level of flexibility required for the specific application. Thermoplastic polyurethane is emerging as an excellent option due to its high flexibility, biocompatibility, ductility, and abrasion resistance. Various printing methods, including inkjet, R2R gravure, and screen printing, each offer distinct advantages and limitations in terms of resolution, cost, and production volume.

Despite the promising developments in FPHs, areas of improvement remain, particularly in achieving high heating conversion efficiency, homogeneous heating, mechanical stability, and low power consumption. The use of hybrid conductive materials shows potential for enhancement, but further research is necessary to optimize the materials, integration techniques, biocompatibility, safety, and the incorporation of vital sign monitoring sensors, making these technologies more practical for wearable health applications. Overall, FPHs have great potential to revolutionize patient care by providing personalized, efficient, and comfortable heat therapy.

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