Liquid Metal Enabled Biodevices

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Biodevices are crucial for monitoring vital physiological signals, managing chronic health conditions, developing artificial organs for assisting people with disabilities, and conducting various clinical and surgical procedures. However, existing biodevices are mostly composed of rigid components, which can cause discomfort to the user, whereas the high stiffness of implants is known to be the major cause of inflammation and scarring. Gallium-based liquid metals are intrinsically soft and possess desirable properties, including low toxicity, high conductivity, and deformability, which make them ideally suited for developing soft, deformable, reconfigurable, and healable biodevices. Herein, recent advancements in the emerging field of liquid-metal-based biodevices are discussed. This includes a description of the properties of gallium-based liquid metals which make them so distinct from conventional materials, a brief outline of various techniques devised for fabrication of liquid-metal-based devices/structures, and an overview of the diverse range of wearable or implantable liquid-metal-enabled biodevices. The outlook and challenges are also discussed.

1. Introduction

Advances in smart digital healthcare have driven innovations in soft and deformable biodevices, including sensors, prostheses, and surgical tools, which have significantly revolutionized precision and personalized medicine for applications in fitness tracking, health monitoring, human–machine interfaces, and disease forecasting.1–4 There are various different implantable and wearable biodevices, which all must effectively capture physiological data and/or aid the ability of the body to carry out certain functions. Biodevices range from commercialized examples such as heartbeat sensors, hearing aids, and pacemakers,5,6 to recently advanced wearable biosensors for body motion and biofluids analysis.7–9 The need of transducing biological interactions into readable signals entails the necessity to develop soft and deformable bioelectronic devices that are wearable, ingestible, or implantable. In recent years, such a fast-growing interdisciplinary field of research has attracted extensive interest from device engineers and materials scientists. In contrast with traditional rigid electronics, soft and deformable biodevices can efficiently capture high-quality signals of patients unobtrusively due to their elastic and conformal characters. Rigid wearable devices can be uncomfortable to the wearer, and the high stiffness of implantable devices has been shown to be a major cause of foreign body reaction, causing inflammation and scarring.10,11 It would be beneficial to use soft and stretchable biodevices instead, to reduce these negative effects. To make flexible electronic circuits in biodevices, one commonly used strategy is to embed intrinsically soft electrical conductors and interconnects in elastomeric materials.

Metals that are in a liquid state at/near room temperature uniquely offer both metallic and fluidic properties, thus, providing the best combination of conductivity and deformability of any known materials and offer great potential as a way to create a range of soft, deformable biodevices. Gallium and its alloys such as eutectic gallium indium (EGaIn) and gallium indium tin (Gallinstan) are the liquid metals focused on here. These liquid metals are low-toxicity alternatives to mercury, so are therefore relatively safe to use in biomedical devices and other biomedical applications.12 For example, liquid metals have been used as a carrier for drug delivery,13 and exploited for enhanced cancer therapy,14 among other uses, as comprehensively reviewed by Yan et al.15 Liquid metals have also been used to create an extensive range of flexible electronic components and devices. Examples include memristor-like devices,16 strain sensors,17 and antennas,18 as extensively reviewed by Dickey.19 See a recent review by Kim et al.20 for a discussion of smart, stretchable electronics using a broader range of materials.

This Review seeks to highlight exciting advances in the recent developments of gallium-based liquid metals within the context of wearable, implantable, and other biomedical devices. Harnessing the unique and desirable properties of liquid metal, such as low toxicity, high electrical, and thermal conductivities, and being able to form a functional oxide layer, researchers have developed a series of innovative patterning methods that lead to the fabrication of a wide range of intelligent functional wearable and implantable biodevices (Figure 1). This includes smart

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sensors such as integrated electronic tattoos that are able to carry out electrocardiogram (ECG) measurements, stimuli-responsive electronic blood vessels that are capable of electroporation and endothelization, robotic eyes that can be used in prosthetics, and flexible eye tracking systems, among others. These intelligent platforms show extraordinary opportunities for applications in human–machine interface, soft robotics, smart prosthetics, and medical equipment. Finally, this Review offers a perspective on the opportunities and challenges for liquid-metal-enabled biodevices in future applications as research progresses toward clinical outcomes.

2. Properties of Liquid Metals

Gallium (Ga) and its alloys such as EGaIn (75 wt% Ga, 25 wt% In) and Galinstan (68 wt% Ga, 22 wt% In, and 10 wt% tin) have many beneficial properties, which can be utilized to create improved biological devices.

2.1. Bulk Properties

Ga has a high thermal conductivity (29.3 Wm\(^{-1}\) K\(^{-1}\)) and a high electrical conductivity (6.73 \(\times\) 10\(^{6}\) S m\(^{-1}\)). Liquid Ga also has a low viscosity (\(\approx 2 \times\) water). It has a negligible vapor pressure, which means there is no danger of inhalation. All of these properties are inherited by Ga alloys. Ga has a low melting point of 29.76 °C, whereas EGaIn and Galinstan have even lower melting points of 15.7 and 11 °C, respectively. These compelling properties of liquid metal create conductors that provide the best combination of stretchability and conductivity. Ga and its alloys also exhibit supercooling, being metastable liquids at temperatures below melting point. They also have a high surface energy value of \(>400\) mN m\(^{-1}\), although they rapidly and predominantly form a Ga oxide layer upon exposure to oxygen, which reduces this value significantly.

2.2. Toxicity

Ga has low cytotoxicity and has negligible solubility in water except as a salt. Ga salts, such as Ga citrate, have been approved for use by the US FDA, with Ga scans used for the detection of cancer, especially lymphoma. A thorough investigation into Ga-based liquid metal toxicity remains to be undertaken, although different research groups have conducted a range of biocompatibility tests. The toxicity of highly oxidized Ga indium (In) alloy has been investigated using a cell viability test. Cell viability was \(\approx 100\%\) for the two different types of cells used after 48 h, showing negligible toxicity. The release of Ga and In ions from EGaIn in an aqueous environment and its effect of toxicity has also been investigated. It was found that Ga ions are the dominant ion released when there is no mechanical agitation, however, after sonication, the concentrations of both ions increase, and the level of In ions is comparable with that of the Ga ions. Cytotoxicity is low without sonication, however, it becomes significant with the rising level of Ga and In ions. Grafting molecules with different designs of anchoring groups and steric structures may also determine the rate of release of Ga ions. Passivating the surface of Ga by introducing a hydrophobic layer, or anchoring groups that can compete with oxygen for surface sites may reduce chemical reaction, and therefore probably the rate of release of ions. Various studies have been undertaken on the toxicity of liquid metal nanoparticle-based nanomedicine. One group discovered that maximum tolerated dose of liquid-metal-based nanomedicine in mice was 700 mg kg\(^{-1}\), which showed low toxicity. Another group determined the toxicity of Ga and Ga–In alloy nanorod-based nanomedicine. The Ga-based nanorods had low toxicity, however, the Ga–In alloy-based nanorods had high toxicity, with 3 out of 4 mice dying 20 days after injection. This was suggested to be due to the high In concentration. Liquid metal has also been shown to degrade slightly after cells were cultured on a liquid metal polymer conductor (MPC), whereas a control group exposed to cell culture alone did not degrade. The degradation of the liquid metal did not compromise its conductivity and the cells showed good viability. It is speculated that the metabolic waste from the cells reduced the pH of the solution, causing the partial degradation of the liquid metal. Considering the complexity and diversity of human body, individual cytotoxicity evaluation must be conducted based on the specific pH, temperature, and biodegradation path.

Table 1 shows various experiments on the toxicity of Ga and their findings. For further information on the biomedical applications of Ga particles and nanoparticles, see two recent review papers.

2.3. Oxide Skin

When exposed to oxygen in the air, Ga quickly forms an oxide skin layer of 0.7–3 nm thickness. The oxide layer has been shown to form even at very low (ppm) oxygen concentrations. The oxide skin gives Ga alloys a core–shell structure, and it has been used to create self-healing devices which can be cut, with
3. Methods for Fabrication of Liquid Metal Enabled Devices

The properties of liquid metals mean that conventional metal microfabrication methods cannot be used. For example, etching causes the liquid metal to flow as a result of the removal of the oxide layer and capillary forces. Also, casting a uniform film of liquid metal is difficult. However, there are a range of fabrication techniques that can be used that make use of liquid metal adhesion due to the oxide layer and its liquidity to pattern the liquid metal in the desired way. Compared with solid metals, the fluidic nature allows liquid metal to be directly injected and printed for forming patterns using various off-the-shelf devices, such as syringes and printers. The ability of liquid metal to freely flow through the channels allows the design of reconfigurable devices. Also, the rapid formation of an oxide layer suppresses the large surface tension and mechanically stabilizes the printed structures, making it possible to form complex 3D metallic networks without extreme temperatures. Here, several examples for patterning Ga liquid metals in biodevices are briefly discussed.

For example, carbon nanotubes sprayed onto silver were shown to protect it from liquid metal corrosion while keeping desired electrical function.

Table 1. Toxicity evaluation of liquid metal.

| Materials | Toxicity test | Main findings | Ref. |
|-----------|---------------|---------------|------|
| Bulk GaIn | Cell viability test by CCK-8 assay in human malignant C8161 cells and normal HaCaT cells cultivated with liquid metal present | 100% viability after 48 h for both types of cell | [12] |
| Bulk GaIn | Subcutaneous injection of 100 μL of GaIn into mice | Analysis of liver toxicity (aspartate transaminase [AST] and alanine transaminase [ALT]) and renal toxicity (urea and creatinine) showed biocompatibility | [12] |
| EGaIn MPC | EGaIn MPC used to culture HUVECs and HAFs in cell culture medium | Cells showed good viability after 7 days. The surface of the MPC is slightly degraded due to metabolic waste from cells reducing the pH of the solution. The degradation does not affect the conductivity of the MPC | [35] |
| Electronic blood vessel made with EGaIn MPC | Electronic blood vessel made of a liquid MPC implanted into a rabbit to replace the native carotid artery | 3 months post implantation, the implant showed excellent biosafety. There were no significant pathological changes or inflammatory response | [93] |
| EGaIn in aqueous solution | EGaIn in aqueous solution (without sonication and with sonication between 5 and 20 min). HeLa cells, ADSCs and NDFs metabolic activity tested by WST-1 assay, live/dead fluorescent dyes after 1 and 3 days | Low cytotoxicity with no sonication. Significant cytotoxicity with sonication | [29] |
| Liquid metal nanoparticle based medicine | Liquid metal nanoparticle-based medicine injected into mice | Necropsy at 3, 7, 20, 40, and 90 days post injection showed no organ or tissue damage, showing no obvious toxicity. Kidney function and hematological assessment were normal compared to the control group. Maximum tolerated dose of 700 mg kg⁻¹ also showed low toxicity | [13] |
| Ga nanospheres and nanorods, Gain nanorods | Ga nanorods and nanospheres, Gain nanorods injected into mice | For Ga nanorods and nanospheres hematological parameters and weight of the mice showed no significant difference compared with the control group. No obvious tissue injury or organ damage. For the GaIn nanorod injected mice, 3 out of 4 mice died on day 20 after injection, showing high toxicity | [33] |
| EGaIn nanoparticles grafted with various molecules | Concentration range of 0.002–0.1 mg mL⁻¹ of liquid metal nanoparticles grafted with various molecules, cultured with MCF-7, tested with Alamar Blue assay | Viability of cells slightly decreased at concentration of 0.1 mg mL⁻¹ for three of the types of grafted nanoparticles. No significant cytotoxicity shown for the remaining type of grafted nanoparticle | [34] |

2.4. Corrosion

Ga and its alloys can corrode some metals such as certain aluminum alloys and copper by the process of embrittlement, infiltration, and alloying. Other metals, such as NiTi alloys and Ti are more resilient, not showing any corrosion until a threshold temperature between 400° and 600°. Alloying with another metal changes the properties of the liquid metal. The liquid metal becomes more conductive when alloyed with copper, for example. To prevent corrosion, a protective layer can be coated onto either the liquid metal or onto the metal to be protected. For example, carbon nanotubes sprayed onto silver were shown to protect it from liquid metal corrosion while keeping desired electrical function.
Figure 2 shows how the different fabrication techniques work. More patterning methods and details are reviewed in depth in previous studies.\[(50)–(53)\]

**Imprinting**: Liquid metal is spread onto a flat surface (Figure 2a). An elastomer such as polydimethylsiloxane (PDMS) with indentations in it is pressed onto the liquid metal. The liquid metal oxide layer adheres to the recesses in the mold but not the other parts of the mold.\[(54)\]

**Direct Writing**: This simple technique involves directly writing the liquid metal onto the surface using a syringe or similar device (Figure 2b). The rapid formation of the oxide allows the formation of 3D structures as the oxide skin can stabilize the structure.\[(55)\]
Injection: Liquid metals can be injected into microchannels as small as 150 nm in diameter. During injection, the pressure used needs to be high enough to cause the oxide layer to yield. The pressure required scales inversely with channel diameter. The pressure differential can be induced by syringe injection or vacuum filling. Small posts serving as Laplace pressure barriers can be used to guide the liquid metal along certain paths. If the liquid metal is frozen in the mold, it can be easily transferred to another component using tweezers in a "freeze casting" process. Microcontact Printing: A layer of liquid metal is adhered to a stamp which then is pressed onto a target substrate, leaving behind an imprint of liquid metal. Selective Wetting: A pattern of wetting and dewetting regions can be made on a substrate. When liquid metal is spread onto the substrate it only adheres to the wetting regions and thus copies the desired pattern. Direct Laser Patterning: A film of liquid metal is encased between two layers of elastomer such as PDMS. A laser is then used to ablate certain regions, vaporizing the liquid metal and the top layer of PDMS, leaving the pattern wanted. Stencil Lithography: A rigid stencil is placed on top of the substrate. Liquid metal is then spread on top of the stencil and substrate, causing the liquid metal to wet the substrate in regions not protected by the stencil. The stencil is then lifted away, leaving the desired pattern. Suspension 3D Printing: Liquid metal is injected into a self-healing gel using an injection needle. The supporting gel is locally fluidized under the shear stress as the needle moves nearby, then stabilizes afterward. This technique enables liquid metal to be printed into arbitrary 3D shapes.

4. Liquid Metal Enabled Biodevices

There are a wide range of biomedical applications, which can benefit from the unique properties offered by liquid metals. Wearable and implantable devices can be made which are soft and stretchable, and almost imperceptible to the user. In this section, the different uses of liquid metals in biodevices are discussed.

4.1. Eye-Related Applications

4.1.1. Biomimetic Eye

A human eye contains a concavely hemispherical retina and other components, and has good resolution and a high field of view. These properties would be highly beneficial for robotics and prosthetics. It is not feasible to create biomimetic hemispherical charge coupled device image sensors, as they are manufactured using planar techniques. Instead, a new type of device has to be created to reap the benefits of a hemispherical design, as demonstrated by Gu et al., who developed a biomimetic eye, containing a lens, a photodetector array and liquid metal wires to transmit the generated signals, as shown in Figure 3. The photodetector array comprises light sensitive electrodes made from perovskite nanowires, a hemispherical shell of tungsten coated on aluminum as the counter electrode, with ionic liquid in-between acting as an electrolyte. An indium layer was placed between the nanowires and the liquid metal wires to improve the contact. Each liquid metal wire transmits the signal for a single photodetector, reading signal from multiple light-sensitive nanowires. The liquid metal wires are encased in soft rubber tubes, with a PDMS socket at the base of the eye to align the liquid metal wires properly. The diameter of the liquid metal wires limits the resolution of the biomimetic eye, due to the difficulty in reducing the wire diameter to the micrometer level. This limitation is addressed using nickel microneedles connected to copper wire rather than liquid metal wires. A series of letters ("A," "E," "Y," "E") were viewed by the biomimetic eye and reconstructed by a computer program to show its effectiveness.

4.1.2. Eye Tracking

Eye movement tracking can be used for early diagnosis of conditions such as Parkinson’s disease and glaucoma. It is possible to use cameras for eye tracking, however, this has 10 times the noise level of the gold standard scleral copper coil-based eye tracking system. This type of system uses an alternating magnetic field, which can be created with Helmholtz coils. Changing magnetic flux across the coil results in a potential difference due to Faraday’s Law. Any change in the position of the eyeball also moves the tracking device, and varies the magnetic flux across the coil, which can then be measured. However, the high stiffness of the copper coils makes the device uncomfortable for the wearer, and anesthetic must be used. This restricts the system for research use only. To address this limitation, Zhao et al. developed a flexible eye tracking system using liquid metal coils encapsulated in PDMS to realize a soft contact lens. Using liquid metals instead of copper increases the flexibility of the system, resulting in increased comfort to the user. The liquid metal coil was shown to have similar performance compared with the copper coil. The copper leads attached to the liquid metal coils can be replaced by double magnetic induction, enabling the device to wirelessly monitor rapid eye movement (REM) sleep patterns.

4.2. Wearable Heating Devices

Liquid metals have been used in wearable heating devices to heat the wearer in a cold climate, or for thermotherapy to help relieve aches and pains. To be mounted on joints such as the knee, the wearable heaters require a high degree of flexibility and stretchability. It is also desirable for the temperature of the heater to be stable at different strain levels.

Wang et al. developed a wearable stretchable heater using a conductive composite comprising liquid metal and PDMS. PDMS was mixed with a high level of liquid metal (70% vol.) to increase the conductivity of the composite. The composite was patterned using direct ink writing and encapsulated in PDMS. This enabled a stretchable heater, which could be stretched up to 100%, with a temperature variation of less than 8%, which is smaller compared with other stretchable heaters at...
similar strain levels. The functionality of the device was showcased by heating a knee while cycling on an exercise bike.

Conductive elastomeric composites (usually an elastomer substrate with conductive fillers) typically exhibit a higher resistance when stretched. This is due to increased spacing between the conductive fillers, which is known as a negative piezoconductive effect. This effect is undesirable for wearable heating devices as, for a fixed potential difference, the increased resistance upon stretching results in a reduced current and a reduced heating effect. To address this limitation, Yun et al.\[73\] created a composite that exhibited positive piezoconductivity—exhibiting less resistance when under compressive or tensile strain. The composite consisted of metallic magnetic microparticles (nickel or iron), EGaIn, and PDMS (Figure 4c). Stretching the composite material facilitated a better contact between the metal microparticles and EGaIn. The electrical conductivity variation was greatest for the nickel-based composite, with its resistivity reduced by seven orders of magnitude when experiencing a compressive or tensile strain of 10%. The iron-based composite also exhibited an increased conductivity when placed in a magnetic field due to magnetostriction deforming the composite, and due to the alignment of iron particles in the direction of the field, further reducing the spacing between the particles. Nickel has much lower magnetic permeability than iron and was less affected by magnetic field changes. The composite was used to develop pressure-sensitive heating devices. Localized pressure was applied by placing magnets atop the device (Figure 4d). A temperature rise of \( \approx 90 \) °C was obtained when applying an external pressure of 0.5 MPa. The unique features of this composite were used for developing handheld heating devices and could in future be used in intelligent heating pads and insoles.

Kent et al.\[74\] created a soft actuator made using channels of liquid metal embedded in liquid crystal elastomer. The liquid metal heaters were patterned using a UV laser or spray coated using a stencil mask. Joule heating from the liquid metal channels induces the liquid crystal elastomer into a shape memory phase transition. The liquid metal channels also experience a change in resistance from deformation. Therefore, the liquid metal channels can simultaneously perform Joule heating to cause actuation, and sense deformation during actuation.

4.3. Liquid Metal Tattoos

4.3.1. Directly Patterned Liquid Metal Tattoos

Liquid metal can be written directly onto the skin to create soft electrical circuits and electrodes. However, the adhesion of EGaIn onto skin is weak—it has been shown that a droplet of EGaIn slides off pig skin at an angle of 45° (Figure 5a).\[12\] Therefore, to draw circuits directly onto skin, the liquid metal has to be used in a modified form. Yu et al.\[75\] developed a drawable liquid metal paste in air. Stirring led to continuous breaking
and reforming of the oxide skin. This in turn increased the oxide concentration, enhancing the viscosity of the paste and its adhesion to skin. This process enabled the liquid metal alloy to be painted directly onto the skin using a paintbrush to act as an electrode. Using this method, liquid metal electrodes were painted onto a rabbit and a human skin to perform ECG measurements (Figure 5b). Painting the liquid metal onto a hand also realized a skin circuit capable of lighting up LEDs (Figure 5c). The resistivity and impedance of the liquid metal paste were determined to be acceptable for use as an electrode or circuit material.

Wang et al.\cite{12} used a similar technique to create a highly oxidized EGaIn paste. The paste was painted onto mouse skin near tumors, and an alternating magnetic field was used to heat up the oxidized liquid metal by eddy currents. This heating effect was used to ablate tumors on the mice, and to release a temperature-controlled hydrogel loaded with a drug.

Another method to create drawable skin circuits was demonstrated by Li et al.\cite{76} This was achieved by sonicating EGaIn in aqueous alginate solution to form microgel shells around the EGaIn droplets. The shells slow the oxidation of the EGaIn, keeping it stable for >7 days. This mixture could be drawn on a surface or directly onto skin. The mixture needed to be mechanically sintered to increase its conductivity. Sintering ruptured the alginate shells and allowed the EGaIn to combine, forming long conductive paths.

Alternatively, Guo et al.\cite{77} created a conductive tattoo by mixing EGaIn with nickel microparticles. This Ni–EGaIn mixture had an electrical conductivity comparable with EGaIn, but had a higher viscosity, and could adhere to polymethacrylate (PMA) glue but not directly onto skin. This feature was used to create a removable conductive tattoo. A pattern was first drawn onto the skin using PMA glue, following which the Ni–EGaIn was rolled and adhered to the glue to replicate the pattern (Figure 5d). This facilitated the quick and simple drawing of electronic circuits onto skin, which was used to fabricate electrodes for ECG readings and Joule heating. The ECG readings were similar to conventional Ag/AgCl electrodes (Figure 5e). The tattoo was shown to be stable after 3000 bending–relaxing cycles. It could be easily removed using a wet paper towel and soap or soaked in alcohol without irritating the skin.

### 4.3.2. Patch Electronic Tattoos

Skin mounted, deformable bioelectronic stickers have great potential for future health monitoring applications.\cite{78} These devices need to be easily deformable and stretchable, adhering to the skin to acquire physiological data, such as biopotentials for electrophysiological monitoring.\cite{79} Liquid metals are highly suited for use on these stickers/transfer tattoos due to their flexibility, stretchability, and high conductivity. Alberto et al.\cite{80} created an electronic tattoo with liquid metal electrodes incorporating a liquid metal antenna for wireless power transfer, as shown in Figure 6a. The electronic tattoo was fabricated by selective wetting onto polymeric tattoo paper. The circuit was

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**Figure 4.** Wearable heating devices. a) Wearable stretchable heating device. b) Wearable stretchable heating device used while cycling. Reproduced with permission.\cite{72} Copyright 2018, Wiley-VCH. c) Schematic for producing the liquid metal elastomer with positive piezoconductivity. d) Localized heating effect of the positive piezoconductive material. Reproduced under the terms and conditions of the CC-BY 4.0 license.\cite{73} Copyright 2019, The Author(s). Published by Springer Nature. e) Ni-EGaIn tattoo heating device on an arm. Reproduced with permission.\cite{77} Copyright 2019, Wiley-VCH.
coated by a thin, transparent layer of a plastic material (Plastik) except for the electrodes, which needed to have direct contact with the skin. The electrodes provided a better signal-to-noise ratio compared with conventional Ag/AgCl electrodes. Energy could be wirelessly delivered to the device at a rate of 300 mW. The device was able to monitor and transmit patient’s heartbeat in real time using a Bluetooth module (Figure 6b).

Jeong et al. [81] developed a liquid metal strain sensor with wireless powering in which all active components (strain sensor, antenna, and interconnections) were made of liquid metal (Figure 6c). The device was patterned with liquid metal using the selective wetting technique and was encapsulated in PDMS. It could be mounted onto the finger to measure the movements of finger joints or onto the throat to monitor the movements of vocal cords when swallowing (Figure 6d). Incorporating a near field communication (NFC) reader facilitated the wireless transfer of power and collected signals. The device was able to function with no degradation at 30% strain.

4.4. Wearable Pulse, Motion, and Strain Sensors

4.4.1. Pulse Monitors

Pulse monitors are wearable devices that are used extensively by athletes to measure their heart rate to determine how hard they need to train. Pulse monitors are also increasingly popular with the general public in the form of “smart watches.” Gao et al. [82] developed a wearable pulse monitor using Galinstan injected into microchannels within PDMS to form a microfluidic diaphragm sensor (Figure 7a). The sensor was proven to detect pressure changes as small as 50 Pa with a response time of 90 ms. Alternatively, Li and Lee [83] created a stretchable wearable pulse monitor using selective wetting technique. The liquid metal channels were patterned with a minimum width of 2 μm. The device used a photoelectric converter to measure the light reflected from a light emitting diode (LED) to measure the pulse and utilized an integrated Bluetooth, low pass filter, and amplifier to transmit the signals. All these elements were encapsulated within PDMS and were interconnected by liquid metal channels. The sensor was used to measure the pulse when mounted on an ear, wrist, or finger.

4.4.2. Wearable Glove Keyboard

Tang et al. [35] created a highly stretchable strain sensor wearable glove keyboard by patterning liquid metal onto polymers (Figure 7b). First, a liquid-metal-based conductive ink was created by sonicating EGaIn in n-decyl alcohol solvent. This resulted in a mixture of solvent and liquid metal particles, which had a core–oxide shell structure. The ink was then printed onto a substrate, called the initial patterning layer (IPL) and the solvent was left to evaporate. A curable polymer was then poured onto the ink. This was called the stripping layer (SL) Following the curing of the polymer, the SL was peeled off IPL. This caused the oxide shell on the liquid metal particles to rupture, forming a conductive path that was embedded on the IPL and/or the SL, dependent...
upon the parameters used. The resultant patterned material was called a metal polymer conductor (MPC). It was patterned with a high resolution of 15 μm, had a high conductivity of $8 \times 10^{-3} \text{ Sc m}^{-1}$, and could endure strains of 500% when cast onto Ecoflex 0030. This method was used to realize a wearable glove keyboard, incorporating liquid metal strain sensors on each finger to detect the finger motion. Each finger was responsible for typing three different letters. The glove keyboard was used to type “HELLO WORLD.”

4.4.3. Stretchable Antenna

The stretchable nature of liquid metal allows for developing antenna sensors with changing resonant frequency in response to strain. For example, So et al.\cite{So18} created a dipole antenna with a 90% radiation efficiency with a resonant frequency that changed from 1840 to 1600 MHz as the dipole was reversibly stretched from 54 to 66 mm. Similarly, Kubo et al.\cite{Kubo84} developed a stretchable half-wave dipole antenna, which exhibited a resonant frequency change from 1.53 to 0.738 GHz in response to 120% strain.

4.5. Stretchable Electroporation and Blood Vessel Devices

4.5.1. Stretchable Electroporation Device

Electroporation is a process whereby an electric field is used to increase the permeability of the cell membrane, which allows drugs, chemicals or DNA to be transferred into the cell\cite{Gao85}. Tang et al.\cite{Tang15} created an MPC that was able to be used as a flexible, stretchable, electroporation device. The biocompatibility of the device was tested by culturing human umbilical vascular epithelial cells (HUVECs) and human aortic fibroblasts (HAFs) on the printed MPC for 7 days. The cells remained viable within this period, suggesting that the MPC and any dissolved metal ions were nontoxic to cells. The device was then used to carry out electroporation, using comb-like liquid-metal-patterned electrodes. The electrodes were first stretched over 100 cycles to test their ability to function after undergoing strain, and then were used to deliver DNA plasmid encoding green fluorescent protein (GFP) into HAF cells by electroporation, by applying five cycles of square waves with a magnitude of 80 V. After 24 h, 95% of the HAF cells exhibited GFP expression.

4.5.2. External Stent

Coronary artery bypass grafting surgery is a surgical intervention in cases of ischemic heart disease. Saphenous vein grafts are the most commonly used vein graft in coronary artery bypass grafting surgery, however, they have a patency rate less than 60% after 10 years,\cite{Lab86} with the main issues including short-term thrombosis, mid-term intimal hyperplasia, and late-stage atherosclerosis.\cite{Lab87} Mechanical support of the vein (such as with external stents, e.g., VEST)\cite{Lab88} to prevent restenosis has been clinically investigated,\cite{Lab89} with results showing reduced intimal hyperplasia compared with nonstented 4.5 years after implantation.\cite{Lab90}

Figure 6. Patch liquid metal tattoos. a) Biomonitoring tattoo with wireless power transfer. b) Using the biomonitoring tattoo to read ECG. Reproduced under the terms and conditions of CC-BY 4.0 license.\cite{Adv20} Copyright 2020, The Author(s). Published by Springer Nature. c) A skin attachable, stretchable integrated system for motion monitoring. d) Sensor detecting swallowing motion in real time. Reproduced under the terms and conditions of the CC-BY 4.0 license.\cite{Adv17} Copyright 2017, The Author(s). Published by Springer Nature.
addition, gene therapy can inhibit the migration of vascular smooth muscle cells (SMCs) by delivering tissue inhibitor metalloproteinases-3 (TIMP-3) into cells. Ding et al. developed a soft, conductive external stent for delivering gene therapy by electroporation and mechanical restriction of vein grafts to inhibit intimal hyperplasia (Figure 8a,b). The stent was made of poly(l-lactide-co-ε-caprolactone) (PLCL) and liquid metal electrodes. PLCL is biocompatible and has been approved by the US FDA as a material for implants. The electrodes were capable of effective electroporation, inducing an electric field of >200 V cm⁻¹. Plasmid DNA was lyophilized on the inner surface of the stent, and was rehydrated by tissue fluids after implantation. Electroporation allowed the plasmid DNA to enter cells to be expressed. Intimal hyperplasia was inhibited under the combined effect of mechanical restriction of the vein and the expression of TIMP-3. The external stent was tested in vivo on a rabbit model (Figure 8b) and was harvested after 14 days for tests. Three different vein graft groups were tested, including those with an external stent but no electroporation, those with an external stent and electroporation, and those with no stent (the control). Results indicated the lowest intima thickness for the group with an external stent and electroporation. In comparison, the group with an external stent but no electroporation did not have significantly reduced intima thickness compared with the control.

4.5.3. Electronic Blood Vessel

The same fabrication process was used to create an electronic blood vessel using PLCL and liquid metal flexible electrodes (Figure 8c). The electronic blood vessel is capable of electroporation as well as endothelization through electrical stimulation. The biocompatibility of the electronic blood vessel was evaluated in a microfluidic model of a human blood vessel comprising layers of HAF cells in the outer layer; SMCs in the middle layer and HUVEC cells in the inner layer (Figure 8d). After incubation within the electronic blood vessel structure for 14 days, the cells exhibited high viability. An electric field has been shown to induce directional migration, elongation, and reorientation of macrovascular endothelial cells. This process was examined in the electronic blood vessel. HUVEC cells were cultured on the device under a range of electrical fields. The application of a 50 mV mm⁻¹ electric field increased the population of cells by a factor of 2.4 times compared with the control. It could also heal the vessel injury mimicked by scratching HUVEC cells with a 10 μL tip, after 24 h. After electroporation, GFP was expressed on all three cell layers of the electronic blood vessel. An acellular electronic blood vessel was implanted to replace the native carotid artery on a rabbit (Figure 8e,f). Three months post implantation, the electronic blood vessel demonstrated normal blood flow, matching the native carotid artery very well. There
was no sign of narrowing of the electronic blood vessel. Three months post implantation, the electronic blood vessel showed no significant detriment to the host.

**4.6. Injectable/Implantable Liquid Metal Electrodes**

**4.6.1. Liquid Metal Nerve Connectors**

Transected nerves can be repaired using surgical techniques. For small gaps (<2 cm), suturing of the nerve stumps can be done.\(^{[95]}\) In contrast, larger gaps require techniques such as nerve autografting, which involves the transfer of nerves from a donor site to the target location. This might lead to issues, including donor site morbidity and limitations on the length of available graft.\(^{[96]}\)

Liquid metal can be used to reconnect transected nerves, as shown by Zhang et al.\(^{[97]}\) who used liquid metal to reconnect a transected sciatic nerve of a bullfrog in vitro. The electrical signal passed through the liquid metal was shown to be similar to that of the original nerve. In addition, the liquid metal injected close to the sciatic nerve of a bullfrog was highly visible in X-ray images and could be easily removed by applying suction using a microsyringe. This means that a secondary surgery to remove the liquid metal after the patient recovery would be relatively simple.

Similarly, Liu et al.\(^{[98]}\) were able to reconnect a transected sciatic nerve in living mice using gallium injected into silicon tubes, with the ends of the tube sutured onto the nerve stumps (Figure 9a,b). The reconnected nerve signals were found to be similar to the intact sciatic nerve signals. The muscle atrophy associated with a transected nerve also significantly reduced for the mice with repaired nerves. Negative bursting firing caused by peripheral nerve injury was also absent for the repaired nerve mice. The resistance and impedance of gallium were found to be suitable for nerve repair applications.

**4.6.2. Implantable Electrodes**

Implantable medical devices such as pacemakers, defibrillators, and cochlear implants have been fitted onto millions of patients over the past few decades. However, the rigid nature of these devices can lead to discomfort and the implantation requires complex surgery. Formation of soft electronics within the body by simply injecting liquid metal can reduce the burden on patients receiving implantable medical devices. Jin et al.\(^{[99]}\) successfully fabricated 3D electronics by injection of liquid metal into gelatin molds. This facilitated the formation of various components with tailored configurations, as shown in Figure 9c. The fabrication process involved injecting gelatin into the target region, boring a channel in the gelatin using a syringe needle, and filling the channel with liquid metal. The gelatin served as a biocompatible, soft insulating material. Electrodes fabricated...
by this method were used to measure ECG signals in mice as well as to electrically stimulate a mouse heart and a bullfrog sciatic nerve.

4.6.3. Cochlear Implants

A cochlear implant is a surgically implanted device, which is used to treat sensorineural hearing loss. The implant electrically stimulates the auditory nerves in the ear using an array of electrodes, based on the signal from a microphone. There is a risk of trauma to the intracochlear structure during implant surgery, which can cause loss of residual hearing. In a recent study, only 23% of postoperative patients experienced no residual hearing loss after cochlear implant surgery. The use of highly flexible cochlear implants could reduce the risk of trauma during implantation. Viik created a proof-of-concept highly flexible cochlear implant using a liquid metal printed circuit board (PCB) on PDMS with platinum electrodes. The PCB was created using atomization deposition of Galinstan onto partially cured PDMS using a mask. The device could be inserted 23 mm into a 3D model of a human cochlear, which is in line with commercially available products. Attempts were made to create soft electrodes from liquid metal, which would be beneficial to reduce scar formation due to the stiffness mismatch between the tissue and the electrodes. However, the liquid metal leaked out when removed from the substrate during rolling up of the device.

4.7. Variable Stiffness Devices

4.7.1. Endoscopes

Laparoscopic single incision surgery (LESS) involves a single incision at the umbilicus, which means that a patient can undergo surgery in an almost scar-free manner. To conduct LESS surgery, it is beneficial to have a surgical instrument that has variable stiffness, to be flexible enough to reach the target area easily while being rigid enough to endure the mechanical forces applied during the surgical procedure. Li et al. used a liquid metal alloy composed of indium, gallium, and stanum to develop a variable stiffness platform for LESS. Liquid metal was encapsulated between two thermally insulating cylindrical layers, along with a spiral copper tube which served as a water heater, regulating the temperature, and in turn, the stiffness of the liquid metal alloy. The surgical instruments were accommodated in the center, inside a snake-like backbone. The liquid metal alloy had a melting point of \( \approx 40 \, ^\circ C \). Applying hot water (\( 89 \, ^\circ C \)) through the copper tube led to melting the alloy, whereas applying cold water (\( 18 \, ^\circ C \)) led to solidifying the alloy. The temperature variations corresponded to a fourfold change in the stiffness of the device. The effectiveness of the device was tested by a number of volunteers successfully using it to carry out a peg transfer task.

4.7.2. Variable Stiffness Bioelectrodes

Bioelectrodes need to have a high rigidity when initially pushed into position, however, it is also desirable for the bioelectrodes to have a variable stiffness to have similar properties to the biological tissue it is embedded in, to reduce the damage the electrode does to the tissue. Ren et al. developed adaptive electrodes using a variable stiffness magnetoactive slurry. The magnetoactive slurry was made by adding a mixture of iron particles and Galinstan to HCl solution. The stiffness of the slurry increased in response to an external magnetic field due to the iron particles preferentially aligning along the magnetic field direction. This enabled increasing the stiffness of the slurry to vary from kPa to MPa range. The bioelectrode was realized by encapsulating the magnetoactive slurry in a PDMS needle-shaped cage. The needle could not penetrate into the artificial biomaterial in its soft state but could easily penetrate in its stiff mode when applying a magnetic field (Figure 10b). The magnetic field could then be reduced to soften the needle.

4.7.3. Active Orthotic Device

People who have experienced a stroke, or suffer from cerebral palsy or multiple sclerosis, may develop abnormal gait over

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**Figure 9.** Injectable/implantable liquid metal devices. a) Liquid metal nerve connector implanted in a mouse leg to repair a transected sciatic nerve. b) Silicone tube used to hold the liquid metal. Reproduced with permission. Copyright 2016, Science China Press. Published by Elsevier B.V. c) Injectable liquid metal devices. Reproduced with permission. Copyright 2013, The Author(s). Published by Springer Nature.
time, such as drop foot or crouch gait. Rigid or semirigid ankle braces can be worn to help remedy this problem, however, long-term usage may lead to muscle atrophy, which leads to the wearer becoming reliant on the brace.

Active orthotics is an alternative method to assist a person’s ability to walk. These devices are able to aid movement of the foot and ankle using sensors and actuators. Park et al. developed a soft, wearable ankle-foot active orthotic device, which incorporated liquid metal strain sensors and pneumatic artificial muscles (Figure 10c). The strain sensors comprised EGaIn injected into microchannels within silicone elastomer. Applying strain increased the length of the channels and simultaneously narrowed them, increasing their electrical resistance. Two strain sensors were used in the orthotic device for measuring mediolateral movement and sensing sagittal angle changes. The device provided an ankle motion of 27° (14° dorsiflexion and 13° plantarflexion).

4.8. Liquid Metal Medical Devices

4.8.1. X-ray Generator

A jet of liquid metal can be used as an anode in an X-ray emitter. X-rays can be generated by accelerating electrons to impact a metal anode, with 99% of the electron energy being converted to heat. The thermal load capacity of the anode limits the electron beam power density, and in turn the X-ray brightness. A liquid metal jet has a higher thermal load capacity than a rotating metal disk and can have a greater power density electron beam incident upon it. Liquid metal X-ray systems using EGaIn have been developed, featuring a line emission dominated by the 9.2 keV Kα line, which can be used for X-ray crystallography and microscopy. However, for biological applications, higher energy X-rays are required for greater penetration into thicker (few cm thick) samples. Larsson et al. created a liquid metal jet X-ray source that used a high indium content (65% wt) Ga alloy. The increased indium content increased the brightness of the 24 keV Kα line. It also raised the melting point to 70°C, for which a water heater was incorporated into the system. The X-ray device was able to produce an image of a mammograph phantom.

4.8.2. Endoscopic Palpation

Tumor cells often have a higher stiffness than healthy cells, meaning that a sensor can measure the stiffness of tissue to locate tumors, including tumors below the tissue surface. Nagatomo and Miki developed a proof-of-concept three-axis capacitive force sensor utilizing liquid metal electrodes for endoscopic palpation. The sensor was small enough to fit onto an endoscope. It was made of eight layers of PDMS with liquid metal injected into channels. The sensor comprised of five capacitors, four of which measured shear force, and the central one measured the normal force. The sensors were able to detect...
shear and normal forces in the order of 0–5 N, which are in the usual range of the forces applied during endoscopic palpation.

4.9. Liquid Metal Energy-Harvesting Devices

The use of energy harvesting for wearable devices increases the amount of time that the device can be operated without being charged. Ideally, wearable devices should gain all of its power by energy harvesting and would not need to be taken off the body to charge. Implantable medical devices also can benefit from energy harvesting, mitigating the drawbacks of batteries associated with their large size and limited lifetime.[113] Liquid metals have been used to develop flexible energy-harvesting devices in two main areas: thermoelectric generators and triboelectric nanogenerators.

A thermoelectric generator produces electrical power from a temperature gradient. Sargolzaeeval et al.[114] developed a flexible thermoelectric generator using liquid metal interconnects between the rigid thermoelectric “legs” and utilizing an encapsulation layer made of high thermal conductivity elastomer doped with liquid metal and graphene nanoplatelets. The high thermal conductivity elastomer acted as a heat spreader, and reduced the encapsulation layer’s thermal resistance. The power density was 1.7 times higher than similar thermoelectric generators using conventional elastomer encapsulation layers. The device achieved a power level of 30 μW cm⁻² at an air velocity of 1.2 ms⁻¹, which is greater than existing flexible thermoelectric devices. Similarly, Zadan et al.[115] fabricated a flexible thermoelectric device using liquid-metal-embedded elastomer and liquid metal interconnects. The device endured 1000 cycles at 30% strain and strains of >50% with limited loss of power.

Malakooti et al.[116] showed that encasing small liquid metal droplets in elastomer leads to a supercooling effect, which reduces the freezing point of the liquid metal from −5.9 to −84.1 °C. This feature was used to create a high thermal conductivity elastomer to operate at low temperatures and was used as part of a flexible thermoelectric sleeve that powered a pulse oximeter. It was shown to function at temperatures as low as −18 °C, which is below the freezing point of bulk EGaIn.

Triboelectric nanogenerators convert mechanical energy into electrical energy using the triboelectric effect. Wang et al.[117] created a flexible triboelectric nanogenerator using liquid metal and shear stiffening gel/polymethylsiloxane (SSG/PDMS) matrix. This nanogenerator had a size of 50 × 50 × 4 mm³ and could generate 182 μW power. Increasing the strain to 80% resulted in a greater output power of 324 μW. This was due to the increased surface area of the triboelectric generator during stretching, and the reduced thickness of the elastomer matrix when stretched, which leads to increased induced charges in the liquid metal during the contact separation process. The device was able to act as a self-powered force sensor. Similarly, Helseth[118] developed a triboelectric nanogenerator by embedding liquid metal electrodes in elastomer. The device was mounted on an arm, and generated energy due to slapping and dragging of a hand across the electrode. The self-healable device was able to be cut and glued together in three dimensions. Yang et al.[119] created a triboelectric nanogenerator by injecting Galinstan into channels within silicone to form a flexible, stretchable electrode. The device could be stretched to 300% with a power output of 8.43 mW m⁻², and could function while being folded, twisted, or stretched. It could generate power from arm shaking, patting, or walking motions, and was used to power various devices, including a watch and a pedometer. Pan et al.[120] created an ultrastretchable wearable triboelectric nanogenerator with a strain limit of >500%, able to function over >10,000 cycles and with a peak power density of ≈1 mW cm⁻². The energy-harvesting device was created by stirring liquid metal in uncured polysiloxane. This resulted in a sediment of liquid metal droplets forming near the bottom of the mixture due to the over six times greater density of liquid metal compared with uncured silicone. The conductive sedimentary layer acted as an electrode, and the nonconductive part served as the dielectric, triboelectric layer. The energy-harvesting device was worn on the knees and was able to fully power a wearable digital hygrometer device after 2.2 min running on a treadmill.

4.10. Liquid Metal Antennas

It is important to create soft, stretchable antenna for data and power transfer for implantable and wearable devices. Wireless transmission of recorded data in real time would improve the usability of wearable devices greatly. Liquid metal antennas have been created that radiate with high (over 95%) efficiency.[84] However, the radiation efficiency of liquid metal antennas compared with copper antennas is lower for certain geometries, such as patch antennas.[121] This is due to the lower conductivity of liquid metal. Liquid metal antennas with variable resonant frequency have been made, however, it may also be desirable to keep a stable resonant frequency through stretching and bending of the antenna. Huang et al.[122] designed a stretchable liquid metal antenna based on two serpentine channels and investigated the effect of the aspect ratio (height of the antenna divided by the width of the antenna) on the resonant frequency change when stretched. It was discovered that for aspect ratios of greater than 1, the resonant frequency of the antenna was stable even up to strains of 50%.

5. Conclusion

Liquid metals show great promise for use in biomedical and wearable devices, as summarised in Table 2. The unique mechanical, electrical, and thermal properties of liquid metal alloys allow for developing a range of flexible, stretchable devices, as discussed earlier. Ongoing research in this area will lead to further beneficial uses for Ga-based liquid metals, however, there are certain areas which require further research for the use of liquid metals in biomedical and wearable devices to become more widespread, which are summarized below:

One issue is the true level of biocompatibility of Ga and its alloys. Several works have reported the low cytotoxicity of Ga, however, further information needs to be gathered on this as there has not yet been a comprehensive study on the biocompatibility of Ga, Ga-based alloys, and Ga ions for conducting in vitro and in vivo experiments. To address this issue, threshold concentrations of Ga and released ions from its alloys (e.g., In and Sb) need to be investigated, and also their cytotoxicity need to be characterized with pharmacokinetics, pharmacogenomic, and biodistribution studies.
Table 2. Summary of the different uses of liquid metals in biodevices.

| Application                | Description                                                                 | Ref. |
|----------------------------|-----------------------------------------------------------------------------|------|
| Biomimetic eye             | Image sensor that has hemispherical rather than planar components, has a large field of view and resembles an eye. For use in robotics and prostheses. Liquid metal wires can be used to transmit the signals | [68] |
| Flexible eye tracking      | A contact lens made of PDMS with a liquid metal coil embedded on it for flexible eye tracking, enabling early diagnosis of conditions such as glaucoma and Parkinson’s | [71] |
| Wearable heating devices   | Liquid metal patterned for use as a heating device for thermotherapy or for comfort of the user in a cold climate | [72,73,77] |
| Liquid metal tattoos       | Drawable or patch-like electrically conductive tattoos, which can measure ECG or be used for strain sensing | [12,75,77,80,81] |
| Pulse monitor              | Heartbeat monitor comprising liquid metal electrodes, a pressure sensor, or light sensor | [82,83] |
| Strain sensor              | Device that measures strain for determining the movement of body parts, e.g., fingers | [35,81] |
| External stent             | External stent for use on a vein graft, also containing liquid metal electrodes. Capable of electroporation and mechanical restriction of the vein graft in order to prevent restenosis | [92] |
| Electronic blood vessel    | Replacement blood vessel made of a biocompatible polymer and liquid metal electrodes. Able to perform electroporation and endotheliazation | [93] |
| Nerve connectors           | Liquid metal used to connect transected nerves | [97,98] |
| Injectable electrodes      | Liquid metal electrodes which are able to be injected into the body. The use of gelatin to form molds enables more complex 3D structures to be formed | [99] |
| Cochlear implant           | Device to improve hearing function in deaf individuals by the use of electrodes stimulating auditory nerves in the ear, using a liquid metal patterned circuit board | [102] |
| Variable stiffness endoscope| An endoscope which has a variable stiffness as a result of liquid metal within the device being made to melt or solidify | [103] |
| Variable stiffness electrodes| Electrodes made of a magnetooactive slurry which can stiffen with the application of a magnetic field and soften after it is removed | [104] |
| Active orthotic            | A device which aids the wearer’s ability to walk, using liquid metal strain sensors and pneumatic artificial muscles | [107] |
| X-ray generator            | X-ray generator using a liquid metal jet anode | [110] |
| Endoscopic palpation       | A device which measures force using liquid metal capacitive sensors to be able to detect tumors | [112] |
| Energy harvesting          | Flexible energy-harvesting comprising rigid thermoelastic components and liquid metal interconnects or a liquid metal triboelectric nanogenerator | [114-119] |
| Soft antenna               | Soft, stretchable antenna comprising liquid metal channels embedded in elastomer | [18,84,122] |

Another area that warrants attention is the oxide layer formation. Although this can be very useful—for example, to increase the adhesion of the liquid metal to a surface, or to create self-healing devices—the oxide may not be desired in certain circumstances. The oxide layer can be removed using an acid or base or by electrochemical reduction, however, in some situations, the use of these methods may not be practical or desirable. For example, using a strong, corrosive acid or base may damage other parts of the device. Electrochemical methods require an electrolyte, which is challenging to pack and may introduce gas bubbles into the device. Also, once the oxide layer is removed, it grows back rapidly upon contact with oxygen. Therefore, an alternative method to remove or limit the growth of oxide layer would be beneficial. Once approach could be passivating the surface of liquid metal using molecules containing anchoring groups (e.g., thiol, silicon dioxide, and phosphonic acid) for inhibiting the growth of the oxide layer.

Ga is a relatively expensive material. Although it is usually used in small amounts, the added cost must be balanced by improved device performance. Liquid metal is also lost during the fabrication of components due to the oxide layer sticking to surfaces/syringes. This further adds to the effective cost per unit mass of liquid metal in the final component. Therefore, it would be beneficial to combine a cheaper material with similar properties with liquid metal (e.g., conductive polymers) that could reduce the overall cost.

Liquid metals have great potential for use in integrated microfluidic systems. The properties of liquid metals mean that they can be used to create components for microfluidic devices, such as pumps, valves, and mixers, as well as used as a fluid for injection. However, liquid-metal-enabled electromechanical devices only work in solutions with a certain range of pH and ion concentrations. To enable the integration of liquid metal into wearable biodevices to manipulating liquids, further investigation of the operating condition of liquid metal is needed. Other innovative mechanisms for actuating liquid metal, such as magnetohydrodynamics, electrostatics, and thermal expansion are probably worth further exploration.

One last critical point needs to be considered is what makes liquid metal indispensable in fabricating biodevices. Although Ga-based liquid metals have properties that are attractive in
fabricating biodevices, many other metals share similar properties and may possess even superior qualities. For instance, in wearable devices, extreme stretchability is not needed in most cases, and standardized deposition methods using solid metals such as nickel and copper is probably more feasible for the mass production of devices at industrial scale. To this end, future studies need to focus more on the unique soft and functional interfaces, as well as the shape reconfigurability provided by liquid metals, as these are their unique selling point.

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Conflict of Interest

The authors declare no conflict of interest.

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