

Diagnosis of micro- and nanoplastic exposure in humans: current status and prospects, technological advances, and clinical implications

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Abstract

The diagnostics of human exposure to micro- and nanoplastics represents an emerging and rapidly evolving field at the intersection of environmental medicine, toxicology, and biomedical sciences. Recent technological advances, including the development of spectroscopic, microscopic, and high-resolution analytical techniques, have enabled the detection of microplastic particles in biological samples such as blood, tissues, and placenta. Despite these achievements, the detection of nanoplastics remains challenging due to their extremely small size, lack of methodological standardization, and the risk of sample contamination. Increasing evidence suggests potential clinical implications of micro- and nanoplastic exposure, including their involvement in inflammatory processes, oxidative stress, and the development of cardiovascular, neurological, and autoimmune diseases. Future directions will focus on the identification of reliable biomarkers of exposure and biological effects, integration of omics approaches, and the application of artificial intelligence in data analysis. Advancing this field may significantly improve our understanding of environmental impacts on human health and support the development of novel diagnostic and preventive strategies.

Keywords: nanoplastics, environmental diagnostics, civilization diseases, microplastics, biomarkers

Introduction

Microplastics and nanoplastics (MNPs) represent an emerging biomedical and environmental problem, and their potential health consequences are currently being intensively studied [1]. Microplastics (<5 mm) and nanoplastics (<1000 nm) are the products of the degradation and fragmentation of plastics, which, as a result of intense anthropogenic pressure, have become a widespread contaminant in aquatic, air, and food environments [2]. Human exposure to MNPs occurs primarily through ingestion, inhalation, and contact, with diet and drinking water remaining the dominant sources [3]. It is estimated that annual exposure may range from tens of thousands to even millions of microplastic particles, indicating their widespread presence in the environmental and food chains [4].

In recent years, MNPs have been detected in the bloodstream, placenta, lung tissue, intestines, and structures of the central nervous system, confirming their ability to undergo biological translocation [5-10]. For this reason, the diagnosis of MNP exposure is emerging as a new field in environmental biomedicine, requiring both the development of analytical

methods and clinical interpretation [7]. Concurrently, diagnostic methods are being developed that include spectroscopic and chromatographic techniques, as well as advanced methods for nanoparticle analysis; however, there is a lack of uniform reference standards [11].

Detection limits vary depending on the technology used and the type of biological material, ranging from single particles to levels of ng- μ g/g [12-14]. Particular difficulties arise in identifying nanoplastics, which, due to their size of less than 100 nm, elude conventional analytical techniques [15].

A growing body of research also points to the potential role of MNPs in the pathogenesis of lifestyle-related diseases through the induction of oxidative stress, chronic inflammation, and immune dysregulation [16].

Aim of the work

The aim of this review was to critically assess the current state and future prospects of diagnosing human exposure to MNPs, with particular emphasis on emerging analytical technologies, methodological challenges, and potential clinical implications.

This analysis is particularly relevant due to the growing environmental contamination with MNPs in Poland and worldwide and their potential health implications.

Methods

This paper is a narrative review covering recent studies (2019-2026) on the detection of MNPs in biological materials and their potential clinical significance. The analysis included: experimental studies, review articles, and toxicological studies concerning spectroscopic methods (Fourier Transform Infrared Spectroscopy (FTIR), Raman Spectroscopy), chromatographic methods (Pyrolysis-gas chromatography-mass spectrometry (Py-GC-MS)), and nanoparticle analysis techniques (Dynamic Light Scattering (DLS), Nanoparticle Tracking Analysis (NTA), Atomic Force Microscopy (AFM), single particle inductively coupled plasma mass spectrometry (spICP-MS)). Article searching was conducted in the electronic databases: PubMed and Science Direct, and articles were searched by title and abstract. The following keywords were used: “microplastic”, “nanoplastic”, and “human tissue”. Studies on the distribution of MNPs in human tissues and animal models describing toxicity mechanisms were

also included. Particular attention was paid to detection limits, sample contamination issues, and the lack of standardization in analytical procedures.

Literature review results

The World Wildlife Fund (WWF) has estimated that the average person may consume about 5 g of microplastics per week. Microplastics have been detected in a number of human biological samples, including samples collected during colectomy, as well as in saliva, sputum, lungs, liver, breast milk, and feces. Microplastics and smaller polymers can be transported throughout the human body via the bloodstream and cross the blood-brain barrier, which may lead to oxidative damage and immune stress, thereby posing a threat to human health [4-11].

The analysis of chronic exposure to microplastics opens up new diagnostic possibilities through the development of methods for detecting particles in biological samples (e.g. blood, vascular tissues, or atherosclerotic plaques), which may enable the identification of a new type of environmental biomarkers for the risk of lifestyle-related diseases [17,18].

The application of “omics” approaches (e.g. proteomics and metabolomics) in microplastic research may enable the identification of early molecular changes in the endothelium, thereby enhancing the potential for early diagnosis of vascular disorders [19].

Experimental studies indicate that microplastics can induce oxidative stress and endothelial dysfunction, paving the way for the development of diagnostic biomarkers based on inflammatory and oxidative markers [20]. The integration of toxicological and pharmacological data may enable the development of new diagnostic and therapeutic strategies, including the identification of molecular targets associated with microplastic accumulation and its impact on the progression of atherosclerosis [21].

Biological materials and the distribution of MNPs

The most conclusive evidence of the presence of MNPs comes from peripheral blood, where concentrations reach levels on the order of $\mu\text{g/mL}$ or several to several dozen particles per milliliter [5]. Polymers such as polyethylene, polypropylene, and polyethylene terephthalate dominate in plasma, reflecting their widespread industrial use [5]. In lung tissue, concentrations ranging from several dozen to several hundred particles per gram of tissue have been detected, suggesting a significant role for inhalation as a route of exposure [8]. The highest concentrations

are observed in feces, where the number of particles can reach thousands per gram, reflecting current intake [10]. In deep tissues, including the brain, nanoplastics predominate, though their quantities remain difficult to quantify precisely [6]. The detection of MNP particles in atherosclerotic plaques in humans suggests the possibility of using them as a prognostic marker that may be associated with the risk of cardiovascular events [22].

Diagnostic methods and limits of detection

Currently, FTIR and Raman spectroscopy are the primary methods used to identify microplastics, enabling the detection of particles ranging in size from 1 to 20 μm [11]. Pyrolysis-GC-MS is an analytical tool used to characterize a wide range of polymers and composite materials that cannot be analyzed using traditional gas chromatography-mass spectrometry (GC-MS). Py-GC-MS allows for the determination of polymer mass at the ng/g level in biological samples; however, it does not provide information on particle morphology [14].

The greatest limitation of classical methods remains their inability to detect nanoplastics and their high susceptibility to contamination [13]. Nanoplastics require the use of analytical methods with higher resolution. DLS enables the assessment of the average particle size but does not allow for their chemical identification. NTA allows for the analysis of particle number and motion in a suspension but requires very high sample purity. AFM provides high topographic resolution but has low analytical throughput [15].

Inductively coupled plasma mass spectrometry (ICP-MS) is one of the leading techniques in atomic spectrometry, originally developed to provide information on isotopes and total elements. However, when used with a very high, continuous data acquisition rate and appropriately diluted suspensions, ICP-MS becomes a particle-counting technique that provides information on a particle-by-particle basis, known as single-particle ICP-MS (spICP-MS). This method is one of the most promising techniques for detecting nanoparticles; however, its application in polymer analysis remains limited [12].

Laboratory diagnosis of microplastics – methods and limitations

The diagnosis of microplastics in biological samples is based on spectroscopic techniques, such as micro-FTIR and Raman spectroscopy [6]. These methods enable the

identification of polymers based on their chemical spectra [11]. Pyrolysis coupled with gas chromatography and mass spectrometry (Py-GC-MS) is also used in diagnostics, particularly in blood analysis [14].

Electron microscopy with energy-dispersive X-ray spectroscopy (EDS) analysis allows for the assessment of particle structure and composition [6]. Modern approaches include the use of fluorescent staining (e.g. Nile Red) and artificial intelligence algorithms [15]. The greatest diagnostic challenge is the low concentration of MNPs in biological samples and their heterogeneity [11]. Another significant limitation is the lack of standardized sample preparation procedures [12]. Laboratory contamination can lead to false-positive results. Some methods may also mistakenly interpret lipids as plastics [13].

Biomonitoring and clinical diagnostics of MNPs – in Poland and global status

MNP diagnostics in clinical medicine remains at the experimental research stage and is not routinely used [7]. In the United States, research is being conducted on the measurement of MNPs in blood and tissues as part of academic projects [17]. In Western European countries, environmental biomonitoring programs are being developed, but these primarily focus on the environment rather than clinical diagnostics [18]. In China and other Asian countries, methods for detecting MNPs in tissues are being developed, particularly in the context of toxicological studies [16]. There are currently no approved clinical standards defining acceptable concentrations of MNPs in the human body [17]. There is also a lack of diagnostic guidelines in healthcare systems [11].

In Poland, the detection of micro- and nanoplastics in the human body is not routinely performed in clinical practice. Research is conducted primarily at scientific centers and focuses on the environment and food, rather than on patient diagnostics. Scientific laboratories at institutes and universities primarily use FTIR and Raman methods in environmental analyses [12].

There is no system for biomonitoring MNPs in the general population. In clinical practice, there is no capability to measure MNPs in standard laboratory tests [11].

MNP diagnostics and lifestyle-related diseases

Microplastic particles have been detected in human blood, demonstrating systemic internal exposure and providing a potential route for distribution to distant organs [5]. MNPs can accumulate in organs such as the brain, liver, and kidneys. Their presence in tissues suggests a potential link to neurodegenerative and cardiovascular diseases [6]. Mechanisms of toxicity include oxidative stress, inflammation, and immune disorders [16]. Studies show that the presence of microplastic particles in the blood may correlate with coagulation disorders [17]. However, the lack of standardized diagnostic methods prevents an unequivocal causal relationship from being established [11,17].

MNPs may affect the central nervous system through several mechanisms, including their potential translocation across the blood-brain barrier (BBB) and induction of oxidative and inflammatory responses. Experimental studies indicate that MNP exposure may impair BBB integrity and promote oxidative stress, neuroinflammation, mitochondrial dysfunction, and disturbances in neuronal signaling and homeostasis [23,24]. Activation of microglia and other inflammatory pathways has also been reported in experimental models, suggesting a potential role of MNP-induced neuroinflammation in neurological dysfunction [24,25]. Although evidence directly linking MNP exposure with neurological diseases in humans remains limited, increasing experimental evidence suggests that chronic MNP exposure may contribute to mechanisms relevant to neurodegenerative disorders, including Alzheimer's and Parkinson's diseases [24,25].

In the context of autoimmune diseases, microplastics may act as modulators of the immune response, potentially by activating the immune system and inducing chronic inflammation. These particles may serve as carriers for other toxic substances (e.g. heavy metals, endotoxins), which further increases their immunotoxic potential. *In vitro* studies and animal models have shown that exposure to microplastics can lead to dysregulation of the immune response, which theoretically may promote the development of autoimmune diseases [25,26].

Plastic materials contain numerous chemical additives, including phthalates, bisphenols, organotin compounds, flame retardants, perfluorinated substances, and heavy metals. Some of these compounds exhibit endocrine-disrupting activity and may interfere with hormone receptor signaling and endocrine regulation, potentially contributing to reproductive and developmental abnormalities [26].

Another important area of research is the impact of microplastics on the gut-brain axis and the gut microbiota, which play a key role in both the regulation of neurological functions and the immune response. Microbiome dysregulation induced by microplastics may indirectly influence the development of neuropsychiatric and autoimmune diseases through inflammatory and metabolic mechanisms. This approach, which integrates environmental toxicology with neuroimmunology, may open up new diagnostic and therapeutic possibilities in the future [27,28].

Blood-brain barrier and the nervous system

Blood-brain barrier (BBB) is an important protective interface of the central nervous system. Experimental and human evidence indicates that certain MNPs can reach the central nervous system (CNS), particularly when BBB integrity is impaired [6,16]. MNPs have been detected in human brain tissue and cerebrospinal fluid, while experimental studies suggest that their accumulation may be associated with oxidative stress, inflammation, and neuronal dysfunction [6,16,29]. These findings indicate a potential relevance of MNP exposure to neurological health, although their contribution to neurodegenerative diseases in humans remains insufficiently established [6,29].

BBB is a key protective mechanism of the central nervous system against xenobiotics [6]. Due to their small size and surface properties, nanoplastics can potentially cross the BBB via transcytosis and vesicular transport [6,16]. Their presence in brain tissue is associated with microglial activation, oxidative stress, and disturbances in neuronal homeostasis [16].

This ability to penetrate the CNS makes nanoplastics particularly significant in the context of neurodegenerative diseases [6].

Neurodegeneration and autoimmune diseases

Experimental studies suggest that MNPs may contribute to neurotoxic processes through oxidative stress, mitochondrial dysfunction, inflammation, and disruption of cellular homeostasis [16,17,20,28,29]. Importantly, MNPs have been detected and quantified in human brain tissue, with higher concentrations reported in individuals with documented dementia, although this does not establish a causal relationship with neurodegenerative diseases [6]. These findings suggest that MNPs may affect biological pathways involved in neuroinflammation and

neuronal dysfunction, but their long-term contribution to diseases such as Alzheimer's and Parkinson's remains insufficiently established in humans [6,16,29].

Future directions in MNP diagnostics

The future of MNP diagnostics involves the development of highly sensitive methods and the standardization of laboratory procedures [12]. The development of biomarkers of exposure and biological effect is of significant importance [7]. The use of artificial intelligence may increase detection accuracy [15]. Epidemiological studies linking diagnostic results to diseases are necessary. The data obtained indicate that the diagnosis of MNPs is in an early stage of development and is characterized by significant methodological limitations [11].

The greatest challenge remains the lack of standardization of analytical procedures and the difficulty in unambiguously identifying nanoplastics in biological materials [13]. The diversity of methods and the lack of exposure biomarkers currently prevent a full clinical interpretation of the results [11-15]. At the same time, the presence of MNPs in human tissues and their potential ability to cross biological barriers suggest the need for further research into their health implications [5,6]. It seems particularly important to develop methods that enable long-term population-based biomonitoring and the assessment of the risk of chronic diseases [11].

Although the link between microplastics and neurological and autoimmune diseases remains at the stage of hypotheses and preclinical studies, the available data point to the biological mechanisms underlying their effects. Further clinical and epidemiological studies will be crucial for determining the actual significance of these particles as a risk factor and a potential diagnostic target in environmental medicine.

Conclusions

The state of diagnostics for exposure to MNPs in humans remains at an early but rapidly evolving stage. In recent years, significant technological progress has been made, particularly in analytical methods such as FTIR spectroscopy, Raman spectroscopy, and advanced microscopy, which enable the detection and partial characterization of microplastics in biological samples (e.g. blood, placenta, or tissues). However, the lack of standardized

procedures, insufficient sensitivity for nanoplastics, and the risk of sample contamination remain limitations, making it difficult to compare results across studies.

From a clinical perspective, there is a growing body of evidence pointing to a potential link between the presence of MNPs and pathological processes, including inflammation, oxidative stress, and vascular changes. Findings regarding the presence of these particles in structures such as atherosclerotic plaques suggest their possible role as a new risk factor for cardiovascular disease. Nevertheless, clinical diagnostics do not yet include routine testing for microplastics, and their prognostic and causal significance requires further study.

Future developments in this field include the integration of “omics” technologies, the development of highly sensitive methods for detecting nanoplastics, and the use of artificial intelligence to analyze complex environmental and biological data. It will also be crucial to develop reliable biomarkers of exposure and biological effects that could be applied in preventive and personalized medicine. In the long term, the development of this branch of diagnostics may contribute to a better understanding of the impact of environmental pollutants on human health and to the implementation of new preventive and therapeutic strategies.

Diagnostics for exposure to MNPs is a rapidly developing area of research. It is currently possible to detect microplastics in various biological materials; however, the identification of nanoplastics remains a significant technological challenge. Research on exposure routes (air, water, soil) and the accumulation of these particles in human tissues enables the assessment of health risks and the development of appropriate models [29]. Collaboration among scientists from various fields may also contribute to the development of materials that are less prone to breaking down into harmful MNPs.

The lack of standardization in clinical methods and standards remains a significant problem, making it difficult to interpret results. The analysis of biological samples (e.g. blood or tissue) is complex; therefore, the development of noninvasive and precise techniques for the identification and quantitative determination of MNPs is of critical importance. An additional challenge is distinguishing MNPs from other particles and accounting for their physicochemical transformations within the body.

Further research should focus on developing standardized detection methods and exposure biomarkers, understanding the mechanisms of toxicity, and identifying potential links between MNPs and diseases, including neurodegenerative and autoimmune diseases.

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