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**Review Article**

# The Microfluidic Revolution in Medical Diagnostics

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## ABSTRACT

A fast expanding field that has completely changed the way we think about healthcare is microfluidics. Small quantities of fluids, usually measured in microliters or nanoliters, are manipulated in tiny chambers or channels that are integrated into a microchip. Because of its high resolution, automation, low cost, and capacity to conduct diagnostic tests with small sample volumes, microfluidic devices have emerged as attractive point-of-care (POC) and customized medicine tools.Many of the most advanced medical diagnostic technologies are unavailable in developing nations; these technologies were created for air-conditioned labs, refrigerated chemical storage, a steady supply of reagents and calibrators, stable electrical power, highly skilled staff, and quick sample transportation.Due to their intrinsic miniaturization properties, low sample consumption, integration, and compatibility with a variety of analytical procedures, microfluidics-based platforms have become attractive substitutes for conventional methods in high-throughput drug screening.The current trend in microfluidics is to develop integrated devices that integrate various fluidic, mechanical, and electronic components or chemical processes onto a single chip-sized substrate, since the principles of microscale flow and species transport are well established. .Since early diagnosis can significantly improve recovery rates and stop the spread of infectious diseases like COVID-19, it is essential. However, timely disease detection can be difficult in many places with inadequate medical services.Rapid and effective analyses for successful intervention in areas such as biology research, infectious disease management, food safety, and biodefense are made possible by developments in molecular biology.By controlling fluid flow and transport processes at the microscale and analyzing and manipulating small fluid volumes and particles at small scales, microfluidic lab-on-a-chip technologies have paved the way for the creation of novel approaches to a wide range of scientific and medical problems.

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## INTRODUCTION

In recent years, biosensors have received a lot of attention in the fields of nanotechnology and medicine since Led and Clark developed the first oxygen biosensor in 1962.[1]Microfluidic technology has been used in many scientific domains, including chemical synthesis, since its groundbreaking discovery in the early 1990s.[2]The technique for creating microminiaturized devices with channels and chambers that have scale dimensions of 1 mm or less in order to regulate the flow behavior of tiny fluid volumes is known as microfluidics.[3]Emerging microfluidic strategies include (i) multilayer soft lithography; (ii) capillary driven and paper-based microfluidics; (iii) EWOD driven droplet microfluidics; (iv) multiphase microfluidics; (v) centrifugal microfluidics; (vi) electrokinetics; and (vii) hybrid microfluidics. These strategies aim to effectively integrate multiple microfluidic components into fully automated lab-on-a-chip systems. [4]Commercially accessible examples of these sensors include paper microfluidic lateral flow technologies, which are used in pregnancy testing, and sample-to-answer solutions, such as continuous glucose monitoring and finger-stick glucose monitoring. [5]Miniaturized, convenient, and integrated microfluidic chip technologies and biosensor technologies have been used more and more for POCT detection in recent years due to advancements in science and technology, sensing technology, advanced manufacturing technology, and the Internet of things. [6]Furthermore, systems utilizing microfluidic devices frequently call for specialized personnel, outside tools, and time-consuming sample preparation processes. [7]

### Types of Microfluidic devices

### Lab on a chip

A lab-on-a-chip (LOC) is a device that conducts one or more experiments that are normally conducted in a laboratory on a tiny scale.It combines and automates a number of high-resolution laboratory processes, including fluid testing, chemical synthesis, and analysis, into a chip-sized machine. Operating at this size has numerous benefits. Instead than being transported to a large laboratory facility, samples can be analyzed on-site, where they are created.[8]

### Organ on a chip

Aiming to replicate the essential functions of biological organs on a computer chip, organ on chips are now 3D cell culture microdevices. Compared to traditional cell culture methods, those microfluidic systems are more effective because they can replicate microenvironments and their effects on organ function. This enables research into the physiology of a particular organ in humans and starts the development of artificial disease models.[8]

### Cell sorting devices

To separate cells according to their physical or biological characteristics, these devices make use of microfluidic channels and different sorting methods. They make it possible to sort cells in large quantities and without labels, which is useful for applications like cancer diagnosis, study of stem cells, and cell-based assays.[9]

### Continuous flow microfluidic devices

These devices give fine control to the rate of fluid flow and mixing by allowing fluids to flow continuously through microchannels. They are employed in processes where accurate fluid control and effective mass transfer are essential, such as chemistry, enzyme reactions, and cell culture.[9]

### Droplet based microfluidic devices

Individual droplets, which may contain cells, chemicals, or other biological components, can be manipulated and analyzed thanks to these technologies. They are employed in processes like digital PCR, high-throughput screening, and single-cell analysis.[9]

### Microfluidic technology and personalized medicine

Personalized medicine is a new discipline that aims to increase treatment effectiveness by utilizing pharmacogenomics, focused medicines, risk factors, and molecular diagnostics. In order to make the best treatment decisions for a patient, personalized medicine connects a person's molecular signature to their medical profile.[10]

**Personalized Medicine Using Multiple Organs on a Chip**

Organs on chips are microfluidic devices with dynamic, controlled microenvironments where cultured cells display physiologic behaviors similar to those of organs. Research on human health could undergo a radical change thanks to multiorgan-on-a-chip technology. By including blood samples, primary human tissue, and cells created from induced pluripotent stem cells based on individual health data, they can theoretically be "personalized" to match individual physiology. Person-specific pharmaceutical efficacy and safety evaluations, as well as tailored disease prevention and treatment strategies, are made possible by the personalized nature of these systems and physiologically relevant readouts. Personalized medicine is a popular topic in the medical sector. Personalized medicine is both an approach to individualizing care and a notion of rational therapies.[11]

**Drug examination**

**Therapeutic drug screening**

Blood, saliva, tears, sweat, urine, and ISF can all have their drug concentrations measured by therapeutic drug screening, sometimes referred to as therapeutic drug monitoring (TDM). Additionally, for better therapeutic efficacy, it guarantees a precise and correct dosage for every patient with little adverse effects. [12] Because of its ease of use, small size, and real-time, extremely precise patient dosage selection, therapeutic drug screening using microfluidics may be used in medical facilities in the future.[12]

**Illicit drug screening**

Addiction and illegal substance usage have grown to be serious issues on a global scale in recent years. Illicit drug analysis typically faces a number of challenges. First, it must be possible to detect a low concentration of the target analyte.Second, the accuracy of the analysis and detection may be impacted by the matrix found in actual samples. In the complicated background of actual samples, precise and reliable analytical measures of the target medication are required .[12]

**Microfluidic devices for diagnosis**

**Early Disease Diagnosis Using Microfluidic POC**

Humans are susceptible to a wide range of infectious diseases, such as tuberculosis, SARS, acquired immune deficiency syndrome (AIDS), influenza A (H1N1) in the early 20th century, and the bubonic plague in the Middle Ages.At the start of an outbreak, early diagnosis also helps to reduce transmission. [13]

**Microfluidic instruments for microorganism identification**

The effects of medications interacting with cells or other chemical-biological interactions are studied using microfluidic systems, which can let fluid flow in desired designed channels. Without requiring cell culture, these instruments are also utilized for pathogen identification and quantification [14]

**Virus detection with microfluidic systems**

Micrometer-scale pathogens known as viruses can infect humans, animals, plants, and even microorganisms, causing a variety of diseases. The only environment in which these protein- coated nucleic acid-based viruses may multiply is within live cells. Viruses are made of DNA or RNA and can be single or double stranded. In certain situations, they can spread very easily.[14]

**Detecting cancer with microfluidic devices**

Microfluidic system technology has a great deal of potential for utilizing sensor devices for a variety of purposes, including biological detection, clinical diagnostics, and environmental or sewage monitoring . Microfluidic technology has emerged as a significant tool for cancer research in the last ten years [15] .A biopolymer system was used by Shah et al. to capture cells and recover them from the microfluidic devices [16] .Prostate cancer is third among cancers in males and is responsible for over 10% of the deaths caused by cancer [17]

**Multiple CVD Biomarker Identification**

Numerous pathogenic variables and different processes contribute to the complex process of cardiovascular disease occurrence and development.[18] Visible microchannels with flexible geometric shapes that can replicate the intricate structural structures of microvascular networks can be provided using microfluidic technologies.[19] Furthermore, sensitive experiments that recreate complex cardiovascular biophysical interactions can be carried out by carefully modifying the surface characteristics of microchannels.[20]

**DNA Amplification and Analysis Using Microfluidics**

Polymerase Chain Reaction (PCR) is one of the most reliable and widely used molecular diagnostic methods in medicine, and DNA analysis and amplification are becoming commonplace in many diagnostic and analytical processes (Chang et al., 2013). The two main categories of DNA amplification methods are isothermal and non-isothermal.[21]

**MDTs' prospects in emerging nations**

The capabilities of present analytical systems should be enhanced by next-generation MF systems, which should also integrate MF into existing devices to increase capabilities and establish interoperability standards across various MF formats to enable digital, discrete, and continuous multifunctional capabilities. [22] There is also a synergistic confluence between artificial intelligence and microfluidics.Amazing mechanical movements could soon be achieved by the use of metamaterials, neuromorphic planning, and updated thinking, among other creative microfluidics-in-new- spaces combinations [23] At the intersection of ultrasound and microfluidics, a new and exciting discipline has emerged. Technically possible, this combination produces beneficial outcomes for medicinal, diagnostic, and drug encapsulation applications [24]. It is anticipated that the advancement of microfluidic technology for diagnostic applications would grow and permeate our daily lives because to the widespread interest in addressing challenges linked to human health across different societal factions.[25] Microfluidics has been hailed as having the potential to replace (or at least supplement) LFIA devices for medical applications in point-of-care (POC) settings by enabling the automation and miniaturization of diagnostic instruments. When compared to LFIA technology, it offers a number of benefits.[26]

**Future scope**

There are numerous infectious diseases that need prompt diagnosis and treatment in order to lessen the death rate, including malaria, HIV and AIDS, measles, TB, lower respiratory disorders, and others [27].Future microfluidic products that satisfy the WHO's POC requirements, which include: (1) being accessible to individuals at risk of infection; (2) having high sensitivity and specificity; (4) being easy to use; (5) being quick and reliable; (6) not requiring any equipment; and (7) being provided to those in need[28].The goal is to create a human-on-a-chip system in the near future by connecting several organ-on-a-chip models. Combining automation, robotics, and disease modeling with human-on-a-chip models can give a customized, in-depth look into how medications impact a person's entire body.[29]Numerous techniques, including fluorescence, magnetic resonance imaging (MRI), and bioluminescence imaging (BLI), are already being used in certain research to determine the destiny of cells

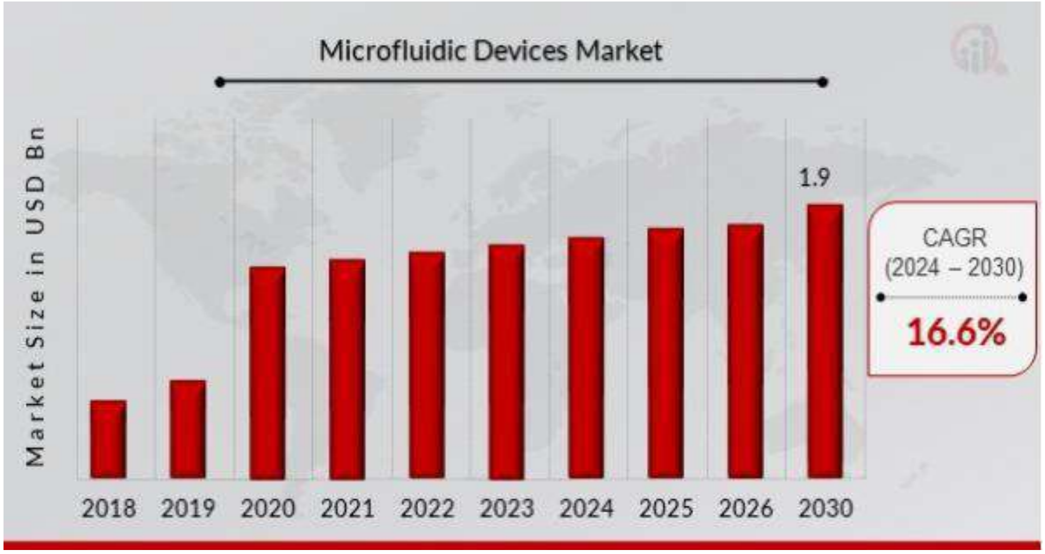


**Fig. Market Size of Microfluid Devices**

throughout time.[30]. Future prospects are bright thanks to advancements in optical instruments and innovative FP, which give a previously unheard-of comprehension of the dynamics of biological function in relation to tissue regeneration and regenerative medicine.[31]

**Case study**

**Microfluidic devices for waste water detection**

Over time, a number of detection techniques have been investigated for water quality monitoring systems based on microfluidics. The most often utilized techniques among the many mechanisms are photoelectrochemical, fluorescence, and electrochemical detection. Additional methods of detection include surface plasmon resonance, colorimetric, chemiluminescence, absorbance-based, quartz crystal microbalance, etc.[32]

**Heavy metal detection**

The toxicity and environmental behavior of metal ions are significantly impacted by the identification of such metal speciation. A metal's speciation affects atmospheric deposition, electron-transfer processes, precipitation equilibria, solubility, and diffusivity in addition to being poisonous . varied forms and stages of methodologies to examine the behavior of metals result in varied speciation.[33]

**Statistics**

During the 2024–2030 forecast period, the microfluidic devices market is anticipated to grow at a 16.6% CAGR to reach USD 1.9 billion by 2030. In the realm of diagnostics, microfluidics is gaining popularity, particularly in point of care (POC) diagnostics. This is complemented by microfluidic integrated biosensor technology, which is expected to improve point-of-care diagnostics in the near future .By combining microfluidic components with POC devices, it aims to acquire minimally invasive POC technology and improve sensitivity, stability, accuracy, and cost.[34] The demand for genomics or complete strand of cells, and proteomes is increasing. This is the main factor propelling the market for microfluidic devices. Only with the aid of microfluidic technologies is it now feasible to test minuscule cells.As the quantity used and preserved for testing is very minute, it has made the handling less cumbersome and the results attained are quicker than primitive methods of testing.[35]

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## CONCLUSION

Microfluidic devices are revolutionizing how we handle and analyze fluids, leveraging micro-scale channels to achieve extraordinary precision and efficiency. These devices enable groundbreaking advancements in biomedical diagnostics, personalized medicine, and environmental monitoring by integrating complex laboratory processes into compact, portable systems. As their design and functionality evolve, microfluidic devices continue to unlock new possibilities, shaping the future of science and technology in transformative ways.

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