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Review Article

FORTUNE JOURNAL OF HEALTH SCIENCES

ISSN: 2644-2906

Gallium Needles: Piercing Through the Future of Nanotechnology and Material Science

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Abstract

Including drug delivery (for instance, vaccines, insulin, chemotherapy), minimally invasive surgery, and pain management. The characteristic properties of gallium are then able to be utilised towards improving patients' health, improving treatment effectiveness and turning the way medical interventions are approached "on its head" through these unique needles. Despite current challenges with mass production and regulatory approval, ongoing research and development are in order to translate the potential of gallium needles from the bench to the bedside.this is all about gallium new revolution

Keywords

* Gallium Needles
* Liquid Metal Needles
* Biocompatible Needles
* Minimally Invasive Procedures
* Drug Delivery
* Vaccine Delivery
* Pain Management
* Needle-Free Delivery
* Tissue Trauma
* Biocompatibility
* 3D Printing
* Microneedles
* Medical Devices
* Nanotechnology
* Material Science

Introduction

One of the most crucial instruments in the medical field is the syringe. Disposable syringes are one of the most widely used medical devices for intravenous or intramuscular injections, though the medication is injected into the patient's body using a syringe [1]. The barrel, plunger, and needle are the three primary parts of a syringe [2]. The needles come in a variety of sizes

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Citation: Syed Owais Akhtar, Ji Woo Kim, Dushan Bosotov, Yussairah Abdullah, Maria Munsif, Fazal Karim, Mahnoor Ahmed, Ghina Naeem, Aliu Olalekan Olatunji, Aqsa Mustafa. Gallium Needles: Piercing Through the Future of Nanotechnology and Material Science. Fortune Journal of Health Sciences. 8 (2025): 46-56.

Received: December 23, 2024
Accepted: December 30, 2024
Published: January 20, 2025

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DOI:10.26502/fjhs.253

and types because of their vast majority of uses for different medical purposes including. Parenteral drug administration (intravenous, intramuscular, subcutaneous, and intradermal) has been administered via injections using 'Hypodermic Needles'. The efficient delivery of medications with poor GIT absorption, medications vulnerable to enzymatic degradation, and medications that irritate the stomach are some of the biggest advantages of using hypodermic needles. Needle-based blood sampling for laboratory tests has become more and more popular due to its high efficiency and affordability [3]. Heat-treated 'Stainless-steel Alloy Needles' are used in surgical procedures. The alloy provides great strength and ductility such that the needles bend without breaking [4].

Needles and Characteristics of an Ideal Needle:

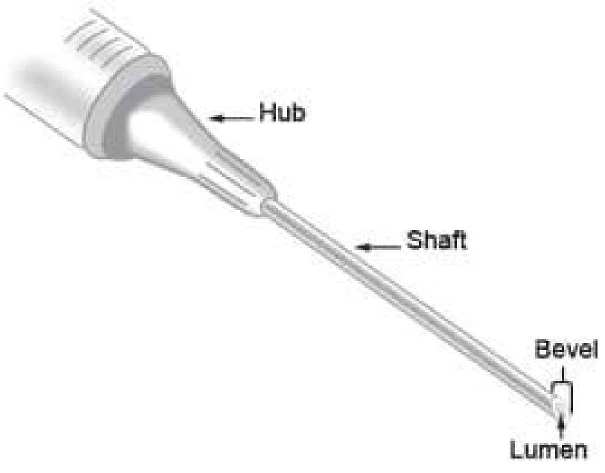
Stainless steel is used to make needles. They come in a range of sizes and lengths and are disposable and sterile [5].

The following characteristics make a syringe ideal [6]:

1. Constructed using premium stainless steel
2. Slender without sacrificing power
3. Firmly held in the needle holder's grasp
4. Go through tissue with little damage.
5. Sharp enough to pierce tissue with little difficulty
6. Stiff to withstand bending: malleable (ductile) to withstand fracture during surgery
7. Sterile and resistant to corrosion to stop the introduction of microorganisms.

The New Gallium Needle and Its Importance:

The hollow, mechanical needle frame of the new softening IV needle is composed of liquid metal gallium and is covered in an incredibly soft silicone material. Gallium is sufficiently



Picture 1: Parts of Needle

hard in its solid state to allow for the piercing of soft biological tissues. Nevertheless, gallium melts when it encounters body temperature after insertion, transforming it into a soft state like the surrounding tissue and allowing for steady drug delivery [7]. The new emerging use of gallium needles lowers the possibility of damaging the blood vessel wall, it permits patients to move painlessly at the injection site. This is made feasible by the needle's adjustable stiffness, which makes it soft and flexible when inserted into the body because of an increased temperature environment. The thin-walled vein's movement is adjusted by the needle. Because the malformed needle remains permanently soft even after it is retracted from the injection site, it is also anticipated to prevent blood-borne disease infections brought on by unintentional needle stick injuries or unethical syringe reuse [8].

Purpose of the Review:

The purpose of this review is to evaluate the potential link between the use of gallium needles and the decreasing risk of injuries to muscle tissue. Researchers think that this revolutionary IV needle can lead to new possibilities for a variety of uses, especially in clinical settings, where it can be used to redesign other medical needles and sharp instruments. The softening IV needle could become even more valuable in the ongoing era, since a 2018 WHO report estimates that 16 billion medical injections are given annually worldwide, and not all those needles are disposed of properly [9].

Traditional Needles:

The needle is made up of bevel, shaft, and hub. The 'hub' attaches to the syringe's tip. All these three components need to stay sterile. The point of the needle that Is angled to make a slit in the skin is called the "bevel." A needle's diameter is referred to as its "gauge [10]. The ability of microneedle devices to penetrate the stratum corneum and create micro conduits that allow lipophilic and high-molecular-weight molecules to pass through has drawn interest from the scientific and medical communities in recent years. It also aims to reduce pain during microneedle application by minimizing contact with blood vessels and nerve endings as much as possible [11].

and its Types:

Different materials and techniques can be used to create microneedles. Every type of microneedle has a unique method for getting the medication to the intended location including:

- 'Solid Microneedle' which was the first microneedle system to be created, is primarily made of silicon, polymers, and metals such as titanium, gold, palladium, nickel, and stainless steel. This kind of microneedle is used to treat skin beforehand.

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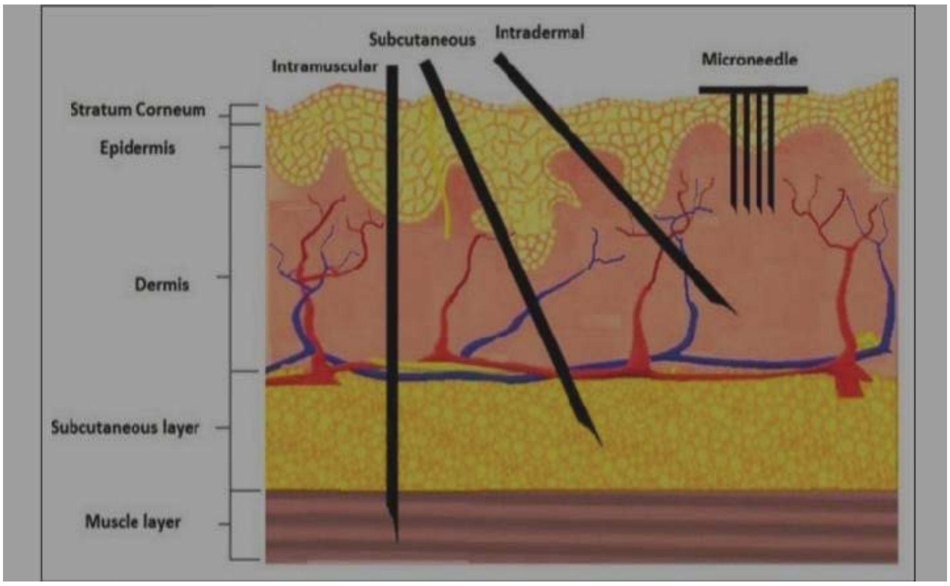
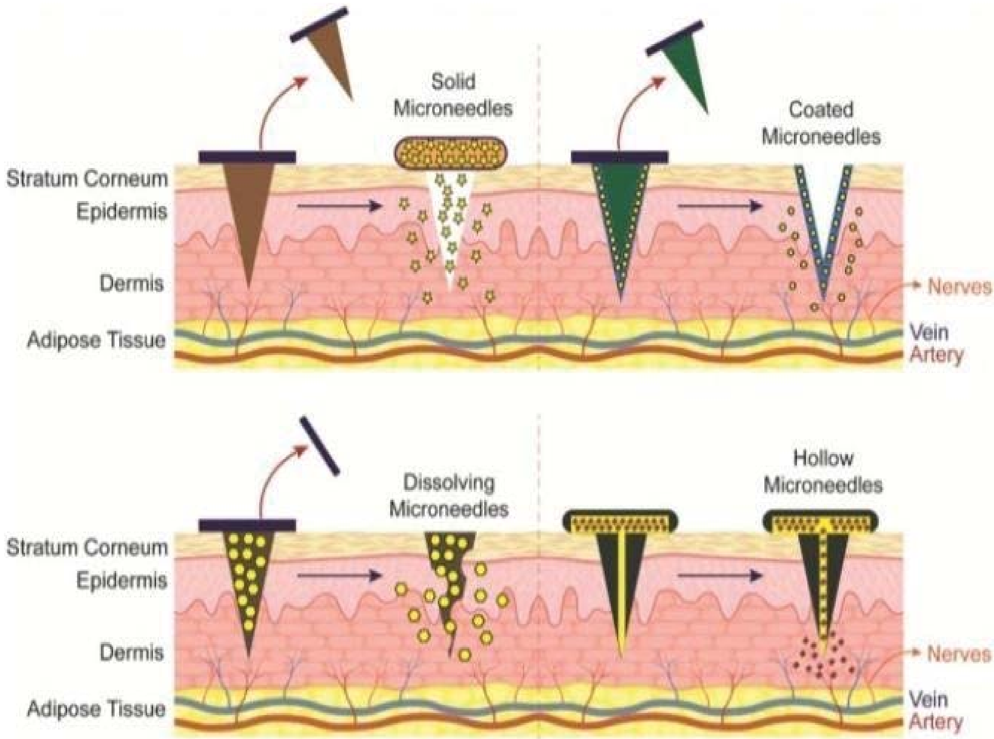


Picture 2: Depth of Skin Penetration by Microneedles Microneedle

- ‘Dissolving Microneedle’ whose usual method for making is to use water-soluble sugars like raffinose or trehalose. Biodegradable polymers such as polyvinyl alcohol (PVA) and polyvinyl pyrrolidone (PVP) can also be used to prepare them.
- ‘Hollow Microneedle’; metal, silicon, and polymers are among the materials that can be used to create hollow microneedles. One of their main benefits is that they can precisely control both the drug release rate and amount.
- ‘Hydrogel-forming microneedle’ consisting of two components: a drug reservoir at the rear that can be in the form of films, patches, lyophilized, or compressed tablets, and an array of microneedles made of a crosslinked polymer which must be a hydrocolloid [12].



Picture 3: Different types of Microneedles

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Fabrication Methods:

There are various methods of needle fabrication including:

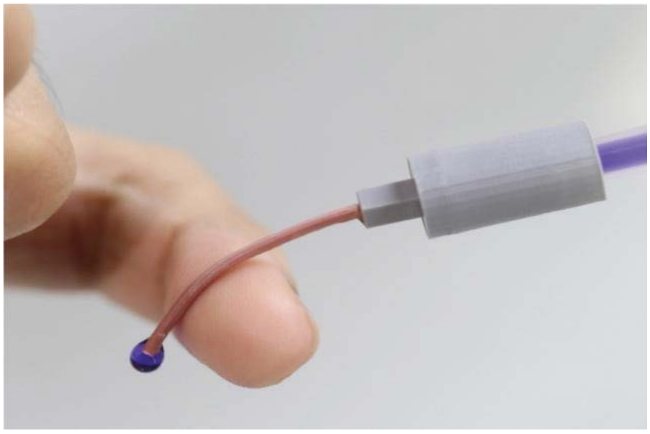
- 'Micro molding', which is the most common method for producing microneedles. This method works with a wide range of materials, such as hydrogels, ceramics, and natural and synthetic polymers.
- 'Laser Cutting' uses an infrared laser to cut titanium or stainless-steel sheets into the shape of microneedles.
- 'Drawing-based Methods' include a variety of approaches that use different drawing forces on precursor materials, such as centrifugal, adhesive, mechanical, and electrostatic forces, to form microneedle-like shapes.
- 'Atomized Spray Method' uses a liquid formulation and a nozzle attached to an air source to create an atomized spray.
- 'Mechanical Micromachining' entails the use of CNC (computer numerical control) milling procedures to manufacture needles.
- Additive Manufacturing' or '3D Manufacturing 'includes fused deposition modeling (FDM), material jetting (MJ), and photopolymerization-based processes. All these techniques are effectively used in the production of microneedles, and they have many advantages over traditional fabrication techniques [13].

Limitations of Traditional Needles

Due to its quick-acting effects, intravenous (IV) injections are a widely used medical treatment method worldwide. However, medical needles can cause serious complications in healthcare settings, ranging from minor tissue damage at injection sites to severe inflammation. This is because they are made of hard materials, such as plastic or stainless steel, which do not mechanically match the soft biological tissues of the body. Rigid medical IV devices' dexterity and structure make it possible to reuse needles unethically to save money on medical expenses, which has a major negative impact on patient outcomes [14]. Furthermore, Needles and other sharp medical instruments (such as scalpels, blades, and scissors) that inadvertently pierce or cut the skin can result in sharps and needle stick injuries. Although they might only result in minor skin wounds, the consequences could be worse. As a result of these injuries, healthcare personnel are at significant risk for blood-borne infections, particularly viruses, such as; the human immunodeficiency virus (HIV), hepatitis B (HBV), and hepatitis C (HCV) [15].

Gallium Needle and Its Properties

With an atomic number of 31 and a molecular weight of 69.72 g/mol, Gallium (Ga) is an element of group IIIA of the periodic table [16]. It is a liquid metal, having a melting point of 29.7 °C [17], adjustable high surface tension and low viscosity [18], and phase convertibility between solid (elastic modulus of 9.8 GPA) and liquid makes it an ideal material for creating medical needles with varying stiffness. [19]. Comparable in hardness to the commercial 18G over-the-needle IV catheter, the gallium needle is stiff enough to pierce tissue. Subsequently, within 60 seconds of insertion, the same needle irreversibly softens under conditions that mimic body temperature, forming a close interface with the thin-walled vein and minimizing the risk of needle stick injury during removal. The needle will soften after use, like tissue, thus, preventing needle reuse. Since new IV needles will come into contact with blood, biocompatibility studies are essential to their development. Comparing the implanted softening IV needles to commercial IV needles and catheters of comparable sizes, the 14-day in vivo animal experiment using a mouse model showed that the former significantly reduced inflammation. The softness of the transformative IV needle attained during indwelling use can lessen the discomfort associated with rigid IV catheter re-siting every 72 to 96 hours and increase mobility for hospitalized patients receiving continuous IV medication. In general, it has been believed that the transformative IV needle can improve patient care during IV administration and offer a viable alternative to the widespread unethical needle reuse [20].



Picture 4: The transformative IV Needle

Fabrication Method of Gallium Needles using '3D Printing':

The intricate process of creating a fluidic channel and polymeric encapsulation for a gallium-based needle comprise of following steps;

1. 3D Printing and Mould Making: Use UV-sensitive resin to 3D print reusable moulds for polymer encapsulation and gallium needle frames. Cure moulds for ten hours at room temperature.
2. Fabrication of PDMS (Polydimethylsiloxane) Mould:

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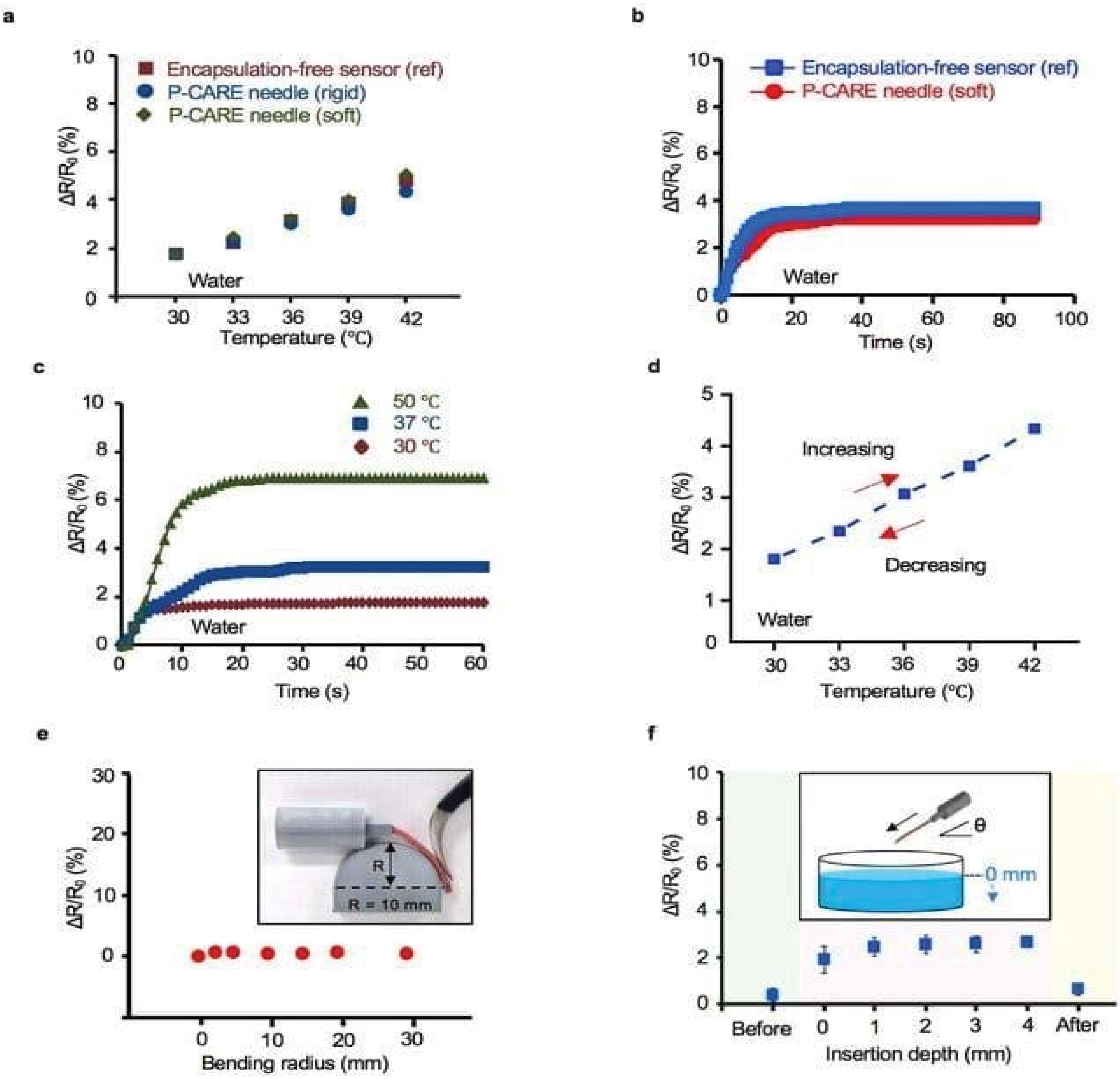
To create a rectangular needle frame structure, cast PDMS onto a 3D-printed mould. Cure PDMS at 70°C for 30 minutes. Then, attach the 3D-printed mould's delaminating PDMS layer to a glass slide.

3. Injection and Solidification of Gallium: Add 0.5 ml of liquid gallium to the interface between the PDMS mould and glass. Solidify gallium at 10°C in the freezer for 15 minutes.
4. Retrieving the Needle Frame: Gently take out the gallium-based needle frame from the mould.
5. Encapsulation and Fluidic Channel: Apply cured outer encapsulation to the entire needle structure and drop cast elastomer onto a 3D-printed mould for encapsulation, Connect two U-channel gallium-based frames with cured inner polymeric channels.
6. Hub Attachment and Adhesion: Use uncured Ecoflex to apply a thin layer of adhesion between the gallium and needle frame interface. Use epoxy resin to join a polymeric needle to a personalized 3D-printed needle hub.
7. Fluid Delivery Testing: Use a commercial syringe plugged into a needle hub to push de-ionized water through to test the fluid delivery [21].



Picture 5: Analysis of Temperature Sensor Nanomembrane Integrated into P-CARE Needle

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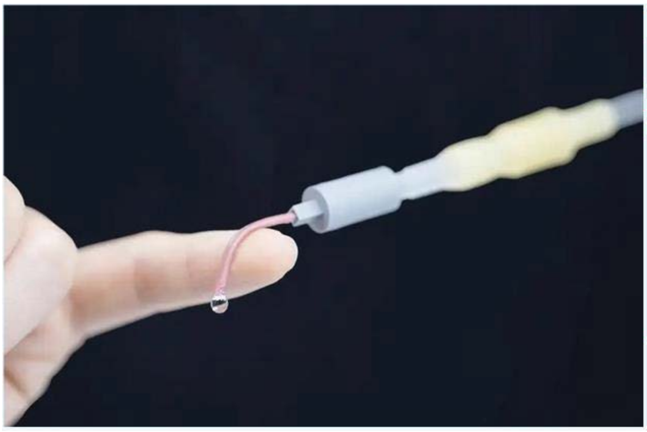

Picture 6: The gallium needle becomes soft after insertion into body.

Fabrication of Temperature-Sensing P-CARE Needle:

The steps for integrating a thin-film temperature sensor with the P-CARE are described as follows:

1. Fabrication of Temperature Sensor: Use photolithography to create a thin-film temperature sensor on polyethylene terephthalate with Cr/Au serpentine traces.
2. Sensor Integration: Using an optical microscope, manually stack the temperature sensor onto the polymeric needle's exterior. Attach an anisotropic conductive film for an external electronic circuit interface to sensor electrodes. Create photolithographic electrical interconnectors.
3. Encapsulation: Apply a thin layer of uncured Ecoflex 00-30 over the laminated layer of cured RT 623 on top of the sensor.
4. Protection: Use 7 µm-thick parylene N (K1 solution) to cover the entire device to shield the metal electrodes from biofluid during in vivo testing (22).

Gallium Needles: Harnessing Unique Properties for Medical Advancements

An intravenous (IV) needle that softens upon insertion has been developed by a collaborative research team at KAIST, reducing the possibility of tissue and blood vessel damage.[23] Children and teenagers who experience more pain when undergoing procedures involving needles are less able to cope.[24]A condition that is poorly understood, needle phobia affects patients having venipunctures and other similar procedures.There is a spectrum of severity for needle fear, which can cause therapy to be delayed.The emergence of needle phobia may be caused by various factors. Pain, however, was found to be the main factor. The most effective tool for lowering needle fear was found to be smaller needles, which were followed by non-invasive substitutes.[25]

Because new technology lowers the possibility of damaging the blood vessel wall while patients receive IV medication, it is anticipated that patients will be able to move around the injection site without experiencing pain. The needle's increased temperature during insertion causes it to become flexible, allowing it to conform to the movement of a vein with thin walls.[26] Melting points of gallium and its alloys are the lowest.[27] LM-gallium, a contrast agent with a melting point of 29.78°C, remains liquid at body temperature, allowing for a smooth and effective injection into the intended site. [28] When gallium is inserted and exposed to body temperature, it melts and transforms into a soft state similar to the surrounding tissue, allowing for stable drug delivery without causing damage to blood vessels. Due to gallium's supercooling phenomenon, a used needle maintains its softness even at room temperature, essentially averting needlestick accidents and reuse issues. [29]

Since the malformed needle stays permanently soft even after it is removed from the injection site, it is also anticipated to prevent blood-borne disease infections brought on by unintentional needlestick injuries or unethical reusing of syringes.[30] The needle is sufficiently rigid to be inserted into soft tissue, but once in place, it becomes permanently flexible, conforming to the contours of the blood vessel and lowering the possibility of a needlestick injury during removal.[31]

When compared to commercial IV catheters, the P-CARE needle's increased biocompatibility makes it a viable tool for reassessing the need for routine catheter replacement because it can significantly reduce inflammation injury at the indwelling site.[32]

Advantages of Gallium Needles: New Standard for Minimally

Invasive Procedures:

By directly delivering the drug moiety to the intended body area (organ, cellular, and subcellular level of a particular tissue), targeted drug delivery reduces the amount of medication needed for therapeutic efficacy while overcoming the general toxic effect of conventional drug delivery. [33]

To safely produce the intended therapeutic effect, a pharmaceutical compound must be transported into the body through a process known as drug delivery. Direct delivery of medications or biomolecules is generally ineffective due to a number of problems.

Nonetheless, liquid metals based on gallium have extremely low toxicity and make good candidates for drug delivery vehicles.[34]

Gallium is sufficiently hard in its solid state to allow for the puncturing of soft biological tissues. On the other

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hand, gallium melts when it comes into contact with body temperature during insertion, turning it into a soft state similar to the surrounding tissue and allowing for steady drug delivery. [35]

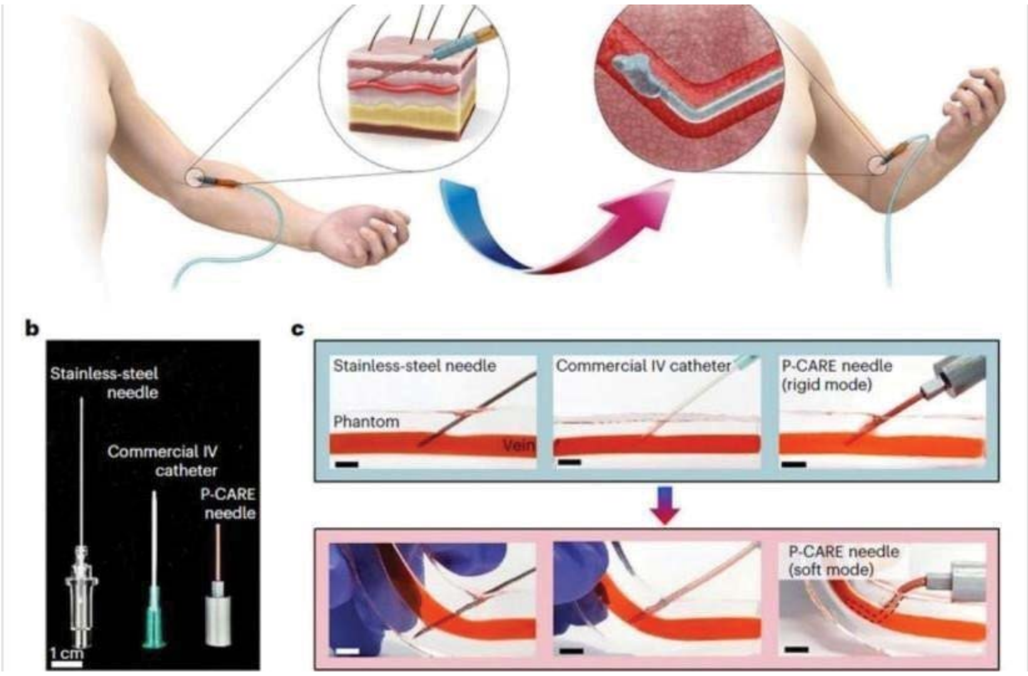
The term "extravasation" refers to the seepage of an intravenous solution into the surrounding tissues, which can seriously harm the patient.[36]The presence of fluid leakage outside the vein's structure can be detected by the needle. All of these results demonstrate that the P-CARE needle, which has the capacity to detect heat, can be used to track the temperature at the site of fluid infusion. This needle may also be used to track the temperature of the patient's core body or the amount of therapeutic drug that leaks into subcutaneous tissue.[37]

Potential Applications of Gallium Needles: Expanding the Horizons of Medicine

Gallium needles, with their unique properties such as biocompatibility, low melting point, and biodegradability, offer tremendous potential across various medical fields. These advantages can enable less invasive procedures, improved patient comfort, and more precise drug delivery. Below is an elaboration on several potential applications of gallium needles.

Drug Delivery

Gallium needles could bring about a transformative approach to drug delivery, addressing current limitations and improving treatment outcomes in a variety of clinical settings:



Picture 7: The Features of P-Care Needles

Vaccines

The painless and minimally invasive nature of gallium needles is particularly well-suited for vaccine administration. Traditional needle-based vaccinations can cause discomfort, leading to anxiety, especially among pediatric patients. Gallium needles, which could melt and dissolve upon contact with body heat, might facilitate needle-free or minimally invasive vaccine delivery, significantly improving patient compliance. Moreover, this technology could be scaled for mass immunization programs, helping healthcare systems more efficiently address public health needs [38]

Insulin Delivery

For diabetic patients, the daily necessity of insulin injections can be burdensome and painful, leading to issues with compliance. Gallium needles could improve the process by allowing for more comfortable, less painful injections, or possibly even needle-free delivery, as gallium dissolves within the body at near-room temperature. Additionally, the ability to fine-tune gallium needles' release properties could enhance glycemic control, leading to fewer complications and better quality of life for patients. Chemotherapy Chemotherapy drugs are often administered through injections, which can be painful and lead to tissue damage. Gallium needles offer a smoother surface and controlled degradation, which can reduce tissue trauma and associated pain during chemotherapy delivery. This could encourage greater patient adherence to treatment regimens, making it easier for healthcare providers to administer cancer therapies more effectively and with fewer side effects.

Citation: Syed Owais Akhtar, Ji Woo Kim, Dushan Bosotov, Yussairah Abdullah, Maria Munsif, Fazal Karim, Mahnoor Ahmed, Ghina Naeem, Aliu Olalekan Olatunji, Aqsa Mustafa. Gallium Needles: Piercing Through the Future of Nanotechnology and Material Science. Fortune Journal of Health Sciences. 8 (2025): 46-56.

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Long-Acting Drug Formulations

Gallium needles can also be engineered for controlled drug release over extended periods. By adjusting the alloy composition and fabrication techniques, gallium needles can be designed to slowly degrade in vivo, releasing drugs in a sustained manner. This could be particularly beneficial for medications requiring steady concentrations in the bloodstream, such as antipsychotics, contraceptives, or antiretrovirals.

Biopsies and Tissue Sampling

Gallium needles could be instrumental in revolutionizing tissue sampling procedures, especially in areas requiring precision and reduced invasiveness.

Fine-Needle Aspiration Biopsy (FNAB)

In procedures like FNAB, where tissue samples are extracted from organs such as the breast, thyroid, or lymph nodes, traditional needles can cause discomfort and may lead to complications like bleeding or infection. Gallium needles, due to their biocompatibility and reduced tissue trauma, may minimize these risks. Moreover, their ability to dissolve after use can prevent retained needle fragments, which is a potential complication in delicate areas like the thyroid [39].

Core Needle Biopsy (CNB)

Core needle biopsies, which are often used to extract larger tissue samples for diagnosis, may benefit from gallium needles in terms of improved precision and minimized tissue damage. The smoother insertion and controlled degradation of gallium needles could reduce inflammation and bleeding, providing clearer biopsy samples with fewer side effects. This is especially important in breast biopsies or liver biopsies where tissue integrity is crucial for diagnosis [40]

Ophthalmic Procedures

The delicate nature of eye structures requires precision instruments that minimize damage while delivering effective treatment. Gallium needles could provide solutions to some of the current challenges in ophthalmic procedures.

Drug Delivery to the Eye

Delivering drugs to specific parts of the eye, such as the retina, can be challenging with traditional needles due to the risk of damage to sensitive tissues. Gallium needles, with their fine, moldable properties and capacity for controlled dissolution, could enable highly targeted drug delivery within the eye. This could be especially beneficial for conditions like age-related macular degeneration, where precision drug application is critical [41]

Minimally Invasive Glaucoma Surgery

Glaucoma, a condition that increases pressure in the eye, often requires surgery to relieve intraocular pressure. Gallium needles could play a key role in procedures like trabeculectomy or canaloplasty, where fine needles are used to create openings in the eye for fluid drainage. The ability of gallium needles to degrade in vivo could reduce postoperative complications and eliminate the need for needle removal, making the procedure safer and more efficient [42]

Microsurgery

Microsurgery, which requires high precision and minimal tissue trauma, stands to benefit greatly from the properties of gallium needles. Several areas of surgery could see significant improvements through the adoption of gallium technology:

Plastic Surgery

In plastic and reconstructive surgery, precision is paramount. Gallium needles could be used for fine suturing or tissue manipulation, where control and reduced tissue trauma are crucial. The biodegradable nature of these needles could allow for more efficient healing, with less risk of foreign body reactions [43]

Neurosurgery

Neurosurgery often involves working in delicate brain tissues, where any damage can have significant consequences. Gallium needles could be used to deliver drugs directly to brain tissues or to perform tissue sampling in areas that are difficult to access. Their ability to dissolve in vivo reduces the risk of retained needle fragments and subsequent complications [44]

Veterinary Medicine

Gallium needles could also be used in veterinary medicine for injections and surgical procedures. In particular, the reduction in tissue trauma and stress on animals could make routine vaccinations or treatments less stressful for both the animals and veterinary professionals.

Advanced Therapeutic Devices

Gallium needles can be integrated with more complex medical devices to further expand their potential applications:

Microfluidic Devices

In microfluidic systems, gallium needles can be utilized to control the precise flow of fluids, such as blood or medication. These devices can be employed in point-of-care diagnostic platforms, enabling faster and more accurate assessments of patient conditions with less invasive sample collection.

Wearable Drug Delivery Systems Gallium needles can be incorporated into wearable patches or automated drug delivery devices, offering continuous, controlled release of drugs for chronic conditions such as diabetes, cardiovascular diseases, or cancer.

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Challenges and Future Directions: Paving the Way for Widespread Adoption Challenges to Overcome:

Cost-Effectiveness of Production:

One of the foremost challenges in the adoption of gallium needles is the high cost of their production. Manufacturing processes, at present, involve sophisticated techniques that are expensive and may not be viable for mass production on a commercial scale. Gallium needles, like many advanced medical devices, require precise fabrication to meet stringent standards for use in healthcare. However, the high costs associated with these processes limit their broader application, particularly in regions with limited healthcare funding. The solution lies in identifying or developing more cost-effective methods of production without sacrificing the quality or precision that is essential for medical tools. For example, advancements in automation, materials science, and nanotechnology might offer ways to reduce manufacturing costs over time. Furthermore, exploring economies of scale in production could help lower costs as demand grows. Without reducing the cost of production, the widespread adoption of gallium needles will remain a challenge, particularly in resource-constrained settings.

Scalability of Manufacturing:

In addition to cost issues, scalability poses a significant barrier to the widespread use of gallium needles. Manufacturing precision medical devices at scale requires maintaining consistency in product quality, which becomes increasingly difficult as production scales up. The current techniques used to manufacture gallium needles, while suitable for smallscale production or research settings, may not yet be optimized for the high-volume manufacturing required to meet clinical demand on a global scale. Addressing this challenge will require innovation in manufacturing technologies, including the use of new materials and more efficient production techniques. Automation and robotics may play a critical role in scaling up production, helping to ensure consistent quality and precision while reducing the time and labor required to manufacture each needle. Furthermore, developing global supply chains that can reliably provide the raw materials and components needed for gallium needle production will be essential for sustaining large-scale manufacturing. As the medical community’s reliance on such advanced materials grows, the ability to scale production efficiently will be a determining factor in the technology's success.

Long-Term Stability and Storage:

Another significant challenge for gallium needles is their long-term stability and storage. In many clinical settings, medical devices need to have an extended shelf life to ensure that they are available when needed, without degrading or losing their efficacy. Gallium, like other metals, can be susceptible to changes over time, including oxidation, corrosion, or structural degradation, particularly in certain environmental conditions such as high humidity or exposure to various chemicals. Research into improving the stability of gallium needles is necessary to ensure they remain effective for extended periods. This includes developing protective coatings or storage conditions that can prolong their shelf life and prevent degradation. Stability is especially critical in environments where regular access to medical supplies may be limited, such as in rural or underdeveloped areas. Addressing this issue would make gallium needles more viable for long-term use and storage, ensuring they are ready and functional whenever needed. This research will need to extend beyond the clinical environment to include considerations for shipping and storage in non-ideal conditions.

Regulatory Approval and Clinical Acceptance:

The path to widespread clinical adoption of gallium needles will also require navigating the complex regulatory landscape that governs medical devices. Regulatory agencies such as the U.S. Food and Drug Administration (FDA), the European Medicines Agency (EMA), and other global health authorities must ensure that gallium needles meet rigorous safety and efficacy standards before they can be approved for widespread use. The approval process typically requires comprehensive clinical trials to demonstrate the safety and effectiveness of the device across different patient populations and clinical conditions. These trials are time-consuming and expensive, and even after approval, gaining widespread acceptance in the medical community may take time. Medical professionals tend to be cautious when adopting new technologies, especially those involving invasive procedures. Therefore, it will be essential to not only prove the safety and efficacy of gallium needles but also to demonstrate clear advantages over existing tools in terms of performance, safety, or cost-effectiveness. Additionally, efforts must be made to engage healthcare providers early in the development process, ensuring that gallium needles address the practical concerns of medical professionals. Incorporating feedback from clinicians, surgeons, and healthcare providers during the design and development phases will help align the technology with real-world clinical needs, thereby speeding up both regulatory approval and clinical acceptance.

Future Directions and Research Opportunities:

Optimizing Needle Design for Specific Applications:

Gallium needles hold promise for a variety of medical procedures, but optimizing their design for specific applications is key to maximizing their potential. Different medical procedures have different requirements for needle shape, size, flexibility, and strength. For instance, needles used in delicate surgeries may need to be thinner and more flexible, while those used for injections or tissue biopsies

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may need to prioritize strength and precision. Customizing the design of gallium needles for specific applications will involve exploring different needle geometries and material compositions. For instance, combining gallium with other biocompatible materials could enhance its mechanical properties for certain uses, or developing coatings could improve its performance in specific clinical settings. Furthermore, designing needles that minimize patient discomfort, reduce the risk of infection, or improve healing times could greatly enhance their clinical utility.

Exploring New Fabrication Techniques:

The development of new fabrication techniques for gallium needles offers exciting opportunities to improve precision, efficiency, and cost-effectiveness. For example, advances in additive manufacturing (3D printing) have the potential to revolutionize the production of medical devices, allowing for highly customized designs and more precise control over needle geometry and size. Similarly, nanotechnology could enable the creation of ultra-thin needles with enhanced mechanical properties or surface textures that improve tissue interaction and reduce patient discomfort. Exploring new methods for needle production, such as laser cutting or micro-machining, could also allow for more precise and efficient manufacturing processes. These techniques could reduce material waste, improve consistency, and potentially lower production costs. Furthermore, new fabrication techniques may enable the development of gallium needles with unique properties, such as self-sharpening tips, increased flexibility, or enhanced durability, further expanding their potential applications in clinical settings.

Conducting Comprehensive Clinical Trials

Large-scale clinical trials are critical to establishing the safety, efficacy, and overall clinical value of gallium needles. Such trials will need to assess the performance of gallium needles in a wide range of medical procedures, from routine injections to more complex surgeries. These trials should also examine patient outcomes, including factors such as recovery time, infection rates, and long-term health impacts. Conducting clinical trials across diverse patient populations and medical settings will help to ensure that gallium needles are suitable for use in various healthcare environments. This research will also provide the data necessary to support regulatory approval and build confidence among healthcare providers. Additionally, clinical trials can offer valuable insights into how gallium needles perform in comparison to existing technologies, highlighting their potential advantages in terms of precision, patient comfort, or ease of use.

Investigating Biodegradability and Biocompatibility

One of the most important areas for future research is the investigation of the biodegradability and biocompatibility of gallium needles. While gallium is generally considered biocompatible, meaning it can be safely used in the human body without causing adverse reactions, more research is needed to fully understand its long-term effects. This includes examining how gallium needles interact with tissues over time, as well as whether they degrade or change in ways that could impact patient safety. Developing needles that are biodegradable could have significant benefits, especially for single-use medical devices. Biodegradable needles would reduce the need for surgical removal after certain procedures and minimize medical waste. However, ensuring that these needles degrade in a controlled and safe manner, without causing harm to the body or the environment, will require extensive research into material properties and degradation mechanisms.

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