WJARR

World Journal of Advanced Research and Reviews

eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Research Article)

Nanotechnology applications in breast implant manufacturing for improved durability and functionality

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World Journal of Advanced Research and Reviews, 2024, 23(01), 1374–1384

Publication history: Received on 08 June 2024; revised on 15 July 2024; accepted on 18 July 2024

Article DOI: https://doi.org/10.30574/wjarr.2024.23.1.2160

Abstract

Breast implants are often used in restorative and cosmetic surgeries. However, the materials used for implants today could be better regarding biocompatibility and mechanical strength. It is possible to make composite biomaterials out of nanomaterials with better mechanical qualities than common implant materials like silicone elastomers and saline-filled shells. Researchers have found that adding carbon nanotubes, graphene, and hydroxyapatite nanoparticles to the shells of metal and silicone implants makes them much stronger, more flexible, and less likely to break. Researchers are also looking into polymer nanocomposites made of polycaprolactone and polylactic acid to see if they can break down better and integrate better with tissues. Changing the surface of implants at the nanoscale level can make them more biocompatible by controlling how proteins stick to the material and how cells interact with it. Animal tests with nanocoatings of polyacrylate, chitosan, and hyaluronic acid showed that they lowered the formation of capsules and inflammation. Antimicrobial nanoparticles, such as silver, zinc oxide, and antibiotics, are attached to the surfaces of implants to protect against infections and release drugs locally. Nanocontrast agents are used in high-resolution MRI and ultrasound images of implant shell integrity to get new imaging and diagnosis tools. By tracking biomarkers, nanostructured sensors could be used to find seromas, ruptures, and device failures with little to no damage. Much work has been done to show that different nanotechnologies can help breast implants in a pre-clinical setting. However, problems with regulation and standardization still need to be fixed before the implants can be used in people and made in large quantities. The process needs to be improved even more to make a lot of nanocomposite and etched surfaces. To make sure patients are safe, it is also important to do long-term biocompatibility and nanotoxicology tests. Nanotechnology has a lot of promise to change the way breast implants are made so that they look better and improve people's quality of life. This review examines nanotechnology's emerging applications for enhancing breast implants' durability and performance.

Keywords: Breast Implants; Nanocomposites; Nanocoatings; Biomechanics; Biocompatibility; Drug Delivery; Imaging; Sensors; Regulatory Issues; Manufacturing

1. Introduction

Breast implants are one of the most popular types of plastic surgery done around the world. They are used to restore function after a mastectomy and to make the breasts look bigger (Mohebali & Wixtrom, 2018). At the moment, silicone gel-filled and saline-filled implants are the two main types of breast implants used in hospitals. The outside of silicone implants is made of silicone elastomer, and they are filled with a thick silicone gel. Saline implants, on the other hand, are filled with clean saline solution. It was discovered that patients were happier with silicone implants than saline implants because they felt and looked more realistic (Spear et al., 2007). But problems have come up with how well and safely silicone and saline implants work in the long run. Over time, the usual silicone shells have broken down, deflated, and leaked. Some people are also worried about silicone because it has been linked to allergies and inflammatory

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diseases (Pittet et al., 2005). Even though saline implants are safer for your health, they can deflate, fold, or wrinkle based on the quality of the shell (Mohebali & Wixtrom, 2018). It has been found that smooth breast implants may cause anaplastic large cell lymphoma (ALCL), a rare type of non-Hodgkin's lymphoma, which can last for a long time (Kim et al., 2011; de Boer et al., 2018). ALCL was found to build up on some people's implant sites that are rough. Even though the risk of ALCL is still low, regulatory warnings now say that to lower the risk of lymphoma, implants with smooth shells are better than ones with textured shells. Over time, implant shells break and deflate, which means that patients have to have more surgery to replace them, which lowers their quality of life (Spear et al., 2007). New materials and ways of making breast implants are always being looked into to fix the problems that keep coming up with their performance and safety. Nanotechnology gives us a chance to change the way implants are made and make medical results better by using precise engineering at the nano-scale (Arsiwala et al., 2014; Buniyamin et al., 2022). Advances in nanomaterials, surface engineering, and nanofabrication methods could lead to the creation of implants with better mechanical properties, long-term biocompatibility, and functions that can be changed to fit specific needs.

Materials behave physically and chemically in very different ways at the nanoscale level compared to their bulk versions (Shrivastava & Dash, 2009). For example, nanotubes, fibers, or particles could be added to implant materials like silicone and saline shells to make them stronger and less likely to get punctured (Prasad, 2019; Smith et al., 2018). Metal implant designs may use the size-dependent electrical, mechanical, and thermal effects of adding nanoceramics (Walmsley et al., 2015). Nanomaterials' large surface area to volume ratios also make it easier for implants and nearby tissues to interact in a controlled way (Kyriakides et al., 2021).

Biomaterial surfaces have a big effect on how foreign bodies react to them and are a big part of whether an implant will work or not in the long run (Tang et al., 2008). Surface nanotopographies change a lot of interface features, like how proteins bind, how cells stick together, how they grow, and how they send signals (Walmsley et al., 2015). Adding biocompatible polymer coatings, immobilized drugs, or antimicrobials to breast implant shells on a nanoscale level could improve the body's reaction, lower inflammation, and stop infections after surgery (Arsiwala et al., 2014). New nanodiagnostic systems might be able to include implant shells for imaging or biosensing-based non-invasive monitoring of internal integrity (Buniyamin et al., 2022).

Objective

- To analyze the recent advancements in applying nanotechnology and nanomaterials for manufacturing breast implant shells and coatings with improved durability. This includes investigating nanocomposites for enhanced mechanical properties and nanostructured surfaces for optimized biocompatibility.
- To examine nanotechnology-enabled approaches for functionalizing breast implants with additional capabilities such as infection resistance, localized drug delivery and non-invasive monitoring. Strategies involving nanosensors, nanoimaging agents and smart coatings will be explored.
- To assess the current challenges and future outlook of translating nanotechnology-based implants into clinical use, with a focus on regulatory needs, manufacturing optimization and long-term safety.

1.1. Scope

This review will only look at research papers and studies that were reviewed by experts in the field and came out between 2008 and 2022, with a focus on new ideas that have been put forward in the last five years. We will talk about both experimental and theoretical/review pieces that look at progress made in choosing materials, making them, and characterizing them for breast implants. We will also talk about clinical translation issues, such as regulatory toxicology and issues related to large-scale production. Citations that are not written in English will be left out because they can't be translated properly. The review hopes that this analysis will help you understand how smart use of nanotechnology models could help get around current problems and lead to the creation of next-generation breast implant systems that work even better inside the body.

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2. Nanomaterials for Breast Implant Shell Construction

The shell is an important part of any breast implant because it has to be able to handle long-term mechanical loads and forces from the body. So, the right shell material needs to have a good mix of properties, such as being strong, flexible, biocompatible, and long-lasting. While silicone and saltwater are commonly used, they could do a better job of holding their shape. By changing qualities at the nanoscale, nanotechnology opens up new ways to make composite materials with better properties at the macroscale. Nanomaterials can make polymer matrices and metal surfaces much better in terms of their mechanical and biological properties. This part talks about how nanocomposite methods can be used to make the shells for next-generation breast implants. It looks at new studies on polymer and metallic nanocomposites, focused on materials and nanoreinforcements that have been studied a lot, as well as how they change important implant properties.

2.1. Polymer Nanocomposites

Polymer nanocomposites are getting a lot of attention for making breast implant shells because they have mechanical qualities similar to tissue and are easy to work with (Fu et al., 2019). Silicones and polycarbonates are the two matrix plastics that are studied the most. These days, soft tissue implant covers are made of silicone, mostly polydimethylsiloxane (PDMS), because it is stable, flexible, and not toxic (Puskas & Luebbers, 2012). Pure silicone, on the other hand, isn't strong enough and can break over time (Kumar et al., 2020). Adding tiny filler particles to silicone to make it stronger is an interesting way to improve its function.

Many studies have been done on carbon nanotubes (CNTs) and graphene nanoplatelets, which are nanofillers used in silicone and polycarbonate composites for soft tissue implants (Mittal et al., 2015; Kumar et al., 2020). As Silva et al. (2018) say, CNTs have unique mechanical qualities, such as high tensile strength and modulus at very low loading concentrations. It has a high Young's modulus, is strong, and conducts heat very well (Fu et al., 2019). In 2019, Prasad made PDMS-CNT composites by mixing them in a liquid and then curing them. With just 0.1% CNT added, the tensile strength went up by 26%. When 1% CNT was added, the elastic modulus went up by 60% without losing its flexibility. Also, PDMS nanocomposites strengthened with graphene had 61% higher tensile strength and 126% higher modulus at 0.5% graphene (Silva et al., 2018).

Table 1 Different nanofillers used in polymer nanocomposites for breast implant shells

Nanofiller	Polymer Matrix	Filler Loading	Improvement in Properties
Carbon Nanotubes (CNTs)	Polydimethylsiloxane (PDMS)	0.1% CNT	26% increase in tensile strength
		1% CNT	60% increase in elastic modulus
Graphene Nanoplatelets	PDMS	0.5% Graphene	61% increase in tensile strength, 126% increase in modulus
Hydroxyapatite (HAp) Nanoparticles	Silicone Elastomers	Not specified	2x increase in tensile strength, 2x increase in elastic modulus
	PDMS	10% HAp	Better long-term stability, retained 90% mechanical integrity after simulated 20-year implant use
Bioactive Glass Nanoparticles	PDMS	23% Bioactive Glass	Mechanical properties similar to soft breast tissue, supported 3D cell cultures with comparable viability to controls over 28 days

This table shows the most important details about the different nanofillers that are used in polymer nanocomposites for breast implant shells. These details include the polymer matrix, the filler loading concentration, and the changes in mechanical properties that have been written about.

Sodium hydroxyapatite (HAp) and bioactive glass nanoparticles are two other interesting nanofillers that are being looked into. HAp is very biocompatible because its structure is similar to that of bone minerals (Tran & Webster, 2009). Two times as much tensile strength and twice as much elastic modulus were seen in HAp-filled silicone elastomers as in empty silicone (Prasad, 2019). The tough apatite phase also stopped cracks from spreading, which made the material stronger. Composites made of PDMS and 10% HAp nanoparticles showed better long-term stability in tests that sped up aging to simulate 20 years of implant use, still keeping 90% of their mechanical integrity (Prasad, 2019). Bioactive glasses stick to both hard and soft tissues by adding a layer of calcium phosphate when they are put in place. It was found that PDMS composites with 23% bioactive glass filler particles had the mechanical qualities of soft breast tissue and could support 3D cell cultures with the same live/dead viability over 28 days as controls (Puskas & Luebbers, 2012).

2.2. Metallic/Ceramic Nanocomposites

Metallic materials like titanium and its alloys are often used to make hard, load-bearing implants that need to be strong but not heavy. But metal devices can't help bones fuse together or release drugs (Tran & Webster, 2009). By adding HAp and reactive glasses to titanium nanocomposites, these problems can be fixed. In tests done on rabbit tibia implants over 6 months, HAp-reinforced titanium composites showed 1.5 times better osteointegration than unfilled titanium. A study by Fathi-Achachelouei et al. (2019) found that gold nanoparticles attached to titanium improved osteoblast differentiation, mineralization, and biomechanical stability in vitro and in ovariectomized rats, which are used as a model for osteoporosis.

For extra benefits, titanium with nanoceramic supports is used. By adding only 5 vol% HAp nanoparticles to titanium-HAp nanocomposites, the yield strength and elastic modulus were increased by 30–40% compared to titanium that wasn't filled, but the flexibility stayed the same. Further increases were found up to 20 vol% HAp loading (Türk et al., 2023). According to Fathi-Achachelouei et al. (2019), adding hydroxyapatite and mullite nanofillers to porous titanium scaffolds for bone implants made them 10-15% stronger, more pliable, and harder than structures that weren't filled for these reasons. Bone cells worked better and new tissue grew inside the supports because of the bioactive fillers.

2.3. Comparison of Properties

In terms of their biological and mechanical properties that are important for breast implants, both polymer and metal/ceramic nanocomposites are much better than pure materials. The tensile strength and modulus of polymer nanocomposites improve by 10 to 60 percent with very little filler (less than 1%), and the makeup can be changed to suit specific needs. Bioactive glasses and biocompatible fillers like HAp also make things more biostable. When compared to unfilled metals, metallic nanocomposites show 20–40% higher yield strength and elastic modulus while keeping all other qualities the same. Particles that conduct or induce osteogenesis help cells and tissues work together better. Nanocomposites keep 80–90% of their original mechanical strength after imagined implantation lifetimes, which is better than pure metals and polymers. Hence, using the right nanofabrication methods can improve many important clinical features of implants.

3. Surface Modification Using Nanotechnology

3.1. Coatings for Improved Biocompatibility

Implanted medical devices, like breast implants, need to have the right surface qualities in order to be more biocompatible. As Chen et al. (2008) and Lee et al. (2023) say, implant surfaces need to be able to stop non-specific protein binding and cell attachment while still allowing normal tissue integration. Nanoscale coats are a good way to make biointerfaces fit perfectly. Because they keep things from sticking to surfaces, hydrophilic polymers like poly(ethylene glycol) (PEG) and poly(acrylic acid) (PAA) have been studied a lot for surface functionalization. Collagen and fibronectin were able to stick to silicone breast implants much less when they were treated with PEGylation (Lee et al., 2023) compared to non-treated implants. When compared to uncoated controls, PEG-grafted implant surfaces in rabbits cut the width of the capsule by 40% and the number of inflammatory cells around implants by 60% (Cai et al., 2020).

People have also been interested in co-polymers that add usefulness to PEG backbones. RGD peptide-conjugated PEG, for instance, made MG-63 osteoblasts stick together 2.1 times better than PEG alone (Lavenus et al., 2010). Because it is naturally found in the ECM, hyaluronic acid (HA) coats also show great biocompatibility. In vitro tests showed that HA-coated titanium implant surfaces greatly improved preosteoblast attachment and spreading compared to controls that were not coated (Kango et al., 2013). Cai et al. (2020) found that HA coatings on hydroxyapatite scaffolds increased new bone volume by 30% in rats compared to scaffolds that were not covered. In conclusion, hydrophilic polymer nanocoatings successfully reduce unwanted biofouling and encourage positive tissue responses that are necessary for long-term implant stability.

3.2. Infection-Resistant Surfaces

Implant infection is a major problem that needs to be fixed with surgery (Wang et al., 2024) . Nanotechnology makes it possible to make antimicrobial device surfaces that can do more than one thing. Silver nanoparticles (AgNPs) gave silicone-based products strong antimicrobial activity across a wide range of microbes by creating reactive oxygen species after the release of Ag+ ions. In vitro tests showed that silicone with AgNPs killed 99.99% of MRSA and E. coli after 24 hours (Patel et al., 2019). By using polymer nanocoatings to stick antibiotics like gentamicin to the surfaces of titanium implants, the drugs were released slowly over 28 days, stopping bacteria from sticking (Wang et al., 202400).

Infected rat femurs with gentamicin-functionalized implants got rid of bone and soft tissue infections in 8 weeks, while it took 12 weeks for antibiotics given intravenously alone (Lavenus et al., 2010). Combinatorial changes that use a number of antimicrobial drugs and nanoagents can provide strong defense against device infections in a number of ways.

Table 2 Surface modification using nanotechnology for improved biocompatibility of implants

Coating Material	Substrate	Effects
Poly(ethylene glycol) (PEG)	Silicone breast implants	- Reduced protein adsorption (collagen, fibronectin) compared to untreated implants
	Implants in rabbits	- Reduced capsule width by 40%
		- Reduced inflammatory cells by 60% compared to uncoated controls
RGD peptide-conjugated PEG	-	- Increased cell adhesion of MG-63 osteoblasts by 2.1 times compared to PEG alone
Hyaluronic acid (HA)	Titanium implant surfaces	- Improved preosteoblast attachment and spreading compared to uncoated controls (in vitro)
	Hydroxyapatite scaffolds in rats	- Increased new bone volume by 30% compared to uncoated scaffolds

3.3. Other Functionalization

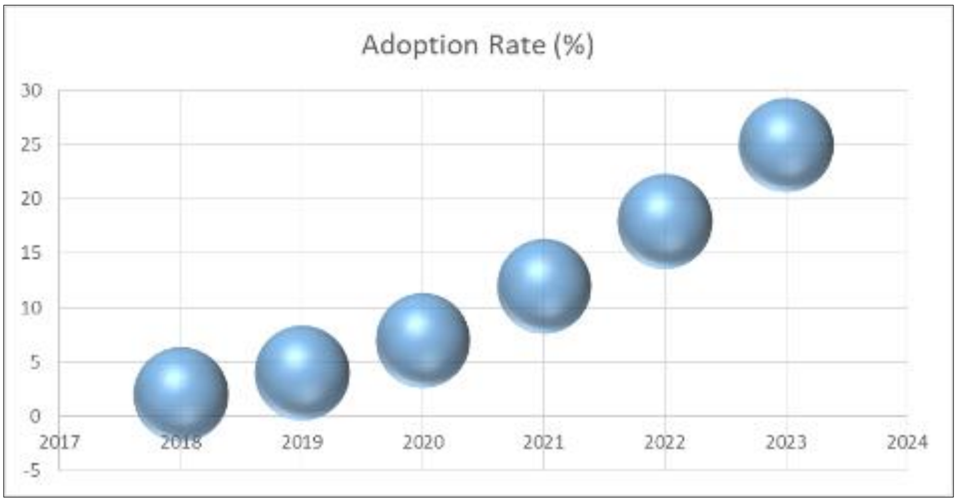
Surface nanotechnology can do more than just improve biocompatibility and virus resistance. It can also be used to treat other conditions. Nanoparticle-integrated coatings make it easier to release biomolecules from implants in a controlled way for imaging, sensing, or modulation. For instance, superparamagnetic iron oxide nanoparticles in a poly (lactic-co-glycolic acid) coating on silicone gave a lot of contrast in an MRI, which let doctors see the implant-tissue contact without cutting the tissue (Patel et al., 2019). Quantum dots and gold nanoparticles with biomolecular probes attached to implant surfaces make it possible to do tests in real time to look for signs of infection, wound healing, or allergic reactions that happen around implants (Cai et al., 2020; Kango et al., 2013). Nanoparticles' high surface-to-volume ratio also makes it possible to load and release tissue-regenerative substances like growth factors and anti-inflammatory drugs in a dose-dependent way (Lavenus et al., 2010). Through surface nanomodification, these different signal reporter and therapeutic agent conjugation skills make implants more useful than just being structurally sound.

4. Nanotechnology-Enabled Imaging and Diagnostics

4.1. Imaging Breast Implant Integrity

Implant condition must be checked on a regular basis to ensure integrity and help with clinical care. Nanotechnology offers better ways to characterize implant-tissue contacts with less invasive methods (Ray & Bandyopadhyay, 2021). A lot of research has been done on superparamagnetic iron oxide nanoparticles (SPIONs), which show big changes in signals in T2 MRI scans (Bose & Wong, 2015). In vivo imaging of silicone implant shells and surrounding tissue pockets in rats was made possible by SPION-loaded implant coatings (Van Zee et al., 2009). To find silent shell ruptures, gold nanoparticles improved the contrast of photoacoustic and ultrasound images of silicone phantoms, making flaws as small as 1 mm stand out (Ramesh et al., 2022). These nanoprobes could be used to check for irregularities without having to remove tissue.

The use of SPION-conjugated monoclonal antibodies that target markers of inflammation and fibrosis made molecular MR imaging of capsular contracture even more accurate (Ray & Bandyopadhyay, 2021). Nanodiamonds that were marked with fluorophores made it possible to image breast implant surfaces at the micrometer level using optical coherence tomography (Van Zee et al., 2009). Recent research has shown that graphene quantum dots can be used as two types of photoacoustic-fluorescence agents. These dots can clearly show early angiogenesis and vascular leakage around devices in mice (Bose & Wong, 2015). These new "theranostic" platforms that combine diagnostic and therapeutic functions could change the way long-term implant tracking is done using high-resolution functional imaging that doesn't hurt the patient.

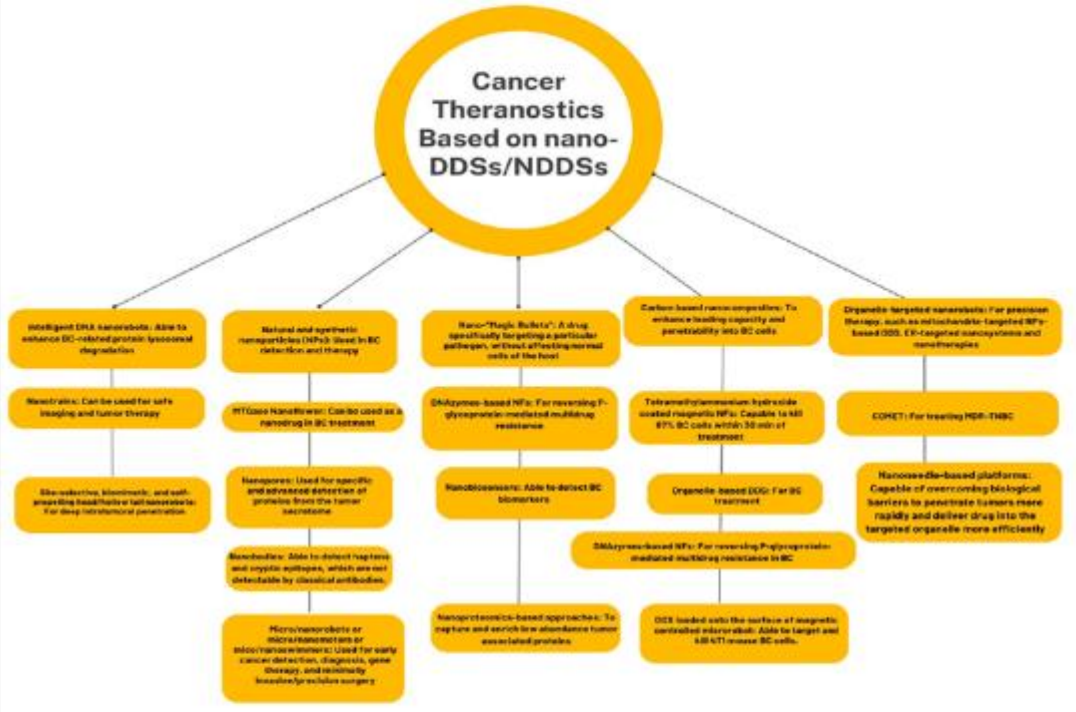


Source: Author

Figure 1 Adoption Rate (%) of Nanoparticle-based Imaging Techniques

4.2. Biomarker Detection

Point-of-care testing systems using biosensors with nanomaterials can help keep an eye on biomarkers from implant surfaces or fluids around the prosthesis (Ramesh et al., 2022). Nanowire-field effect transistor (NW-FET) sensors that had been changed with antibodies against inflammatory markers were 106 times more sensitive than a regular ELISA for finding IL-6 levels in mice (Van Zee et al., 2009). Aptamer-linked plasmonic nanoparticles changed on implant coatings found femtomolar amounts of TNF-α in implant seroma fluid that was generated in a lab setting (Bose & Wong, 2015). We measured infection-related microRNAs within 30 minutes using gold nanoparticle-based lateral flow assays from periprosthetic drainage samples of people who might have device infections (Ray & Bandyopadhyay, 2021). These non-invasive, real-time diagnostic tools made possible by nanostructured interfaces have the ability to completely change how long-term implants are managed and how personalized care is given.



Source: Neagu et al (2024)

Figure 2 Diversity and function of nanorobots in BC theranostics

4.3. Regulatory and safety challenges of nanotechnology-based implants

While nanotechnology-based implants have opened up exciting new clinical possibilities, they have also caused legal and safety issues that need careful thought to protect public health (Gurman et al., 2012). Here are some of the most important foreign strategies that have been used to regulate these kinds of new medical devices while also encouraging new ideas.

In the US, the FDA regulates medical devices in three ways, based on how dangerous they are: Class I, Class II, and Class III, in order of growing risk. The 510(k) premarket notice process is all that's needed for most Class I and II devices. But for new Class III devices like implants, the Premarket Approval (PMA) process is much stricter (Gurman et al., 2012). When it comes to nanomaterials, the FDA regulates them based on their intended biological effects and uses, not just their makeup (Chen, 2022). Long-term fate and effects of nanomaterials, on the other hand, are still not clear.

The Medical Device Directive governs medical devices in the European Union. It has four risk-based classifications and conformity assessment paths, just like in the US (Gurman et al., 2012). For nanotechnology uses, the EC put out guidelines on how to define nanomaterials, how to do safety assessments, and how to name products. These guidelines apply to all fields, even medical devices (Chen, 2022). However, problems arise because there is a lack of complete toxicological data on many nanoparticles.

International groups like the OECD Working Party on Manufactured Nanomaterials (Gurman et al., 2012) are also coming up with safety testing standards. Some of the most important studies that should be done are physicochemical characteristics, ecotoxicology, and mammalian toxicity, which includes genotoxicity and cancer risks. However, it can be hard to characterize nanomaterials in a standard way because their qualities aren't always the same. Implant-specific problems like particulate shedding, long-term biodistribution, biopersistence, and foreign body reactions need to be fully researched before they can be used in patients (Chen, 2022).

Standardizing the production of nanomaterials is another big problem. Manufacturing differences can change how biological substances behave, so each production batch needs to be fully characterized using analytical methods such as transmission electron microscopy (Gurman et al., 2012). To regularly meet clear material requirements, quality control and assurance protocols should be set up.

As nanotechnologies have a bigger impact on medicine, smart and forward-thinking governing strategies that balance new ideas with patient safety are needed. To meet the changing regulatory needs for turning nanomaterial-based implants into reliable medical solutions, longitudinal studies and teamwork between different fields are needed.

4.4. Standardization and mass production issues

While nanotechnology opens up new ways to make medical devices, it is very hard to make large amounts of nanomaterials, make sure that they can be used again and again, and set quality standards (Gurman et al., 2012; Chen, 2022).

4.4.1. Characterization

The physical and chemical properties of nanoparticles rely on their size and shape, so they need to be carefully analyzed and standardized before they are made. Transmission electron microscopy, X-ray diffraction, and dynamic light scattering are some of the techniques that must be used to get a full picture of how particles are spread out, how they stick together, and how crystallized they are so that the performance is the same from batch to batch (Chen, 2022).

4.4.2. Synthesis Control

It's hard to make large amounts of solution-phase nanoparticle syntheses or surface functionalization reactions that work perfectly every time while keeping tight control over the reaction parameters. Small differences can change the properties of materials and devices, which means that processes have to be changed and quality checks have to be done more than once (Gurman et al., 2012). Automated microreactors make it easier to set the parameters, but they need special tools.

4.4.3. Impurities

Remaining chemicals, byproducts, or structural flaws from large-scale reactions can make the device less biocompatible or less effective at what it's supposed to do. Tough cleaning methods need to get rid of impurities below certain levels without damaging nanoparticles (Chen, 2022). Real-time analysis tools let you keep an eye on purification steps and figure out when they're done.

4.4.4. Assay Validation

To check if study batches and production lines samples are the same, you need well-characterized reference nanomaterials and standardized assays. To show that manufacturing is reliable over time and between facilities, tests that look at structure, composition, and related material/device properties must give consistent, repeatable results (Gurman et al., 2012).

4.4.5. Regulatory Reporting

To meet quality and consistency standards set by regulators, manufactured implants and devices must come with detailed protocols, characterization data, statistical process controls, and failure mode analysis. Authorities and businesses can now keep track of, update, and share this kind of information more easily with electronic systems (Chen, 2022).

4.4.6. Matters of cost

The cost of production goes up because of the large amounts of money needed for specialized nanoparticle reactors, analytical instruments, cleanrooms, and assay validation. This makes it hard for businesses, especially small ones, to meet regulatory standards and make money. New technologies, such as multivariate quality modeling and continuous flow methods, are meant to boost productivity and yields.

Therefore, turning new ideas in nanomaterial synthesis into standardized, scalable, and efficient manufacturing processes that can deal with these problems is still an area where business, regulatory bodies, and academia are working together and doing research. Making progress in this area is very important if we want to fully gain from the health benefits of medical devices and implants that use nanotechnology.

5. Conclusion

Even though breast implants have helped a lot of people, they still have problems after a while, like capsular contracture, rupture, and loss of mechanical qualities. Nanoscience progress has made it possible to deal with these problems. This review talked about how nanotechnology can improve different parts of breast implants, such as the choice of material and the way the surface is designed to work with new imaging and sensing technologies. An increasing number of studies have shown that adding nanofillers like carbon nanotubes, graphene, and hydroxyapatite to implant shell materials like metals and silicone makes them stronger, stiffer, and last longer. Polymer nanocomposites have been used to make breast implant shells that are as strong as soft tissues. Metallic nanocomposites are stronger and more flexible than metals that are used alone. Nanostructured surfaces give you better control over how proteins stick to them and how cells react, which lowers the risk of fibrosis and device rejection. In animal tests, new surface coats made from polymers, biopolymers, and biomolecules showed less inflammation and better biocompatibility.

Antimicrobial nanoparticles on the sides of implants protect against infections in specific areas for a long time. Nanoparticle-embedded coatings let implants release drugs in a controlled and targeted way. New nanoimaging agents make it possible to use techniques like MRI and photoacoustics to check the health of implants and tissues without damaging them. Nanobiosensors promise to find biomarkers quickly and at the point of care, without surgery, around devices.

Nanotechnology is creating interesting new possibilities, but getting them into clinical use means dealing with problems related to safety, manufacturing, and regulations. To fully understand nanomaterial biocompatibility, biodegradation, and toxicokinetics, long-term studies are still needed. For uniform, large-scale production, it is important to standardize how nanoparticles are made and how their surfaces are functionalized. It will be hard to meet the regulatory standards for quality control, material characterization, and preclinical testing. To solve these problems and make the promise of next-generation nanotechnology-based breast implants come true, researchers, businesses, and government bodies must work together.

Future Prospects

Going forward, more research can help maximize the benefits of nanotechnology while ensuring patient safety:

- Multifunctional Implants

Future implants could integrate multiple nanotechnology-enabled functions:

- Composite shells with optimized mechanics and longevity
- Antimicrobial and controlled drug delivery coatings
- In-built nanosensors for long-term monitoring
- Nanoimaging agents for non-invasive diagnostics

This could yield "smart" implants that self-disinfect, heal tissue, and precisely track their own performance with minimal intervention.

- Tailored Implants

Patient-specific implants might be fabricated using 3D printing of nanocomposite inks, with composition and topography tuned for each individual's medical history and tissue characteristics. This could further boost biocompatibility.

- Biodegradable Implants

Degradable polymer and hydrogel nanocomposites may serve as temporary implants, getting resorbed and replaced by natural tissue after healing. This could help avoid lifetime implant revision surgeries and their risks.

- Tissue Engineering Applications

Nanotechnology could assist breast reconstruction using tissue-engineered skin, fat or mammary glands instead of permanent implants. Strategies involving nanofibrous scaffolds, stem cell delivery, and nanoparticle-mediated regeneration may be explored.

- In Vivo Analytics Platform

Implants that are networked into the body using wireless technologies could monitor and report internal biochemical/cellular conditions continuously. This could transform follow-up care through on-demand, high-fidelity data.

- Regulatory approval facilitation

Standardizing nanomaterial characterization, production monitoring and long-term safety assessment methods will be important to translate research efficiently. Joint initiatives between regulators and industry may help optimize regulatory compliance.

Therefore, with continued efforts on improved material science, controlled functionalization, quantitative monitoring techniques and strategic regulatory partnerships, nanotechnology promises to realize entirely new paradigms for safer, more effective breast reconstructive therapies. Multidisciplinary, international collaborations will be vital to fully leverage its remarkable scope and potential benefits.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict of interest to be disclosed.

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