Review

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

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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 (FPH) 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, and power efficiency are desirable for stand-alone medical thermotherapy applications. This paper reviews recent advancements in the design of FPHs for wearable thermal applications. Materials for FPHs, fabrication methods, designs, temperature control mechanisms, medical applications, and performance analysis of specific FPHs are all thoroughly discussed. Materials for FPHs, such as conductive and substrate materials, have received special attention, along with the heater design parameters. Finally, the challenges and future directions for developing FPHs for wearable medical applications are addressed.

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

1. Introduction

The use of heat for medical purpose has a long history, dating back to primordial times. Sandbathing has been used in ancient Rome for the treatment of asthma, arthritis, chronic pain and congestion in breast or abdomen [1]. In the same way, Egyptians buried individuals in hot sand to relieve joint pain and obesity. Hippocrates used ceramic bowls filled with hot water to ease congestion [2,3].

In present time, heat is typically used in hospitals, nursing homes, and at home by healthcare professionals and patients for pain treatment, warming owing to low body temperature, facilitating procedures like intravenous line (IV) insertion, providing comfort and relaxation and other therapeutic applications [3,4]. Heat therapy, a non-pharmacological treatment method, is the application of external heat to a specific body area to increase tissue temperature to alleviate symptoms associated with specific conditions[2,5,6].

For instance, heat therapy is used for low back pain treatment [7], treatment of musculoskeletal pain [8], and malignant tumor [9]. It is widely used in the treatment of neonatal hypothermia [10], a reduction in body temperature in neonates below 36.5 °C resulting in a high burden of neonatal mortality, at healthcare facilities [11,12].

The main goal of heat therapy is to expand blood capillaries, increase blood flow to the affected area, and promote healing by providing nutrients and oxygen [2]. Heat therapy can be dry or moist, and it can be applied directly or indirectly to the body. Dry heat therapy uses dry heat sources such as electric heating pads, hot packs, heating lamps, and ovens while moist heat therapy uses moist heat sources such as sitz baths, hot water baths, chemical packs, and moist heating pads [3,13]. But there are several reports of burn injuries due to the use of these heat application methods on patients skin [14–17].

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; hence, it is not suitable for long-term wearable applications [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 in textiles [20–22]. Polymer-based (conductive yarn-based) heaters are an advancement over metal-based (traditional wire-based) heaters in terms of flexibility and safety [19]. These heaters are flexible and operate at low power supply, but there are problems with heat uniformity due to the thermal conductivity of the conductive yarns, comfortability, and decreased durability after subjecting them to various washing cycles [19,23].

Recent advancements in the area of flexible printed electronics, paved the way for development of more flexible, comfortable and efficient printed heaters for various applications [24]. FPHs are a heating technology that utilizes flexible printed electronics technology to create electrically conductive patterns on various flexible substrates. This works by the Joule heating principle in which heat is produced when electrical current flows through a heat-generating conductor [25]. Compared to traditional wired heaters with rigid and bulky wires, printed heaters are flexible, comfortable, suitable for wearable applications, can be fully customized, and their production is easily scalable to high volumes [26,27].

To be used for wearable applications, FPHs need to deliver uniform heat utilizing a portable power supply, have a rapid response time, great repeatability, and biocompatibility [28]. Wearable printed heaters should prioritize low voltage (for safety, which means low resistance), high heat transfer coefficient, and high heating conversion efficiency within their effective area [29]. However, achieving high heat conversion efficiency highly depends on the choice of conductive material, substrate material, fabrication method, and integration of the heater [30].

This paper discusses the latest developments in FPHs. The first section discusses the materials used in FPHs, including conductive and substrate materials. The second section covers fabrication methods such as screen printing, inkjet printing, and gravure printing. The third section focuses on FPH designs and temperature control mechanisms for safe operation of the heater. Following that, the performance of selected FPHs developed by researchers is evaluated, and the applications and use cases of FPHs for wearable medical applications are discussed. Finally, the challenges, solutions, and future directions of developing FPHs for wearable medical applications are addressed.

2. Materials for Flexible Printed Heaters

FPHs work based on 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 made of conductive material and flexible substrate material. The conductive material is printed on the flexible substrate based on the predefined heater patterns, either as series or parallel resistors (or a combination thereof). The electrodes on both ends of the heater patterns are also printed using conductive material to supply electric power to the heater, as shown in Figure 1.

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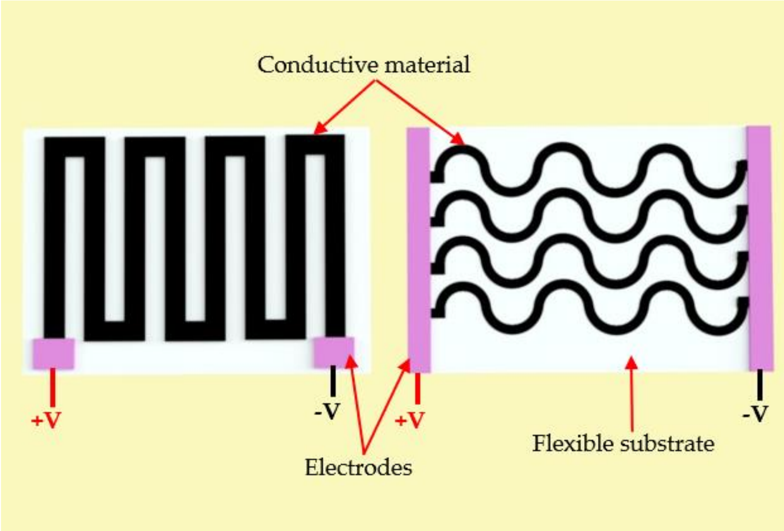

Figure 1. Illustration of FPH components using sample heater trace patterns.

2.1. Conductive Materials

Conductive materials are materials that allow the flow of current through them [31]. They also act as an electric resistor and thus can be used as a heating element [32]. Conductive materials used for FPHs are commonly categorized as metallic, carbon-based materials, conductive polymers, and hybrid conductive materials. The manufacturing of printed heaters has given considerable attention to metal based materials because of their low sheet resistance and mechanical flexibility [33,34]. Silver is the most popular conductive metal used in printed heaters due to its excellent electrical conductivity (6x10^7 S/m) [5,25,35,36]. It also offers low resistance and high thermal conductivity (429 W/m.K), which makes it effective for generating heat [37]. Some of the silver-based materials that are reported in the development of FPHs include silver nanoparticles (AgNPs) [38], silver nanowires (AgNWs) [39], and silver fractal dendrites (AgFDs)[40]. Copper, on the other hand, offers good electrical (5.98 x10^7 S/m) and thermal conductivity (401 W/m.K), making it suitable for heat generation, but its instability against oxidation under ambient conditions limits the use of copper compared to silver [41]. Carbon-based materials such as carbon nanotubes (CNTs) and graphene are also frequently used in FPHs [42,43]. Carbon materials have moderate electrical and thermal conductivity, outstanding tensile strength, and can be easily printed onto various substrates [44]. High thermal conductivities in the range of 2000–3500 W/m.K for carbon nanotubes and 1600–4000 W/m.K for single-layered graphene were reported [45]. Thermal conductivities for carbon based materials are reported in ranges since the conductivities increase with temperature increments. On the other hand, the electrical conductivity can be as high as 10^6 to 10^7 S/m for pure CNT and 10^8 S/m for pure graphene [46]. 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 [42,47]. Conductive polymers, such as poly(3,4-ethylenedioxythiophene) (PEDOT), polyaniline (PANI), polythiophene, polypyrrole, and polyethylene dioxophene thiophene:polystyrene sulfonate, are sometimes used in printed heaters for certain applications due to their flexibility and good electrical conductivity [25,48]. Single material-based conductive materials (metals, carbons, and polymers) have their own limitations on stability, homogeneous heating, mechanical stability, and power consumption. These limitations of using single material conductive element can be improved by the use of hybrid conductive materials, such as the combination of two or more single conductive materials, for the development of FPHs [49,50]. The combination between silver and carbon to form silver-carbon composite ink [51] and between silver nanowires (AgNWs) and polymers (PEDOT:PSS) [52] have been among the hybrid conductive inks used in FPH development, as reported in the literature. Besides this, self-regulating positive temperature coefficient (PTC) materials are developed through the combination of different conductive materials and other constituents. PTC inks such as Loctite ECI 8001, Loctite ECI 8090, Loctite ECI 8120, and Loctite ECI 8060HV developed by Henkel which are combining carbon particles, polymer binders, and wax particles are some of the examples [53]. Figure 2 shows the structures and illustrations of various conductive materials.

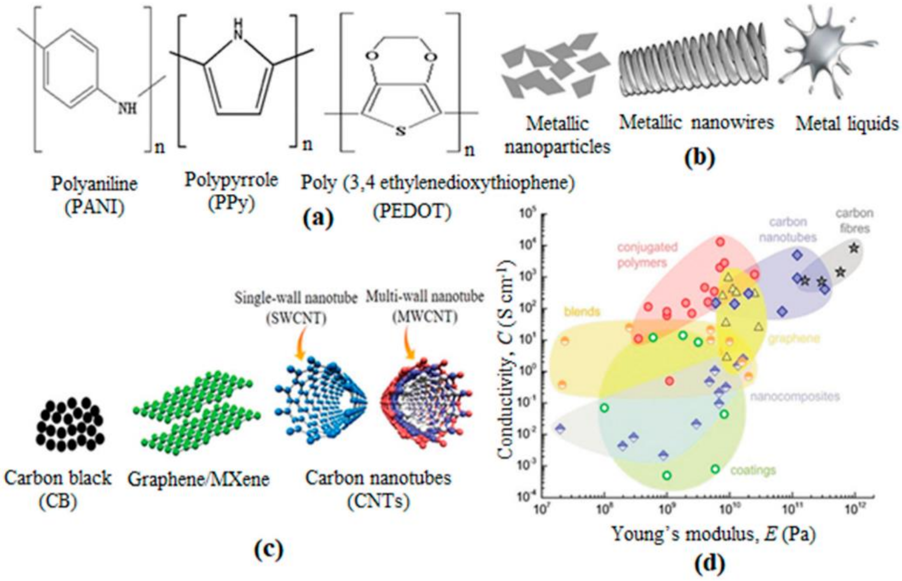

Figure 2. (a) Polymeric, (b) metallic, and (c) carbon-based conductive materials. (d) Electrical conductivity vs. Young's modulus of different electroactive fibres based on CNTs (blue diamonds), carbon fibers (gray stars), ICPs (red circles), blends of conjugated and insulating polymers (orange/white circles), graphene (yellow triangles), nanocomposites of CB (blue/white diamonds), CNTs or graphene embedded in an insulating polymer matrix and (green/white circles) coatings of textile fibers with ICPs, CNTs, or graphene [54].

2.2. Substrate Materials

In printing, a substrate is a base material or a surface to which the coating or printing is applied [55]. The substrate material used governs the flexibility, stability, and safety of FPHs [25]. To provide stable heating performance for FPHs under stretching, bending, and twisting circumstances, the right selection of flexible or stretchable substrates is essential. Flexible plastic films, stretchable elastomers, and textiles are the types of substrates considered in the development of FPHs. Polyethylene Terephthalate (PET) [56,57] and Polyimide (PI) [58–60] are widely reported as flexible plastic films for printed heaters. Thermoplastic polyurethane (TPU) [61] and polydimethylsiloxane (PDMS) [62] are widely reported as stretchable elastomers used for FPHs. TPU possesses strong ductility, excellent biocompatibility, great hydrolysis, and abrasion resistance, making it suitable for wearable applications [63,64]. On the other hand, textiles such as cotton, nylon, and polyester were considered as substrate materials [65]. However, direct deposition and patterning on textile surfaces are complicated by the weave associated with the textile. In addition, resolution, adhesion, and permeation of surface material are influenced by the weave [65].

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 [66]. 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 [67]. The most commonly 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 simple, easy-to-use, and highly customizable technology that uses a doctor blade to extrude and transfer conductive inks onto the substrate via a mesh of the screen printing plate's graphic section, allowing the formation of conductive circuits on soft surfaces by selectively coating conductive nanoparticles [68]. It has five important components: a screen printing screen, ink, squeegee or doctor blade, a printing table, and a substrate, as shown in Figure 3. A screen printing screen incorporates a specific graphic design engraved on it in the form of a mesh. A printing table is used to position and hold the substrate under the screen printing plate during printing. Screen printing has several advantages, including the capacity to cover a large area, produce high volume, be inexpensive, and make long-lasting prints. But it is only suitable for simple designs that requires low print accuracy and low complexity [69].

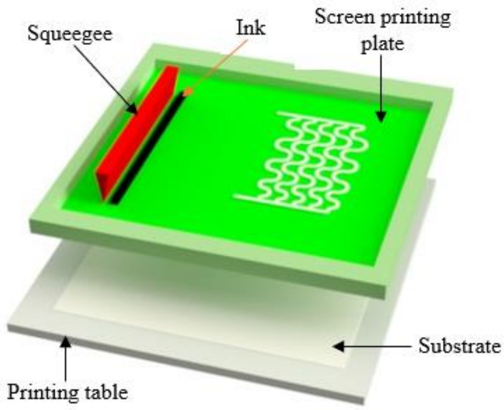

Figure 3. Schematic illustration of screen printing components.

3.2. Inkjet Printing

An inkjet printer is a device that creates a conductive path on a substrate by injecting selected conductive ink through a nozzle in the form of small droplets [70] as shown in Figure 4. The droplets of ink through the nozzle are derived by the pressure pulse generated by a piezoelectric transducer. It is a fully digital printing process that offers high deposition resolution [71]. Inkjet printing is more precise than other printing methods. However, the method necessitates strict attention to ink specifications and properties, since any variations can cause clogging issues, affecting equipment maintenance and subsequent experiments [69].

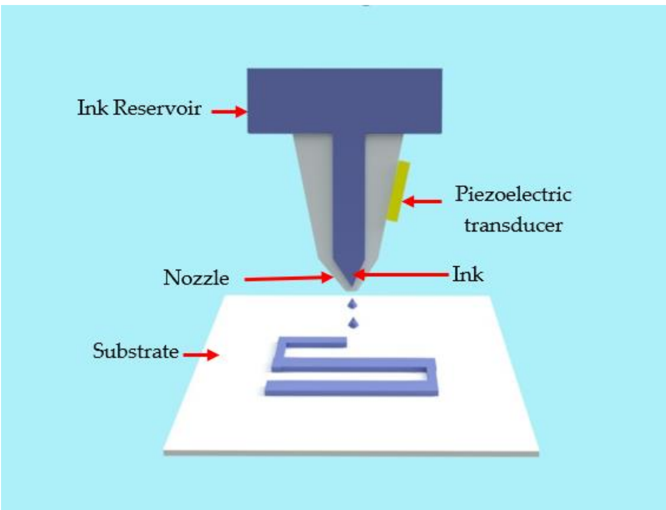

Figure 4. Schematic illustration of main parts of Inkjet printing machine.

3.3. Role-to-Role Gravure Printing

In R2R gravure printing, the desired pattern of the heating element is designed and displayed on a printing plate, which is fixed on a printing roller as shown in Figure 5. The flexible heater is then produced by transferring the relevant conductive ink from the printing plate to substrates with a suitable impression procedure in which the substrate is placed between the printing plate and impression roller [72]. In this process, the entire surface of the printing plate is coated with conductive ink, and then the ink is removed from the blank areas using a special scraping method (using a blade), leaving the ink to remain in the screen cavity of the printing plate only, as shown in Figure 5. Finally, the inks in the screen cavity of the printing plate will be transferred to the substrate by applying a certain pressure using an impression roller [69]. It is used for a wide range of paper applications and is resistant to wear and tear; however, making the printing plate is expensive, the printing cost is high, and it is not suitable for low volume runs [69].

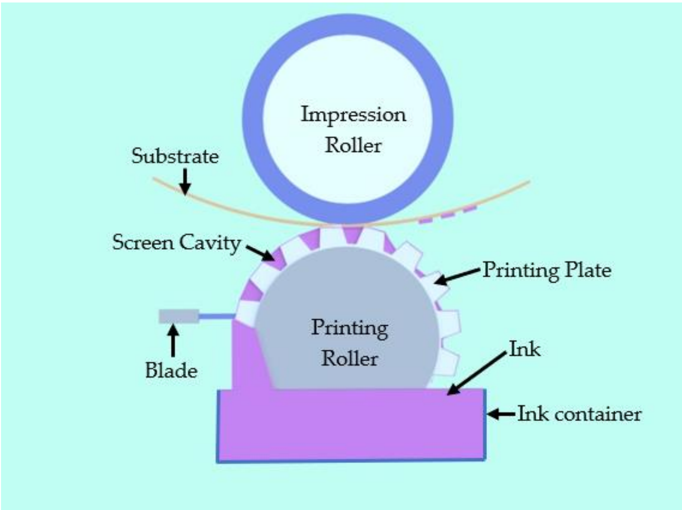

Figure 5. Schematic illustration of main parts of gravure printing machine.

4. Flexible Printed Heater Design and Temperature Control Mechanisms

The design of FPHs plays a crucial role in the performance, cost, and safety of the heater. The choice of heater trace pattern and the arrangement of the resistors, either as series or parallel connections, must be given careful attention together with the selected heater ink in the design process. Horseshoe patterns [73], rectangular meander patterns [51], and membrane heaters [74] as shown in Figure 6, are mainly used in the design of printed heater trace patterns.

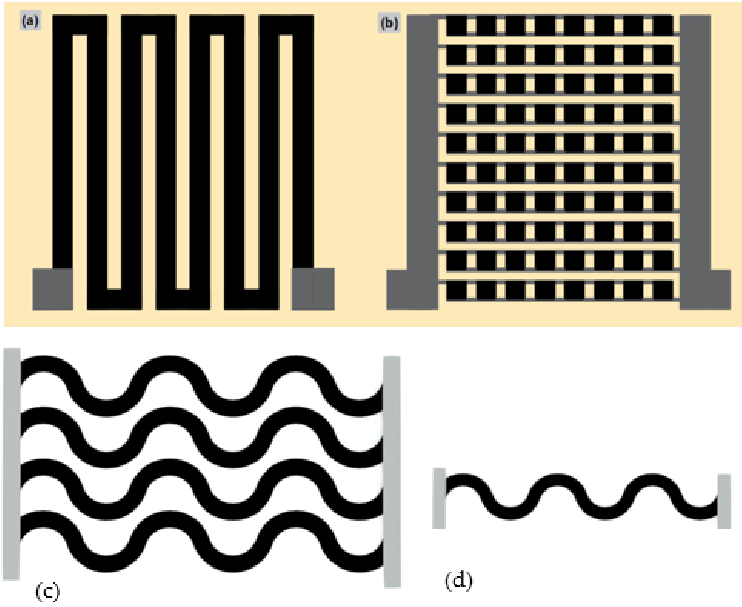

Figure 6. Sample FPHs design patterns: a) Rectangular meander pattern heater design and b) membrane pattern heater design, c) Horseshoe patterns in parallel and d) Single resistor horseshoe pattern.

The estimation of heater resistance depends on the sheet resistance of the heater material, the length of resistor (s), resistor trace width, thickness and arrangement of resistors. Hence, the resistance of the heater is given by Equation (1) [73].

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

where Rs is sheet resistance in ohms per square (Ω/□), 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 length calculation considers the length of the arcs involved in the resistor from one electrode end to the other electrode end. The length of the arc is given by Equation (2) [75].

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

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 single horseshoe resistor is obtained by Equation (2), the total arc length of a single resistor is obtained by multiplying it with the total number of curves.

For example, if we take a horseshoe pattern in Figure 6c, it consists of 4 resistors connected in parallel. Each resistor has six (6) arcs (horseshoes). Suppose the radius of the arc is 3 mm, and the angle covered by the arc is 120^0. Thus, the arc length according to Equation (2) equals (2x3.14x3mm)(120/360) = 6.28 mm. Then the total arc length of a single resistor is obtained by multiplying the arc length by six (6): 6x6.28 = 37.68 mm.

For a horseshoe pattern with multiple resistors connected in parallel, the total resistor (R_T) of the heater is obtained by using Equation (3) [76].

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

where R1, R2, R3…R_N are individual resistance in ohms(Ω).

The power output (P) of the flexible heater is given by Equation (4) [77].

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

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).

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Now, using the above equations, one can estimate the temperature of the heater at different power supplies. The temperature (T) of a FPH is given by Equation (5) [77].

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

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

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

$$h = \frac{K}{L} \tag{6}$$

where K is the thermal conductivity of the heater material in watts per meter per kelvin (W/m.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 value of a single resistance for a total arc length of 37.68 mm and a width of 2 mm according to Equation (2) will be 32,028 Ω. The total resistance, considering equal values for all four resistors, will be 8,007 Ω. The power output of this heater for 9V power supply, according to Equation (4), will be 10.12 mW. Using these values, the estimated equilibrium temperature, according to Equation (5), will be 75.6 ^{0}C.

Temperature control for FPHs could be performed through external controllers, or the heaters could be designed as self-regulating heaters that limit the temperature to a predefined value. There are a number of options for external controller-based temperature control for FPHs, such as On/Off switching, proportional controllers (PD), and proportional integral derivative (PID) controllers [78]. In the On/Off switch temperature control mechanism, the heater will be turned ON when the temperature is below the set point, and it will turn OFF when the temperature reaches the set point and it is not stable. A proportional controller works by reducing the power supplied to the heater as the temperature reaches the set point, allowing the heater to reach the desired temperature with less energy. It is simple to construct and has higher stability, but the offset error and instability at higher gain are the limitations of proportional control [78][79]. A PID controller uses a closed-loop feedback mechanism to control the temperature by properly tuning the three gains: proportional, integral, and derivative. It provides the least steady-state error with stable performance, but the offset from the set temperature never reaches zero [79]. All the controller-based temperature monitoring systems require feedback from a temperature sensor to control the temperature. Another way of controlling the temperature of a FPH is by using positive temperature coefficient (PTC) heater material for the development of the heater. PTC materials enable the development of a self-regulating heater that limits the temperature to a certain constant value due to its special property of increasing its resistance in response to increasing temperature, which in turn limits the flow of current [66].

5. Medical Applications and Performance Analysis of Flexible Printed Heaters

5.1. Medical Applications

It is evident that printed heaters could be utilized for numerous medical applications. So far, different studies have been conducted on the development of FPHs for medical applications. For instance, Zeng et al. [80] developed a flexible wearable heater with a size of 12cm by 5cm by printing silver fractal dendrites (AgFDs) on a thin polyethylene terephthalate (PET) substrate using screen printing technology for potential heating of the human body, exhibiting excellent heating performance, as shown in Figure 7 (a-c). Pillai et al. [51] developed a wearable thermography device for superficial heat therapy of the wrist using silver-carbon composite ink printed on a polyester substrate using screen printing technology and achieved a steady-state heating temperature of 50 ^{o}C at 55 mW/cm^2. Claypole et al.[29], on the other hand, developed a flexible heater sized 15 cm by 4 cm utilizing a conductive ink composed of graphite nanoplatelets and carbon black, as shown in Figure 7 (d &e). The heater was refined and integrated into a wearable garment that was used by British athletes for body warming during training sessions and in Tokyo in 2021 [29,81].

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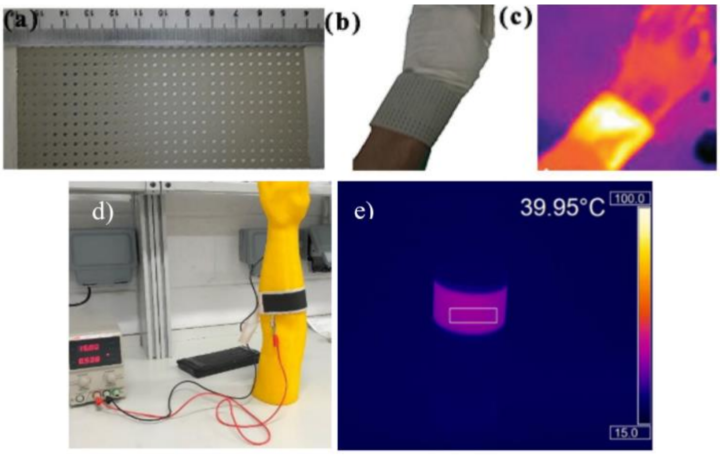

Figure 7. Photograph of a large-area FPH by Zeng et al. [80] a) printed on PET substrate; b) attached to the human wrist; and c) a thermal image of the heater attached to the human wrist (reproduced with permission, Copyright 2024 Wiley). And a FPH by Claypole et al. [29] d) attached to a 3D prosthetic arm, and e) a thermal image of the heater.

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 the rest of the body's trunk [82]. Currently, there are some industrial companies producing FPHs for different medical applications. Buttler Technologies, Inc. has developed flexible wound recovery badges and wearable heating braces for applications of back pain and neck problems using TPU substrates [83]. The flexibility and stretchability of the TPU substrate allowed for easy integration with badges to apply heat for fast wound recovery. A flexible heater was also used in heating braces to relax muscles and relieve pain [83]. Quad Industries has also developed smart heating garments in the form of flexible body warming jackets for patient warming, glove heaters for arthritis or joint pain, and heated socks [84]. These flexible heating products from Quad Industries can also be used for various purposes, in addition to their significance in medicine. Figure 8 shows some of the FPH products from the industries.

Figure 8. a) photograph of a textile integrated FPH and b) its thermal image (developed by Quad Industry [84]). c) heated wound recovery badges; and d) a heating back brace (developed by Butler Technology Inc. [83]).

5.2. Performance Analysis

FPHs made from various conductive materials, substrate materials, and designs were chosen and evaluated to determine the differences in performance in terms of power consumption, saturation temperature, response time, and durability. Comparing the printed heaters of the same size (60 cm^2) developed by Zeng et al. [80] using silver fractal dendrites (AgFDs) ink screen printed on PET substrates and Claypole et al. [29] using nanocarbon ink with silver busbar screen printed on

PET/TPU substrates, the former heater was able to achieve a saturation temperature of 38.3°C under a 5 volt power supply and a fast response time of 35 seconds, while the latter achieved a saturation temperature of 40°C using a 9 volt power supply and a slower response time of 120 seconds. The difference in response time and power consumption observed here is due to the difference in resistance of the conductive materials used, such that nanocarbons have a higher resistance than silver fractal dendrites. In addition to this, the heater developed by Claypole et al. [29] was designed as a single resistor heater, while the heater designed by Zeng et al. [80] has a quadrate mesh structure, which also has a further effect on the resistance variations between the two heaters. When we see another comparison between heaters of the same size (25 cm^2) developed by Pillai et al. [51] using silver-carbon composite ink screen printed on polyester (PE) substrate and Li et al. [85] using silver nanowires (AgNW) conductive ink screen printed on PET substrate, the heater developed by Li et al. [85] demonstrated a slightly higher temperature of 55 °C at the expense of high power consumption and slower response time, while the heater developed by Pillai et al. [51] was able to achieve a close temperature of 50°C with less power consumption and faster response time. Again, in addition to the resistance difference between the conductive materials used, the heater design patterns of the two heaters have their own effect on the performance of the two heaters since Pillai et al. [51] used a rectangular meander pattern heater design, which gives higher resistance compared to the mesh design used by Li et al. [85]. The details of the performance analysis on some selected FPHs are summarized in Table 1. From this performance analysis, a variation in performance metrics across various FPHs was observed. The choice of conductive materials and substrate materials could be decided based on the specific application of the wearable FPHs. For applications that need quick response times, high saturation temperatures, and low power consumption, silver-based conductive materials could be a suitable choice. For applications that require a low saturation temperature, carbon-based conductive materials could be suitable.

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 x 5	5	38.3	35	-	Stable after 2000 bending cycles	[80]
Silver-Carbon composite ink	PE	Screen printing	5 x 5	5	50	60	0.811	Maintained excellent performance under various bending radius	[51]
Nanocarbon ink with silver busbar	PET/TPU	Screen printing	15 x 4	9	40	120	3.78	Temperature decreases with applications of nominal strains	[29]
AgNW conductive ink	PET	Screen printing	5 x 5	4	55	80	1.86	Shows stable performance	[85]
Ag NWs/ PEDOT:PSS	PET	Inkjet printing	5 x 2	6	85	30	-	Less than 20% resistance variation after 10,000 bending cycles	[86]
AgFDs	Textile	Screen printing	3x0.4	1	89	100	-	Workable strain range of 105%	[52]
Silver particle-based ink	TPU&PET	R2R gravure printing	9.8 x 4.3	4	78	240	6.67		[87]

6. Challenges

There are several challenges to achieving the desired outcomes from the FPHs. First, achieving high durability and reliability could be a challenge as wearable FPHs could be subjected to mechanical stresses such as stretching, twisting, and bending. For this, the selection of the right

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conductive materials and substrate materials for FPHs is critical [72]. The material has to be flexible, durable, low-cost, withstand high temperatures, and exhibit excellent thermal conductivity, oxidation resistance, and electrical insulation properties for effective heat transfer and safe operation. The selection of flexible and stretchable substrates is ideal for excellent print resolution and to maintain good mechanical properties under bending, stretching, or twisting conditions. Second, minimizing power consumption is another challenge, especially for large area heaters, as wearable heaters are required to operate using portable power sources with limited power, such as batteries. Designing a heater with low power consumption and integrating efficient energy management systems is ideal to reduce 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 [88]. Finally, the lack of standard 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.
2. 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.
3. Multidisciplinary collaboration among researchers, healthcare professionals, industry, and regulatory bodies to enable the development of a regulatory standard for wearable printed heaters for medical applications. 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 and advancement in the development of flexible printed electronics have played a major role in the development of FPHs for various applications. The current progress in the development of FPHs holds great promise for revolutionizing patient care through the development of wearable heaters. A FPH that is comfortable, flexible, safe, and efficient could be developed for wearable medical applications with the proper choice of conductive material, substrate material, and fabrication method. Metal-based conductive materials, such as silver-based inks or pastes, provide excellent electrical conductivity and high thermal conductivity and are suitable for applications that require high temperatures and low power consumption. Carbon-based materials have high resistance and good tensile strength. Even though carbon-based materials consume more power, they are suitable for applications that require low temperatures. The choice of substrate materials depends on the temperature applied and the level of flexibility required for the particular application. Among the reported substrates, thermoplastic polyurethane is an excellent choice for wearable medical applications due to its high flexibility, biocompatibility, ductility, and abrasion resistance. Inkjet printing provides high-resolution printing and is more precise than screen printing and R2R gravure printing, but its wide use could be limited to the requirement to pay attention to ink specifications and properties. R2R gravure printing is suitable for large-volume printing but expensive for low-volume printing due to the high cost of making the screen plate. Screen printing, on the other hand, has the capacity to cover a large area, produce a high volume, be inexpensive, and make long-lasting prints.

Despite the promising results of the current developments of FPHs, there are areas of improvement that require attention, such as achieving high heating conversion efficiency, homogeneous heating, mechanical stability, and low power consumption. The use of hybrid conductive materials shows some improvement in this regard, but further research has to be conducted to optimize the materials, integration techniques, biocompatibility, safety, and the addition of vital sign monitoring sensors to make them more practical for wearable health applications. With this, the FPHs have great potential to revolutionize patient care by providing personalized, efficient, and comfortable heat therapy.

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