

Polystyrene microplastics size as a key localization determinant for isolated adult cardiomyocytes

Alzbeta Marcek Chorvatova^{1,2} , Michal Cagalinec³ , Ljuba Bacharova¹  and Dusan Chorvat Jr.¹ 

¹ Department of Biophotonics, International Laser Center, Slovak Center of Scientific and Technical Information, Bratislava, Slovakia

² Faculty of Natural Sciences, University of Ss. Cyril and Methodius, Trnava, Slovakia

³ Department of Cellular Cardiology, Institute of Experimental Endocrinology, Biomedical Research Center, Slovak Academy of Sciences, Bratislava, Slovakia

Abstract. There is growing evidence of the cytotoxic effects of micro- and nanoplastics (MPs) on the cardiovascular system. However, the proof of their direct interaction with living cardiomyocytes is limited. This study aimed to analyze the interaction of polystyrene (PS) MPs with freshly isolated adult cardiomyocytes. The primary cardiomyocytes from adult rat hearts were exposed to solutions with MPs of different sizes (20, 100, 200, 500, 1000, and 2000 nm, respectively) for up to six hours. We observed that small MPs, sized 20 nm, showed mostly intracellular localization, and MPs sized 100 nm had partial intracellular location. On the other hand, MPs sized 200–1000 nm had predominantly surface localization. The larger MPs, sized 2000 nm, did not interact with the cardiomyocytes. These findings reveal the complexity of MPs-induced interaction with cardiac cells and suggest the size of the MPs as one of the key localization determinants for these cells.

Key words: Cardiomyocytes — Microplastics — Nanoplastics — Confocal microscopy

Introduction

There is growing evidence of the toxic effects of micro- and nanoplastics (MPs) on the cardiovascular system (CVS) (for review, see Prattichizzo et al. 2024). Regarding these effects of MPs on CVS, MPs are now considered a novel cardiovascular risk factor (Zhu et al. 2023). The high exposure to MPs is associated with functional and structural alteration of CVS, such as decreased cardiac output (Sun et al. 2021), accelerated heart rate and blood velocity (Duan et al. 2020; Yang et al. 2020), but also myocardial fibrosis (Wei et al. 2021), endothelial dysfunction (Shiwakoti et al. 2022), and cardio-metabolic disease (Zhao et al. 2022). The presence of MPs

derived from plastics of various origins was documented in humans in atherosclerotic plaques and thrombi (Wu et al. 2023; Wang 2024), arteries (Liu et al. 2024), atheromas (Marfella et al. 2024), saphenous vein tissue (Rotchell et al. 2023), as well as in the left atrial myocardium, epicardial, and pericardial adipose tissues (Yang et al. 2023).

Studies at the tissue and cellular levels have shown toxic effects of MPs on several processes underlying the manifestation of CV damage, such as inflammation, oxidative stress (Xiong et al. 2025), endothelial dysfunction (Vlácil et al. 2021), platelet aggregation (Wu et al. 2023), cell senescence (Shiwakoti et al. 2022), an increased expression of interleukin (IL)-1 β , IL 18 (Wei et al. 2021) (for review, see Banerjee et al. 2021; Prattichizzo et al. 2024). MPs can be internalized *via* inhalation or ingestion (Kahan et al. 2025), and internalization-related cytotoxicity was described in several systems (reviewed in Chulkov et al. 2025); namely in an *in vitro* model of intestinal epithelium (DeLoid et al.

Correspondence to: Alzbeta Marcek Chorvatova, International Laser Center, Slovak Center of Scientific and Technical Information, Ilkovicova 3, 84104 Bratislava, Slovakia
E-mail: Alzbeta.MarcekChorvatova@cvtisr.sk

2021) and in lung cells (Zhou et al. 2026). Time- and dose-dependent internalization was also observed in human iPSC-derived cardiomyocytes (Wang et al. 2024). These findings underscore the necessity of elucidating the effect of MPs on myocardial cells.

The size of MPs is shown as one of the key determinants of cytotoxic effect in different experimental models (Sohaebuddin et al. 2010; Lei et al. 2018; Wu et al. 2019; Xu et al. 2019; and reviewed in Zhou et al. 2026). Size-dependent cardiotoxicity of PS MPs is also demonstrated on myocardium (Li et al. 2020; Wei et al. 2021) and neonatal (Roshanzadeh et al. 2021), or human iPSC-derived (Ma et al. 2025) cardiomyocytes. However, the proof of direct interaction of MPs of different sizes with living primary adult cardiac myocytes is still missing. The aim of this study was therefore to evaluate the interaction of cardiomyocytes, freshly isolated from living hearts, with PS MPs ranging from micro to nanoplastics.

Material and Methods

Isolation of cardiac myocytes

All experiments were conducted in accordance with the guidelines for the care and use of laboratory animals and were approved by the State Veterinary and Food Administration of the Slovak Republic, in compliance with Order No. 289/2003 of the Slovak government (approval No. 6556-3/2023-220).

Left ventricular cardiac myocytes were isolated from the Wistar rats ranging 250–450 g, using a protocol described previously (Cagalinec et al. 2019). Briefly, excised hearts were retrogradely perfused with modified Tyrode solution containing 1 mmol/l CaCl_2 , followed by the perfusion with modified Tyrode solution with no calcium and the addition of EGTA (0.1 mmol/l) to relax completely the heart muscle. The heart was then enzymatically digested by perfusion with modified Tyrode solution with the addition of 0.05–0.2 mg/ml Liberase TM and low calcium (50 $\mu\text{mol/l}$). Finally, the left ventricle was cut into small pieces and incubated in the solution with attenuated enzyme activity (BSA, 1% w./v.). The suspension was filtered through a nylon mesh (100 μm), washed, and stored in the modified Tyrode solution with low calcium (50 $\mu\text{mol/l}$). All steps were performed at 37°C. Only the best-quality cells were used for experiments for up to 10 hours after isolation. Each experiment was repeated 3–5 times, and at least 3 different cell isolations were tested. Each observation was thus confirmed on 10–15 individual cells.

MPs of different sizes

PS MPs of different sizes were purchased commercially as a FluoSpheres® size kit #2 (F8888, Invitrogen by Thermo

Fisher Scientific), carboxylate coupling surface, labeled with yellow-green fluorescence (Ex/Em 505/515 nm), as previously described (Marcek Chorvatova et al. 2025a). We compared MPs of six sizes with nominal bead diameters of 20, 100, 200, 500, 1000 and 2000 nm. MPs were added to cells at a concentration of 2 $\mu\text{l/ml}$ (corresponding, with 2% solids in the original solution, to cca 500 $\mu\text{g/l}$), and the cells were recorded (following a 1-hour incubation with MPs of particular size) during approximately 1 hour at room temperature.

Application of metabolic modulators

Selected metabolic modulators: H_2O_2 , rotenone, and dinitrophenol (DNP; all Sigma-Aldrich, Germany) were applied in 1 $\mu\text{mol/l}$, 1 $\mu\text{mol/l}$, and 50 $\mu\text{mol/l}$ concentrations, respectively, and tested 5–60 minutes following their application.

Confocal microscopy

Laser scanning confocal microscopy (LSCM) was employed to record images following excitation with the 450 nm laser line (Kvant, Slovakia), taken with Axiovert 200 LSM 510 Meta NLO (Carl Zeiss, Germany), equipped with objective C-Apochromat 40x, 1.2 W, and detected using a spectral META detector, as previously described (Marcek Chorvatova et al. 2019, 2025b). Recording with bandpass filter 500–550 nm served to monitor the fluorescently-labeled MPs (Fig. 1A and 2A). Spectrally resolved images were taken across 8 spectral channels from 499 to 573 nm with an 11 nm step to record the fluorescence of the labelled MPs (Fig. 1B,C and 2B,C). However, as no differences were recorded in the presence of MPs, the recorded spectra are, not illustrated.

Results

To study the interaction of isolated cardiomyocytes with different sizes of PS MPs, ranging from micro to nanoplastics, confocal microscopy imaging was employed. The protocols were chosen to visualize the MPs' fluorescence, while minimizing the contribution of the endogenous fluorescence of flavins (Fig. 1A), naturally present in cardiac cells (reviewed in Marcek Chorvatova et al. 2021). MPs concentration of 500 $\mu\text{g/l}$ was chosen to correspond to a higher, but not acutely cytotoxic concentration (Ma et al. 2025).

The results revealed different interactions between the PS MPs and cardiomyocytes, depending on the particle size. As shown in Figure 1A, the smallest PS MPs, of 20 and 100 nm, showed predominantly intracellular accumulation. Mostly surface localization was observed for PS MPs with sizes between 200 and 1000 nm, while no interaction was

noted with PS MPs of larger sizes (2000 nm); these large particles were dispersed outside the cells without attaching to the cardiomyocytes. Each recording was confirmed on 10–15 individual cells.

This observation was further substantiated by the spectrally-resolved recording between 499–573 nm (step 11 nm; Fig. 1B,C). It confirmed that most PS MPs sized 20 nm were located inside the cardiac cells, as evidenced by the presence of intracellular fluorescence and unstained nuclei (Fig. 1; 20 nm). Minimum surface localization was present. For 100 nm particles, partial intracellular location was also noted, as evidenced by the presence of unstained nuclei.

The cells were also tested for their responsiveness to metabolic modulation to prove their viability: more specifically, metabolic modulators (H_2O_2 , 1 $\mu\text{mol/l}$; rotenone, 1 $\mu\text{mol/l}$, and DNP, 50 $\mu\text{mol/l}$) were applied to verify the cells' sensitivity. In agreement with our previous observations (Chorvat et al. 2005; Marcek Chorvatova et al. 2019; reviewed in Marcek Chorvatova et al. 2021), an increased endogenous fluorescence was recorded following the application of H_2O_2 , inducing oxidative stress, as well as following an uncoupling of the respiratory chain with DNP, as shown in Figure 2. The expected decrease in endogenous fluorescence following exposure to rotenone was not recordable, most likely due to a very low endogenous fluorescence in control cells related to the optimization of the protocols, which allowed for the visualization of the strong fluorescence of the MPs.

Discussion

The results of this study demonstrated that the size of the PS MPs is a key localisation determinant for isolated adult cardiomyocytes. We observed mostly intracellular localization of the small MPs, sized 20 nm. MPs sized 100 nm showed partial intracellular location, while those sized 200–1000 nm have predominantly surface localization. The larger MPs, sized 2000 nm, did not interact with the cardiomyocytes.

The size of MPs as one of the key determinants of their harmful effects was already proven in other experimental models (Sohaebuddin et al. 2010; Lei et al. 2018; Wu et al. 2019; Xu et al. 2019; Ruan et al. 2023). Although size-related cardiotoxicity of PS MPs was also demonstrated on myocardium (Li et al. 2020; Wei et al. 2021; Zhang et al. 2023) and neonatal (Roshanzadeh et al. 2021), or human iPSC-derived (Ma et al. 2025) cardiomyocytes, the proof of the differential interaction of MPs of different sizes with freshly isolated living cardiac myocytes from adult hearts was missing.

The accumulation of the smallest particles inside cardiomyocytes, as found in our study, is consistent with the work of Xiong et al. (2025), where PS MPs of the size 89 ± 12.3 nm penetrated the cell membranes of murine myocardial cells

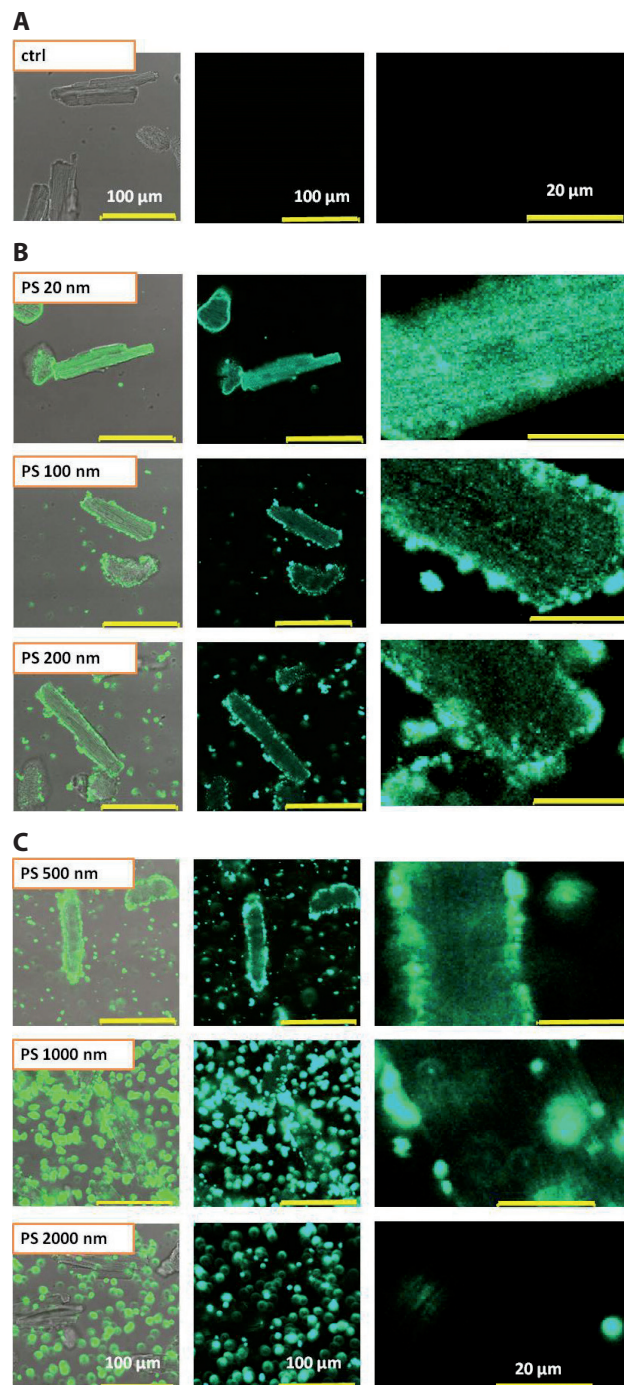


Figure 1. Visualization of PS particles of varying sizes (ranging from 20 nm to 2000 nm) in isolated cardiomyocytes. **A.** Merged transmission and fluorescence confocal images, recorded following excitation at 450 nm with a bandpass filter of 500–550 nm (scale bar: 100 μm). Spectrally resolved images of PS particles of sizes ranging from 20–200 nm (**B**) and 500–2000 nm (**C**) in isolated cardiomyocytes, recorded from 499 to 573 nm with an 11 nm step (scale bar: 100 μm and on the right a zoomed part of the middle image (scale bar: 20 μm)). Control corresponds to a condition where no PS particles were added.

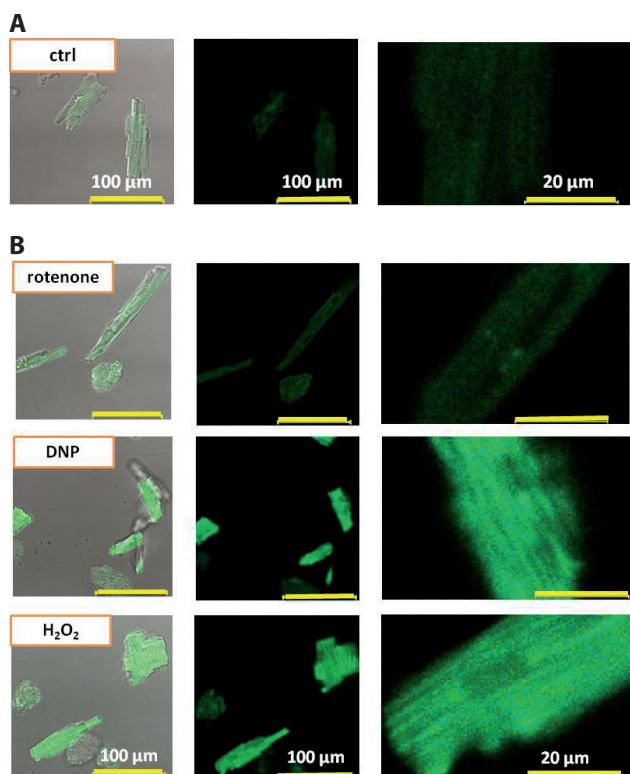


Figure 2. Effect of metabolic modulators on isolated cardiomyocytes. **A.** Merged transmission and fluorescence confocal images, recorded following excitation at 450 nm with a bandpass filter of 500–550 nm (scale bar: 100 µm). **B.** Spectrally resolved images of isolated cardiomyocytes, recorded from 499 to 573 nm with an 11 nm step (scale bar: 100 µm; left and middle) and on the right a zoomed part of the middle image (scale bar: 20 µm). Metabolic modulators (H₂O₂, 1 µmol/l; rotenone 1 µmol/l and DNP, 50 µmol/l) are tested.

and caused oxidative stress and inflammatory response. On the organ level, exposure to PS MPs resulted in ventricular enlargement, thinned ventricular walls, decreased ejection fraction, reduced heart rate, and a drop in blood pressure (both systolic and diastolic) (Xiong et al. 2025). Roshanzadeh et al. (2021) showed that the location of the smallest particles is time-dependent. Using neonatal rat ventricular cardiomyocytes, the 50 nm PS particles aggregate on the cellular membrane during the early short-lasting phase of the exposure. Soon, they penetrated inside the cardiomyocytes, causing decreased myocardial contractility, altered intracellular calcium levels, electrophysiological activity, and cellular metabolism. These findings also correspond to the histological findings of Zhang et al. (2023) in mice exposed to 40 nm PS nano-plastics *via* inhalation. In this study, the dose-dependent and time-dependent cardiotoxicity was demonstrated. The histology uncovered the myocardial fibers' distortion and disruption, including fractured myofila-

ments and damaged mitochondria. In human iPSC-derived cardiomyocytes (Ma et al. 2025), long-term exposure caused contractile dysfunction through disruption of Ca²⁺ handling and had pro-hypertrophic cardiotoxicity at both 50 and 1000 nm. Unfortunately, understanding longer exposures, although highly interesting, is not possible under our experimental conditions due to the degradation of isolated cardiomyocytes several hours following isolation.

The protocols of our study were optimized to visualize the MPs' fluorescence, while minimizing the contribution of the autofluorescence of flavins, which is naturally present in cardiac cells (Marcek Chorvatova et al. 2019). However, in the case of the smallest nanoparticles (20 nm), we cannot exclude possible changes in the autofluorescence of cardiomyocytes, related to modification of their metabolic state. We previously reported modulation of the cardiomyocyte autofluorescence with their metabolic state (Chorvat et al. 2005; Marcek Chorvatova et al. 2019), which can be an additional factor underlying the recorded increase in the fluorescence, particularly in the case of the smallest nanoparticles. This result is in agreement with a finding that the smaller-sized MPs induce cellular toxicity in mammalian cells (for a review, see e.g. Banerjee et al. 2021), causing structural and functional changes in cells. Altogether, our findings demonstrate that the interaction of MPs with cardiomyocytes is strongly related to the MPs' size.

For PS MPs sized 200–500 nm, clear surface localization on the membrane of the cardiomyocytes was present. Partial surface localization was also noted for MPs sized 100 nm and 1000 nm. Li et al. (2020) presented histological findings in Wistar rats exposed to different concentrations of 500 nm PS particles. The PS MPs' exposure resulted in structural damage to myocardial tissue, including apoptosis and collagen proliferation, which were reflected in the increased levels of biomarkers of cardiac injury. Similar findings are reported by Wei et al. (2021).

No interaction was found between the PS MPs and cardiomyocytes using 2000 nm particles. Using other cell models (Ruan et al. 2023), it was demonstrated that larger particles did not enter the cells and that particles above 500 nm did not induce inflammatory responses. These findings are in agreement with our observation of larger-microsized particles employed in this study. However, it was also shown that, following inhalation in animals, large PS MPs of the size 1 µm (Vlacil et al. 2021) or even 10 µm (Zhang et al. 2023) can penetrate the pulmonary-to-bloodstream barrier, enter the circulation, and lead to cardiac injury, possibly *via* structural damage of the heart tissue and interference with normal cardiac contraction. Consequently, despite their incapacity to penetrate the cardiomyocytes, these particles can also present cardiotoxicity risks.

It is now well-established that the environmental pollution by MPs is becoming one of the most serious burdens

of the 21st century and that the potentially toxic effects of MPs pose a new threat to human health (Li et al. 2023). This is also related to the fact that MPs enter the human body *via* oral intake, inhalation, or skin (de Oliveira et al. 2024). Consequently, MPs are now present in human blood (Leslie et al. 2022), where they can affect cellular systems and organs, including the heart, thus necessitating further investigation of the effect of MPs on cardiac cells.

Conclusion

In this study, we demonstrated that the size of the PS MPs is a key localization determinant for isolated adult cardiomyocytes. Recognizing these relationships can be crucial for understanding the mechanisms of the MPs' cardiotoxicity. Based on their localization, MPs can significantly affect the cardiomyocyte functioning: while the surface localization is likely to affect the membrane polarization and electrophysiological properties, the intracellular localization is most likely to affect cell metabolism and have lasting effects on the cell functioning. Further study is necessary to comprehend this relationship.

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Conflict of interests. The authors declare no competing interests.

References

- Banerjee A, Shelper WL (2021): Micro- and nanoplastic induced cellular toxicity in mammals: A review. *Sci Total Environ* **755**, 142518
<https://doi.org/10.1016/j.scitotenv.2020.142518>
- Cagalinec M, Zahradnikova A, Zahradnikova A, Jr, Kovacova D, Paulis L, Kurekova S, Hotka M, Pavelkova J, Plaas M, Novotova M, Zahradnik I (2019): Calcium signaling and contractility in cardiac myocyte of wolframin deficient rats. *Front Physiol* **10**, 172
<https://doi.org/10.3389/fphys.2019.00172>
- Chorvat D, Jr, Kirchnerova J, Cagalinec M, Smolka J, Mateasik A, Chorvatova A (2005): Spectral unmixing of flavin autofluorescence components in cardiac myocytes. *Biophys J* **89**, L55-L57
<https://doi.org/10.1529/biophysj.105.073866>
- Chulkov, V, Gasanov, M, Isakov, V, Denisenko, A, Nwosu, C, Rodkin, S (2025): Molecular and cellular effects of microplastics and nanoplastics in the pathogenesis of cardiovascular, nervous, urinary, digestive, and reproductive system diseases: A global systematic review. *Int J Mol Sci* **26**, 11194
<https://doi.org/10.3390/ijms262211194>
- DeLoid GM, Cao X, Bitounis D, Singh D, Llopis PM, Buckley B, Demokritou P (2021): Toxicity, uptake, and nuclear translocation of ingested micro-nanoplastics in an in vitro model of the small intestinal epithelium, *Food Chem Toxicol* **158**, 112609
<https://doi.org/10.1016/j.fct.2021.112609>
- de Oliveira RB, Pelepenko LE, Masaro DA, Lustosa GMMM, de Oliveira MC, Roza NA, Marciano MA, Dos Reis LM, Kamel S, Louvet L, Mazon T (2024): Effects of microplastics on the kidneys: a narrative review. *Kidney International* **106**, 400-407
<https://doi.org/10.1016/j.kint.2024.05.023>
- Duan Z, Duan X, Zhao S, Wang X, Wang J, Liu Y, Peng Y, Gong Z, Wang L (2020): Barrier function of zebrafish embryonic chorions against microplastics and nanoplastics and its impact on embryo development. *J Hazard Mater* **395**, 122621
<https://doi.org/10.1016/j.jhazmat.2020.122621>
- Kahan MS, Bleier BS, Amiji MM, Workman AD (2026): The effects of microplastics and nanoplastics in the nasal airway and upper respiratory tract. *Sinusitis* **10**, 1
<https://doi.org/10.3390/sinusitis10010001>
- Lei L, Wu S, Lu S, Liu M, Song Y, Fu Z, Shi H, Raley-Susman KM, He D (2028): Microplastic particles cause intestinal damage and other adverse effects in zebrafish *Danio rerio* and nematode *Caenorhabditis elegans*. *Sci Total Environ* **619**, 1-8
<https://doi.org/10.1016/j.scitotenv.2017.11.103>
- Leslie HA, van Velzen MJM, Brandsma SH, Vethaak AD, Garcia-Vellejo JGG, Lamoree MH (2022): Discovery and quantification of plastic particle pollution in human blood. *Environ. Int* **163**, 107199
<https://doi.org/10.1016/j.envint.2022.107199>
- Li Z, Zhu S, Liu Q, Wei J, Jin Y, Wang X, Zhang L (2020): Polystyrene microplastics cause cardiac fibrosis by activating Wnt/β-catenin signaling pathway and promoting cardiomyocyte apoptosis in rats. *Environ Pollution* **265**, 115025
<https://doi.org/10.1016/j.envpol.2020.115025>
- Li Y, Tao L, Wang Q, Wang F, Song M (2023): potential health impact of microplastics: A review of environmental distribution, human exposure, and toxic effects. *Environ Health* **1**, 249-257
<https://doi.org/10.1021/envhealth.3c00052>
- Ma J, Ladd DM, Kaval N, Wang HS (2025): Toxicity of long term exposure to low dose polystyrene microplastics and nanoplastics in human iPSC-derived cardiomyocytes. *Food Chem Toxicol* **202**, 115489
<https://doi.org/10.1016/j.fct.2025.115489>
- Marcek Chorvatova A, Kirchnerova J, Cagalinec M, Mateasik A, Chorvat D, Jr (2019): Spectrally and spatially resolved laser-induced photobleaching of endogenous flavin fluorescence in cardiac myocytes. *Cytometry Part A*, **95**, 13-23
<https://doi.org/10.1002/cyto.a.23591>
- Marcek Chorvatova A, Cagalinec M, Chorvat D, Jr (2021): Time-resolved imaging of mitochondrial flavin fluorescence and its applications for evaluating the oxidative state in living cardiac cells. *Methods Mol Biol* **2275**, 403-414
https://doi.org/10.1007/978-1-0716-1262-0_26
- Marcek Chorvatova A, Mateasik A, Chorvat D, Jr (2025a): Differential effect of nano vs. micro-sized plastics on live *Chlorella* sp. algae in water environment. *Microplastics and Nanoplastics* **5**, 1-9
<https://doi.org/10.1186/s43591-025-00111-2>
- Marcek Chorvatova A, Garcia Bucio M.A, Jurasekova Z, Noskovicova E, Nulandaya L, Bondarev D, Chorvat D, Jr, Miskovsky P

- (2025b): Identification of microplastics in the aquatic environment, or in the presence of algae *Chlorella* sp, by comparison of biophotonic methods. *Polymer Testing* **145**, 108749 <https://doi.org/10.1016/j.polymertesting.2025.108749>
- Marfella R, Prattichizzo F, Sardu C, Fulgenzi G, Graciotti L, Spadoni TD, Onofrio N, Paolisso G (2024): Microplastics and nanoplastics in atheromas and cardiovascular events. *N Engl J Med* **390**, 900-910 <https://doi.org/10.1056/NEJMoa2309822>
- Prattichizzo F, Ceriello A, Pellegrini V, La Grotta R, Graciotti L, Olivieri F, Paolisso P, D'Agostino B, Iovino P, Balestrieri M.L, et al (2024): Micro-nanoplastics and cardiovascular diseases: evidence and perspectives. *Eur Heart J* **45**, 4099-4110 <https://doi.org/10.1093/eurheartj/ehae552>
- Roshanzadeh A, Oyunbaatar NE, Ganjbakhsh SE, Park S, Kim DS, Kanade PP, Lee S, Lee, DW, Kim ES (2021): Exposure to nanoplastics impairs collective contractility of neonatal cardiomyocytes under electrical synchronization. *Biomaterials* **278**, 121175 <https://doi.org/10.1016/j.biomaterials.2021.121175>
- Rotchell JM, Jenner LC, Chapman E, Bennett RT, Bolanle IO, Loubani M, Sadofsky L, Hobkirk J, Palmer TM (2023): Detection of microplastics in human saphenous vein tissue using μ FTIR: a pilot study. *PLoS One* **18**, e0280594. <https://doi.org/10.1371/journal.pone.0280594>
- Shiwakoti S, Ko JY, Gong D, Dhakal B, Lee JH, Adhikari R, Gwak Y, Park SH, Jun Choi IK, Schini-Kerth VB, et al (2022): Effects of polystyrene nanoplastics on endothelium senescence and its underlying mechanism. *Environ Int* **164**, 107248 <https://doi.org/10.1016/j.envint.2022.107248>
- Sohaebuddin SK, Thevenot PT, Baker D, Eaton JW, Tang L (2010): Nanomaterial cytotoxicity is composition, size, and cell type dependent. *Part Fibre Toxicol* **7**, 22 <https://doi.org/10.1186/1743-8977-7-22>
- Vlácil AK, Banfer S, Jacob R, Trippel N, Kuzu I, Schieffer B, Grote K (2021): Polystyrene microplastic particles induce endothelial activation. *PLoS One* **16**, e0260181 <https://doi.org/10.1371/journal.pone.0260181>
- Wang K, Du Y, Li P, Guan C, Zhou M, Wu L, Liu Z, Huang Z (2024): Nanoplastics causes heart aging/myocardial cell senescence through the Ca²⁺/mtDNA/cGAS-STING signaling cascade. *J Nanobiotechnology* **22**, 96 <https://doi.org/10.1186/s12951-024-02375-x>
- Wang T, Yi Z, Liu X, Cai Y, Huang X, Fang J, Shen R, Lu W, Xiao Y, Zhuang W, Guo S (2024): Multimodal detection and analysis of microplastics in human thrombi from multiple anatomically distinct sites. *EBioMedicine* **103**, 105118 <https://doi.org/10.1016/j.ebiom.2024.105118>
- Wei J, Wang X, Liu Q, Zhou N, Zhu S, Li Z, Li X, Yao J, Zhang L (2021): The impact of polystyrene microplastics on cardiomyocytes pyroptosis through NLRP3/Caspase-1 signaling pathway and oxidative stress in Wistar rats. *Environ Toxicol* **36**, 935-944 <https://doi.org/10.1002/tox.23095>
- Wu B, Wu X, Liu S, Wang Z, Chen L (2019): Size-dependent effects of polystyrene microplastics on cytotoxicity and efflux pump inhibition in human Caco-2 cells. *Chemosphere* **221**, 333-341 <https://doi.org/10.1016/j.chemosphere.2019.01.056>
- Wu D, Feng Y, Wang R, Jiang J, Guan Q, Yang X, Wei H, Xia Y, Guan Q, Yang X, et al (2023): Pigment microparticles and microplastics found in human thrombi based on Raman spectral evidence. *J Adv Res* **49**, 141-150 <https://doi.org/10.1016/j.jare.2022.09.004>
- Xiong Z, Kong Q, Hua J, Chen Q, Wang D (2025): Cardiotoxicity of polystyrene nanoplastics and associated mechanism of myocardial cell injury in mice. *Ecotoxicol Environ Saf* **290**, 117712 <https://doi.org/10.1016/j.ecoenv.2025.117712>
- Xu M, Halimu G, Zhang Q, Song Y, Fu X, Li Y, Li Y, Zhang H (2029): Internalization and toxicity: A preliminary study of effects of nanoplastic particles on human lung epithelial cell. *Sci Total Environ* **694**, 133794 <https://doi.org/10.1016/j.scitotenv.2019.133794>
- Yang H, Xiong H, Mi K, Xue W, Wei W, Zhang Y (2020): Toxicity comparison of nano-sized and micron-sized microplastics to Goldfish *Carassius auratus* Larvae. *J Hazard Mater* **388**, 122058 <https://doi.org/10.1016/j.jhazmat.2020.122058>
- Yang Y, Xie E, Du Z, Peng Z, Han Z, Li L, Zhao R, Qin Y, Xue M, Li F, et al (2023): Detection of various microplastics in patients undergoing cardiac surgery. *Environ Sci Technol* **57**, 10911-10918 <https://doi.org/10.1021/acs.est.2c07179>
- Zhang T, Yang S, Ge Y, Wan X, Zhu Y, Yang F, Li J, Gong S, Cheng Y, Hu C, et al (2023): Multi-dimensional evaluation of cardiotoxicity in mice following respiratory exposure to polystyrene nanoplastics. *Part Fibre Toxicol* **20**, 46 <https://doi.org/10.1186/s12989-023-00557-3>
- Zhao J, Gomes D, Jin L, Mathis SP, Li X, Rouchka EC, Bodduluri H, Conklin DJ, O'Toole TE (2022): Polystyrene bead ingestion promotes adiposity and cardiometabolic disease in mice. *Ecotoxicol Environ Saf* **232**, 113239 <https://doi.org/10.1016/j.ecoenv.2022.113239>
- Zhou G, Li J, Chen Y, Cui Y, Wang Y, Zheng L, Zhang D, Luo T (2026): Size-dependent toxicological effects of microplastics: A review. *Ecotoxicology and Environmental Safety* **311**, 119831 <https://doi.org/10.1016/j.ecoenv.2026.119831>
- Zhu X, Wang C, Duan X, Liang B, Genbo Xu E, Huang Z (2023): Micro- and nanoplastics: A new cardiovascular risk factor? *Environ Int* **171**, 107662 <https://doi.org/10.1016/j.envint.2022.107662>

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