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Review article

An overview of MEMS/NEMS-based applications with the potential to be used in medicine

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Abstract

The technology of MEMS/NEMS is based on the integration and relationship of mechanical, electronic, and even optical components at the micro- and nanoscale. This technology has provided more sensitive and more effective devices/systems for medical diagnosis, treatment, and monitoring. For example, it has enabled molecular imaging and early diagnosis of diseases with its integration with medical imaging and biosensor technology. Also, its use in drug targeting and controlled drug release systems has paved the way for promising, effective, and personalized treatments. In short, the technology of MEMS/NEMS currently plays a significant role in medicine and will have even greater potential in the future. Due to increasing studies, researchers who work or will work in this field have started to need a general perspective. For this reason, this review study aims to provide an overview of MEMS/NEMS-based medical applications. This review addresses the applications of MEMS/NEMS in medicine, including biosensors, medical imaging, surgical devices, drug studies, Lab-on-a-Chip, and Organ-on-a-Chip systems. Also, it briefly expresses the fundamentals of MEMS/NEMS and highlights the challenges, and future uses for MEMS/NEMS in medicine.

Keywords: *Electromechanical biosensors; electromechanical drug delivery; electromechanical drug release; microelectromechanics; nanoelectromechanics; nanoelectromechanical surgery*

1. Introduction

Studies on electricity from the Ancient Egyptians to the present paved the way for electronic systems and devices, such as transistors, diodes, thyristors, and so on (Dylla and Corneliussen, 2005). With the development of technology, efforts to transform tools into smaller and more portable structures have led to the need for microelectronic devices. Gordon Moore predicted that the size of electronic components could be reduced to the nanoscale today, arguing that the number of electronic components per chip, especially transistors, would double every two years (MacK, 2011). This situation showed that microelectronic technology would transform into nanoelectronics. In parallel with these developments, efforts to add functionality to microelectronic structures and integrate moving structures into them have led to their evolution into microelectromechanical systems (MEMS), including electronic and mechanical components (Tilli et al., 2015; Madou, 2018). With the development of semiconductor technology, the metal-oxide-semiconductor field-effect transistors have also paved the way for the progress of MEMS.

Moreover, the integration of all electronic components on a single card or chip led to the emergence of integrated circuits. These circuits have been developed and have become digital integrated circuits. Over time, these digital integrated circuits were both improved and miniaturized and became microprocessors. Today, increasing their usage areas and transforming portable devices into smaller structures have enabled MEMS to shrink down to the nano level and led to the rise of nanoelectromechanical systems (NEMS) (Bie et al.,

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2017; Feng et al., 2017; Shulaker et al., 2017; Lyshevski, 2018; Padha et al., 2023; Fan et al., 2024; Stapf et al., 2024).

Different techniques, such as low-pressure chemical vapor deposition, plasma-enhanced chemical vapor deposition, electrodeposition techniques, thermal oxidation, physical deposition techniques, lithography, and etching techniques, are generally preferred for the fabrication of MEMS/NEMS (Gonçalves et al., 2022). However, it is more troublesome to produce MEMS/NEMS based on biocompatible materials such as polymers and hydrogels with these techniques because the materials used in these techniques are limited. Likewise, there are still some disadvantages in the fabrication methods of MEMS/NEMS that need to be eliminated (Feng et al., 2017). Their use in biological applications has taken these disadvantages to a different dimension, and their fabrication as biocompatible MEMS/NEMS has remained limited. In this context, polymers fabricated for biological systems have started to be used in MEMS/NEMS (Schulz, 2009; Basu et al., 2021). For this reason, the fabrication of polymer-based MEMS/NEMS has become very important. At this stage, fabrication methods, such as hot embossing, injection molding, casting, stereolithography, inkjet printing, and micro-milling, can be used to produce polymer-based MEMS/NEMS (Rezai et al., 2012; Manvi and Mruthyunjaya Swamy, 2022; Langari et al., 2023).

Regarding characterization methods on MEMS/NEMS, one uses many different systems depending on the properties desired to be analyzed. One can analyze them using microscopic techniques such as scattering and transmission electron microscopes or atomic force microscopy and can use systems such as an X-ray diffractometer for crystal structure. Also, one can use X-ray photoelectron spectroscopy for chemical analysis. In addition, one can mechanically characterize them by micro- and nano-mechanical testing methods (Shaporin et al., 2005; Zhu and Chang, 2015; Manvi and Mruthyunjaya Swamy, 2022).

Different fabricating techniques and characterization methods that are continuously developed facilitate the applications of MEMS/NEMS to the different fields. With this development, not only MEMS/NEMS technology but also nanotechnological systems have begun to be integrated into medical fields and thus their usage in the field of medicine has been increasing day by day (Kalaiarasi and Aishwarya, 2023; Podder et al., 2023; Shen, 2023; Bakri et al., 2024; Drexler et al., 2024; Reddy et al., 2024; Kuru and Ulucan-Karnak, 2024; Pachkawade, 2025).

However, among all nanotechnological systems, MEMS and NEMS technologies have attracted much attention because they can simultaneously indicate magnetic, mechanical, electrical, and optical features (Young et al., 2010; Feng et al., 2017). They have the potential to overcome many problems in medical applications, especially since they can be used in different roles. In this context, they can offer sensitive, portable, and effective systems or devices for medical and biological diagnosis, treatment, and control. In this review, MEMS- and NEMS-based medical applications were discussed in detail.

2. Basic definition and principles of NEMS & MEMS

MEMS are microscale systems that convert physical, electrical, mechanical, and optical stimuli or parameters into each other. Thanks to these physical properties, one uses MEMS and NEMS for tasks such as transducing, sensing, and controlling. The basic working mechanisms of MEMS are the same as traditional electromechanical systems. Physically, they are based on the principles and laws of classical electromechanics, classical mechanics, and electromagnetism. In other words, one uses Newtonian mechanics, Lagrangian mechanics, and Maxwell’s equations in the working mechanisms of MEMS (Madou, 2018). However, one uses nanoelectromechanical and quantum theories in the basic working principle of NEMS. Although their physical operating mechanisms depend on different physical laws, both MEMS and NEMS can be basically controlled by a stimulus (Lyshevski, 2018). A simple representation of an electromechanical system is in Fig. 1. The moving part in this representation may differ depending on the design. In electromechanical systems, the mechanical moving part moves or vibrates under a physical stimulus, as seen in Fig. 1 (b). This mechanism may work similarly at the micro and nano scales, but the working mechanisms can differ physically.

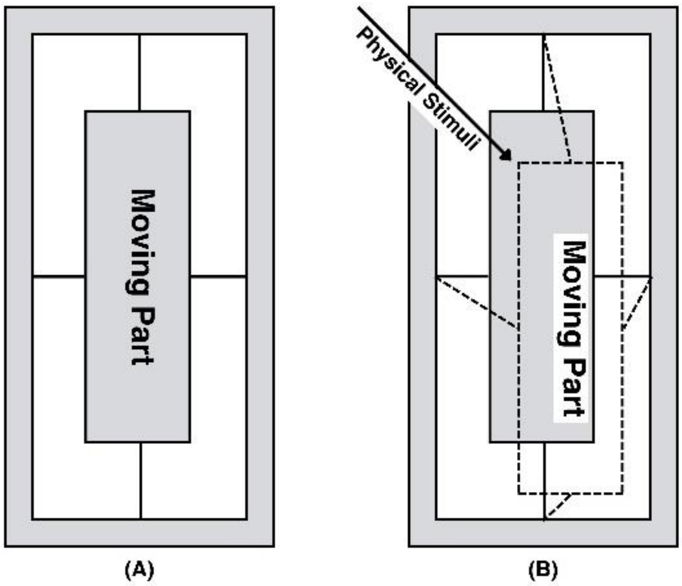

Fig. 1. A simple representation of an electromechanical system (A) without any stimulus, and (B) under a physical stimulus. (Copyrighted picture).

3. MEMS/NEMS-based applications in medicine

MEMS/NEMS technology can offer sensitive, portable, and effective systems or devices for medical and biological diagnosis, treatment, and control. Fig. 2 is a simple representation of their medical application. In this section, one will discuss MEMS- and NEMS-based medical applications under three main sub-titles, as in Fig. 2. Also, MEMS/NEMS-based medical studies have been listed in the Table 1. The table includes research articles, reviews, research conference papers, and book chapters. In the table, the subject part refers to the general aims of the relevant articles.

3.1. MEMS/NEMS-based medical imaging systems & biosensors

Biosensors, which can be fabricated from inorganic, organic, or biological materials, are systems capable of generating electrical or other physical signals in response to interactions with biochemical or biological substances (Al-Gawati et al., 2022; Kalaiarasi and Aishwarya, 2023; Langari et al., 2023; Harun-Or-Rashid et al., 2024; Neumann et al., 2024;

Table 1
MEMS/NEMS-based medical studies list.

MEMS/NEMS-Based Medical Application Studies			
Authors	**Year**	**DOI/URL**	**Subject**
Pachkawade, V.	2025	10.1016/B978-0-443-22002-9.00011-7	Sensor
Acharya, N.	2024	10.1016/j.mtcomm.2023.107844	Drug Delivery
Neumann et al.	2024	10.1002/anie.202317064	Sensor
Kuru and Ulucan-Karnak	2024	10.1039/9781837673476-00221	LoC, OoC, Personalized Medicine & Healtcare Management
Bakri et al.	2024	10.1016/j.nxmate.2023.100084	Sensor & Wearable Technology
Harun-Or-Rashid et al.	2024	10.1039/D4SD00086B	Sensor
Stapf et al.	2024	10.1021/acsaelm.3c01732	Biosensor
Drexler et al.	2024	10.3390/S24092922	Sensor, Cardiological Application & Telemedicine
Ewii et al.	2024	10.1016/J.NTM.2024.100042	Sensor & Drug Delivery
Kalaiarasi and Aishwarya	2023	10.1007/S42341-022-00421-9	Biosensor & Cancer Detection
Biswas et al.	2023	10.1007/978-981-19-8714-4_11	Sensor & Neurological Disorders
Mehdipoor and Ghavifekr	2022	10.1007/S10470-021-01963-3	Biosensor
Al-Gawati et al.	2022	10.1002/SIA.7132	Biosensor & COVID-19
Sitaramgupta et al.	2022	10.1109/TIM.2022.3141168	Sensor, Catheter & Cardiac Ablation
Nalini et al.	2021	10.1016/j.matpr.2021.02.019	Sensor & Contact Lens
Economidou et al.	2021	10.1016/j.addma.2020.101815	Drug Delivery
Manikandan et al.	2019	10.1016/j.vacuum.2019.02.018	Sensor & Neuro Sensing
Sun et al.	2018	10.3390/mi9020090	Sensor & Wearable Technology
Kaisti et al.	2017	10.22489/CinC.2017.143-140	Sensor & Biomedical Monitoring
Qiu and Piyawattanamatha	2017	10.3390/mi8070210	Sensor & Biomedical Imaging
Song et al.	2013	10.1002/adhm.201200356	Drug Delivery
Bhushan, B.	2011	10.1007/978-3-642-15263-4_23	Biosensor

Stapf et al., 2024). These signal conversions can be categorized into three main types: biological transformations (such as biochemical reactions, biophysical changes, and organismal effects), chemical transformations (including physicochemical changes and electrochemical processes), and physical transformations (such as thermoelectric, thermomagnetic, thermoelastic, photoelectric, photomagnetic, magnetoelectric, magnetoelastic, and piezoelectric effects) (Yeom et al., 2011).

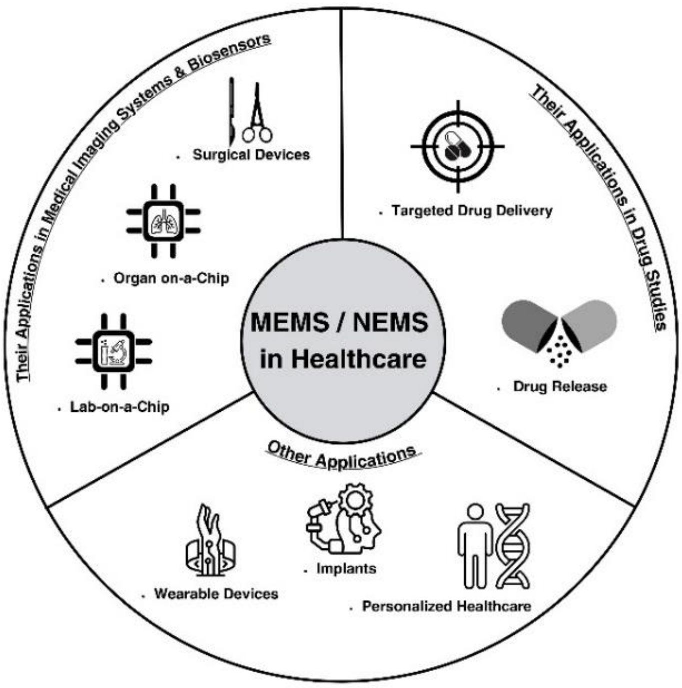

Fig. 2. MEMS/NEMS-based medical applications (Copyrighted picture).

MEMS/NEMS-based biosensors offer several advanced features, including high sensitivity, stability, resolution, and rapid response times. These characteristics make them particularly suitable for detecting, diagnosing, and monitoring a wide range of diseases by identifying and quantifying biological analytes and chemical substances. Common medical applications include blood glucose monitoring, DNA analysis, and the diagnosis of infectious diseases (Al-Gawati et al., 2022; Phan et al., 2022; Kalaiarasi and Aishwarya, 2023; Langari et al., 2023; Harun-Or-Rashid et al., 2024; Stapf et al., 2024). In this context, a study conducted at the Chinese Academy of Sciences focused on the development of integrated MEMS/NEMS resonant microcantilever sensors for ultrasensitive detection of biological molecules (Li et al., 2009). This study successfully demonstrated trace-level detection of alpha-fetoprotein antigens at nanogram-per-milliliter concentrations. By modifying the cantilever surface to enhance specificity and sensitivity, and optimizing resonance modes to improve mass detection capabilities, the study presented a promising approach for the early diagnosis of hepatocellular carcinoma.

Another significant development is the Oral Fluid MEMS/NEMS Chip (OFMNC), a point-of-care diagnostic platform designed to utilize oral fluids for health monitoring and disease detection (Li et al., 2005). This study underscored the diagnostic potential of saliva-often referred to as the “mirror of the body”-as a non-invasive medium for detecting systemic diseases. Also, because saliva contains thousands of mRNAs, some of which have been identified as diagnostic biomarkers for diseases like head and neck, the OFMNC platform has strong potential for cancer diagnostics.

Beyond their utility in cancer diagnostics, MEMS/NEMS-based biosensors also demonstrate substantial potential in advancing cancer treatment strategies (Li et al., 2005; Kalaiarasi and Aishwarya, 2023). One study that was conducted for this purpose introduced a MEMS-based microcantilever biosensor capable of detecting cancer biomarkers at low concentrations, along with a micro-actuator designed to vibrate at the resonant frequency of cancer cells for targeted destruction. This novel approach can provide a more effective, targeted, and less invasive strategy for cancer treatment. This biosensor vibrates at the specific resonant frequency (within the frequency range of 10^7 Hz-10^8 Hz) of cancer cells to selectively disrupt and destroy them, however, healthy cells remain unaffected at this frequency due to distinct mechanical and chemical properties, thus minimizing treatment side effects (Kalaiarasi and Aishwarya, 2023). This groundbreaking approach has significant potential to transform cancer diagnosis and treatment, offering more precise and patient-friendly solutions.

Beyond diagnostics and therapy, MEMS and NEMS technologies have also made significant contributions to medical imaging systems. They are utilized to enhance image quality in low-scale imaging systems such as microscopes and endoscopes. MEMS/NEMS technologies can facilitate the miniaturization and clinical application of biomedical optical imaging modalities by enabling the development of compact, functional optical and mechanical components. Within this scope, a study by Qiu and Piyawattanamatha (2017) explored innovations in endoscopic imaging based on MEMS sensors and actuators. The study highlighted advancements in fiber-optic imaging techniques, including confocal microscopy, optical coherence tomography, and photoacoustic imaging. The paper demonstrated that MEMS-based optical fiber endoscopy has strong potential for real-time, in-vivo imaging, offering cellular and molecular insights with deep tissue penetration, which can lead to better treatment outcomes and improved clinical applications. Additionally, MEMS/NEMS devices can offer high-resolution imaging through their micro- and nanomechanical and optical properties. Specifically, MEMS/NEMS-based sensors allow for sensitive and precise imaging using movable optical structures at the micro- and nanoscale (Bhushan, 2011).

In summary, such studies highlight the potential of integrated MEMS/NEMS technologies in biosensor applications and reveal their significant contribution to future biomedical advancements. MEMS/NEMS-based biosensor technology has transformative potential across various fields, from biomedical applications to defense. This technology paves the way for creating more robust, sensitive, and versatile systems in the future.

3.1.1. MEMS/NEMS-based surgical devices

Numerous challenges can arise before, during, and after surgical procedures. For instance, insufficient tactile and visual feedback complicates critical tasks such as tissue manipulation, cutting, and suturing. Furthermore, a limited range of motion reduces the ergonomic efficiency for surgeons, while low-resolution imaging and poor three-dimensional spatial perception, particularly in tools like endoscopes, hinder surgical precision (Ong and Al-Sarawi, 2005; Chircov and Grumezescu, 2022; Sitaramgupta et al., 2022; Shen, 2023; Reddy et al., 2024). MEMS and NEMS technologies offer promising solutions to address these challenges and overcome the limitations associated with traditional surgical methods. The integration of MEMS/NEMS technologies into surgical processes can significantly enhance the precision and effectiveness of surgical interventions (Grumezescu, 2022; Sitaramgupta et al., 2022; Chircov and Shen, 2023; Reddy et al., 2024). For example, MEMS- and NEMS-based sensors can function as navigation aids during surgical procedures, thereby enabling more accurate and precise interventions. Similarly, the applications of MEMS/NEMS-based sensors in procedures such as biopsies and catheterizations allow for operations with minimal error, owing to the piezoelectric properties of these sensors that facilitate precise surgical manipulation. In addition, MEMS/NEMS-based devices provide real-time feedback on tissue stiffness, blood vessel locations, and motion tracking, thereby offering critical tactile information during surgeries. MEMS/NEMS-based accelerometers and gyroscopes are particularly employed for these purposes. Moreover, the integration of MEMS/NEMS-based pressure, force, ultrasonic, and optical sensors into surgical instruments enhances the ability to measure applied forces and pressures, further improving surgical accuracy (Gertner and Krummel, 2004).

In summary, the incorporation of MEMS/NEMS devices into surgical instruments not only enhances surgical precision but also improves patient safety and reduces overall surgical costs. This innovative technology holds the potential to transform the field of surgery, offering substantial benefits to both surgeons and patients.

3.1.2. MEMS/NEMS-integrated lab-on-a-chip systems & organ-on-a-chip systems

Lab-on-a-chip (LoC) systems are technological platforms that enable small-scale laboratory studies based on the principles of microfluidics and standardization efforts in drug formulation (Lim et al., 2010). LoC systems enable the simultaneous execution of multiple analytical processes and biomedical analyses. They are widely used in the medical field, not only for diagnostic and examination purposes but also for pre-clinical research (Ziober et al., 2008; Islam and Sayed, 2012; Azizipour et al., 2020; Zhu et al., 2020; Mehdipoor and Badri Ghavifekr, 2022; Kuru and Ulucan-Karnak, 2024).

The integration of MEMS and NEMS technologies into LoC systems can further enhance precision and standardization (Islam and Sayed, 2012; Mehdipoor and Badri Ghavifekr, 2022; Kuru and Ulucan-Karnak, 2024). Consequently, MEMS/NEMS-enhanced LoC platforms can be particularly beneficial for a wide range of laboratory research applications, such as cell culture studies and the conjugation of active substances, as well as medical applications, including the detection of cancer biomarkers, blood analyses, and genetic testing. Notably, they can make obtaining results faster and more effectively because they can automate many diagnosis and examination processes (Azizipour et al., 2020). Similarly, LoC systems designed for cell culture applications can perform cell analyses and counting more efficiently using MEMS/NEMS-based sensors (Mehdipoor and Badri Ghavifekr, 2022; Kuru and Ulucan-Karnak, 2024). These systems can also be employed for molecular diagnostics and genetic material analyses. Although genetic analysis and DNA sequencing are traditionally complex and time-consuming, MEMS/NEMS-based LoC technologies can significantly streamline and accelerate these processes (Ehrlich et al., 2002).

Organ-on-a-chip (OoC) systems represent an advancement of LoC technology, designed to mimic organ, cell, and tissue functions (Wu et al., 2020). In OoC systems, the integration of MEMS/NEMS-based sensors ensures that the physiological functions of organs are replicated with high fidelity. As a result, OoC platforms provide a promising avenue for pharmaceutical research, allowing drugs to be tested on structures that closely resemble those in living organisms. Moreover, MEMS/NEMS-based OoC systems enable safer and more effective evaluations of the toxic limits of substances and pharmaceuticals, particularly in toxicology studies (Azizipour et al., 2020).

3.2. MEMS/NEMS-based drug studies

Research studies on the treatment of cancer, neurological disorders, and many genetic diseases continue (Manikandan et al., 2019; Biswas et al., 2023). In this context, research areas such as effective treatment methods, active agent research, and effective drug systems are up to date (Pattni and Torchilin, 2015; Sevim et al., 2025). In this context, MEMS/NEMS-based approaches for drug studies are one of the active research topics (Lee et al., 2018). Among these, drug delivery and drug release are the most studied fields (Economidou et al., 2021; Kalaiarasi and Aishwarya, 2023; Acharya, 2024; Ewii et al., 2024; Reddy et al., 2024). There are many drug delivery and release studies to obtain the ideal system because the biological, physical, and chemical differences can occur at the macro and micro levels specific to diseases. These differences differentiate the components and structures of the studied drug delivery and release systems. One also tries to use MEMS/NEMS-based systems, one of these studies, for drug delivery and release (Lee et al., 2018; Economidou et al., 2021; Ewii et al., 2024; Reddy et al., 2024). One can apply MEMS/NEMS-based drug delivery mechanisms as implantable, noninvasive, and oral. They can offer an ideal drug delivery system because one can control these systems by internal and external stimuli after applying (Lee et al., 2018; Ewii et al., 2024). One of the most vital steps of pharmaceutical treatment methods is drug release. It is essential that a therapeutic agent remains in the treatment site during a therapeutic period for effective treatment. Also, the agent must keep within the therapeutic index limits, which express the value between the dose that shows the minimum effect and the dose concentration that shows the minimum toxic effect. In this context, the controlled release of the therapeutic agent is vital. The use of MEMS/NEMS technology in drug delivery systems can provide controlled drug release. These MEMS/NEMS-based systems can optimize the treatment process. Also, MEMS/NEMS systems enable time-controlled drug release because they can be stimulated with different physical stimuli and contain a mechanical system. One can use MEMS/NEMS-based systems such as micro- and nano-injectors and nano-pumps (Meng and Hoang, 2012). Another study aimed to examine the transportation of MWCNT-Fe_3O_4-water hybrid nanofluidic under the influence of magnetic fields in micro-wavy channels and offer a new MEMS design for controlled drug distribution. The study focused on optimizing heat transfer and flow dynamics in channels with different wave patterns. Three different channel designs were analyzed by the finite element method, and heat transfer and flow dynamic parameters were optimized. The results have shown that increasing the amplitude channels provides the highest heat transfer and improves thermal performance, even though the flow of the magnetic field slows down. Also, nanoparticle concentration increased viscosity, but it has been determined that thermal conductivity maintains system efficiency (Acharya, 2024). These findings revealed the potential of microwave channels for controlled drug emissions and local hyperthermia treatment.

3.3. Other applications

The usage areas of MEMS/NEMS technology in medicine are vast. Although they generally have a high potential for use in biosensors and drug systems, one can also use them in areas such as wearable medical devices, implants, personalized medicine, etc.

3.3.1. MEMS/NEMS-based wearable medical devices

Today, wearable technology can be defined as a technology that collects information about users through different sensors and processes it. The communication protocol between devices over the internet network, which emerged with the concept of the Internet of Things (IoT), forms this information collection and processing mechanism in wearable devices. Rapid developments in health technologies and the widespread use of portable medical systems have increased interest in wearable technologies for monitoring body vitality (Sevim, 2024). Users' health conditions can be analyzed by monitoring basic body parameters such as heart rhythms, respiratory rates, blood pressure, and body temperatures (Kaisti et al., 2017; Sun et al., 2018; Phan et al., 2022; Padha et al., 2023; Bakri et al., 2024). Different sensors are used in wearable medical devices to collect or process this information. However, MEMS/NEMS-based sensors can be more effective for wearable devices because of their functional features (Padha et al., 2023). In addition, these sensors provide low power consumption and high sensitivity, allowing users' health data to be collected precisely for long periods. In addition, thanks to their multiple functions, they can provide an opportunity to monitor many parameters simultaneously (Kaisti et al., 2017; Sun et al., 2018; Preeti et al., 2019; Phan et al., 2022; Padha et al., 2023; Bakri et al., 2024).

3.3.2. MEMS/NEMS-based implants

Although one uses medical implants to improve people's quality of life, they have aspects that need improvement. At the same time, small-sized and sensitive implants need to be developed for some disorders. At this stage, one can use MEMS/NEMS-based implants. For example, highly sensitive implants with nerve connections to the brain can be used in the treatment of neurological disorders (Biswas et al., 2023; Manikandan et al., 2019), or eye implants can be used to measure intraocular pressure (Nalini et al., 2021). This study, performed by Nalini et al., focused on a MEMS-based smart contact lens design to continuously monitor the vision problems and intraocular pressure caused by digital screens. The study aimed to reduce the need for surgical intervention by diagnosis and warn users about vision changes. In the study, MEMS image sensors and flex sensors integrated into the contact lens produced from hydrogel material were used. The system performed two basic functions (Nalini et al., 2021):

- MEMS image sensor and retinal images are captured, and visual defects (myopia, hypermetropia) are determined,
- The risk of glaucoma is determined by measuring the intraocular pressure through hydrogel-based flexors.

The collected data is processed in a cloud environment, and an alert is sent to the user in abnormal situations. The results showed that this technology can help maintain vision health, especially in individuals who have been exposed to digital screens for a long time.

3.3.3. MEMS/NEMS-based personalized healthcare

Personalized healthcare is an area that has come to the fore recently. Determining and applying treatments specifically for individuals provides more effective treatment. For this reason, one has turned towards personalized healthcare services. Integrating MEMS/NEMS into personalized medicine can enable the personalized functioning of medical applications such as implantable sensors, drug systems, and implantable drug delivery mechanisms. These systems may increase patients' compliance with treatment (Song et al., 2013; Economidou et al., 2021; Kuru and Ulucan-Karnak, 2024). This study, done by Economidou et al. (2021) aimed to develop a new microneedle system for personalized and user-controlled transdermal drug distribution by combining 3D printing technology and MEMS. Especially in the treatment of diabetes, the effectiveness of insulin distribution and patient compliance was tried to increase. In this study, hollow microneedles were produced by using stereolithography and integrated with a MEMS pump. This technology promises hope for the personalized distribution of insulin, especially in diabetic patients, and it also offers potential for transdermal application of vaccines and protein-based drugs.

4. Conclusion

MEMS/NEMS technology can eliminate many deficiencies in medical applications, and many innovative approaches to be applied. They can facilitate many medical practices to be more effective, from examination and diagnosis to treatment and new treatment research. This technology, which is still under development, will provide more innovative applications to emerge in the field of medicine in the future. However, one must overcome its existing difficulties for this. One of these obstacles is production and cost problems. In particular, the widespread use of MEMS/NEMS may be a challenge for mass production systems. In this case, costs may increase. In addition, the data security of these systems is another crucial challenge. Since the large amounts of data collected by MEMS/NEMS-based sensors must be reliably stored and analyzed, one must establish powerful data management strategies. In addition, one must define the standards and calibrations for the systems to function well. In this context, one should do more studies to determine the standards. Such difficulties need to be solved for the widespread use of MEMS/NEMS technology in the medical field and its commercial use. But even now, it has a serious market. Increasing rates of chronic diseases, aging populations, demand for wearable medical devices, and home healthcare solutions are fueling the growth of MEMS/NEMS technologies in medicine, especially in diagnostics, monitoring, drug delivery, and surgical applications. In this context, the global medical MEMS market was valued at $4.8 billion in 2023 and is projected to reach $7.2 billion by 2028, growing at a CAGR of 8.5%. The Bio-MEMS market is expected to grow from $9.79 billion in 2022 to $24.88 billion by 2030, with a CAGR of 12.2%. The Surgical MEMS market is projected to grow from $2.5 billion in 2023 to $8.1 billion by 2032, with a CAGR of 14.2%. In these markets, major uses are in diagnostic devices (40%), monitoring devices (30%), and therapeutic devices (20%). Common sensor types include pressure sensors (35%), optical sensors (25%), and temperature sensors (20%) (Industryarc, 2023; MarketandMarkets, 2023). It is obvious that more studies will be done on new medical application areas of MEMS/NEMS in the future. Different areas of use will likely emerge with the full integration of MEMS/NEMS technology into medical applications. Especially, in the future, the integration of the Robotic System, Artificial Intelligence, Augmented Reality, and IoMT (Internet of Medical Things)-based technologies into the medical field will be inevitable. In this context, MEMS/NEMS technologies will form the most basic components of integration. Also, Telemedicine, which is still working on the integration of the medical sector, will be able to remotely control robotic systems thanks to NEMS/MEMS technology. Furthermore, MEMS/NEMS-based biosensors will also have an important place in developing tissue engineering in recent years, because these sensors could provide real-time feedback on blood flow, pressure, vibration, and temperature, improving surgical precision and reliability.

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Informed consent: The author declares that this manuscript did not involve human or animal participants and informed consent was not collected.

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