



HAL
open science

Recent progress in the toxicity of nitric oxide-releasing nanomaterials

Joana Claudio Pieretti, Milena T Pelegrino, Ariane Boudier, Amedea Barozzi Seabra

► **To cite this version:**

Joana Claudio Pieretti, Milena T Pelegrino, Ariane Boudier, Amedea Barozzi Seabra. Recent progress in the toxicity of nitric oxide-releasing nanomaterials. *Materials Advances*, 2021, 10.1039/D1MA00532D . hal-03369765

HAL Id: hal-03369765

<https://hal.univ-lorraine.fr/hal-03369765v1>

Submitted on 7 Oct 2021

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons Attribution 4.0 International License

Materials Advances

Accepted Manuscript

This article can be cited before page numbers have been issued, to do this please use: J. C. Pieretti, M. T. Pelegrino, A. Boudier and A. B. Seabra, *Mater. Adv.*, 2021, DOI: 10.1039/D1MA00532D.



This is an Accepted Manuscript, which has been through the Royal Society of Chemistry peer review process and has been accepted for publication.

Accepted Manuscripts are published online shortly after acceptance, before technical editing, formatting and proof reading. Using this free service, authors can make their results available to the community, in citable form, before we publish the edited article. We will replace this Accepted Manuscript with the edited and formatted Advance Article as soon as it is available.

You can find more information about Accepted Manuscripts in the [Information for Authors](#).

Please note that technical editing may introduce minor changes to the text and/or graphics, which may alter content. The journal's standard [Terms & Conditions](#) and the [Ethical guidelines](#) still apply. In no event shall the Royal Society of Chemistry be held responsible for any errors or omissions in this Accepted Manuscript or any consequences arising from the use of any information it contains.

Recent progress in the toxicity of nitric oxide-releasing nanomaterialsView Article Online
DOI: 10.1039/D1MA00532DJoana Claudio Pieretti,¹ Milena Trevisan Pelegrino,¹ Ariane Boudier,² Amedea BarozziSeabra^{1*}¹Center for Natural and Human Sciences (CCNH), Federal University of ABC (UFABC),
Santo André, SP, Brazil² Université de Lorraine, CITHEFOR, F-54000 Nancy, France

*Corresponding author

Amedea B. Seabra

Center for Natural and Human Sciences (CCNH), Federal University of ABC (UFABC)

Av. dos Estados 5001, CEP 09210-580, Santo André, SP, Brazil, E-mail:

amedea.seabra@ufabc.edu.br

Abstract

View Article Online
DOI: 10.1039/D1MA00532D

Nitric oxide (NO) is a signaling molecule controlling important biological processes. Depending on its concentration, location and cellular environment, NO can have protective or toxic effects. As NO is a free radical, several classes of NO donors/generators have been prepared and combined with nanomaterials, in particular with polymeric nanoparticles. Engineered nanoparticles are attractive nanocarriers extensively used in biomedical applications, in particular in cancer biology due to their ability to promote a site-target therapeutic effect, with minimum side effects to health tissues. NO-releasing nanoparticles can have direct toxic effects to tumor cells, or it can promote cancer cells sensitization to traditional cancer treatments. The combination of NO-releasing nanoparticles with conventional anticancer therapies is a promising approach in the reversion of multidrug resistance (MDR) cells. This review presents and discusses the recent progress in the cytotoxicity (tumoral and non-tumoral cell lines) of NO-releasing polymeric and/or polymer-coated nanomaterials and the *in vivo* biocompatibility of NO-releasing nanoparticles. Moreover, the ability of these nanoparticles to combat MDR, their mechanisms of toxicity and drawbacks are also discussed.

Keywords: Nitric oxide donors, nanomaterials, cytotoxicity, cell sensitization, multidrug resistance cells, *in vivo* biocompatibility.

1. Introduction: The biological importance of nitric oxide

Nitric oxide (NO) is a small signaling molecule associated with several cellular functions.^{1,2,3} NO is relatively a simple molecule, composed only by a covalent bound



between nitrogen and oxygen atoms with an unpaired electron on the antibonding $2\pi^*$, therefore, a free radical.⁴ Until the 1970 decade, NO was majority known as an atmospheric pollutant and a toxic agent.^{2,5,6} However, the Nobel Prize of Medicine and Physiology awarded by Louis J. Ignarro, Robert F. Furchgott and Ferid Murad identifying NO as the EDRF (endothelium derived relaxing factor) shed light on the importance of this signaling molecule in several physiological and pathophysiological processes.⁷⁻¹¹ In 1992, NO was elected the 'molecule of the year' by the journal Science due to the increasing number of published articles regarding its impactful cellular effects.¹²

NO is endogenously synthesized by the action of cluster catalytic enzymes named nitric oxide synthase (NOS). NOS enzyme family includes three isoforms: (i) endothelial (eNOS), (ii) neuronal (nNOS) and (iii) inducible (iNOS).^{1,13,14} Both eNOS and nNOS synthesize NO at lower amounts for a longer time-period in the presence of calcium, while iNOS produces NO only when induced by an external signal at higher concentrations for longer time frame.^{1,15,16} All members of NOS enzyme family catalyze the oxidation of *L*-arginine to *L*-citrulline with formation of one NO molecule.^{4,16}

In cancer biology, NO serves multiple functions, being considering an anti- and proapoptotic agent, promoting vasodilation, angiogenesis and interaction with macrophages.^{4,6,14,15,17} For instance, a member of NOS family, eNOS, in endothelium has been linked to a prognostic factor for patients with stomach adenocarcinoma (STAD).¹³ In this sense, NO is well recognized for playing a dual role in cancer cells, having deleterious or beneficial features.^{2,6,18} In some studies, NO or NOS levels are correlated with tumor suppression, however, in other studies to tumor progression and metastasis.^{1,2,18} NO interaction with cellular targets can vary based on spatial and temporal distribution of NO influx within tumor cells and tumor microenvironment.^{17,19} Thus, key factor linked to modulate the dichotomous effect of NO are the amount of NO released, the time-period and



the spatial distribution of this signaling molecule in tumor tissue.²⁰ In addition, tumor microenvironment and heterogeneity also play an important role in the dichotomous effect of NO.¹ Thus, for proposing the use of exogenous NO to cancer cells/tissues, it is of fundamental importance to tailor the desired amounts of NO released to the target site of application. To this end, the combination of NO donors with nanomaterials represents an important approach.^{3,9,21,22}

Tumor tissue has unique vascular characteristics such as hypervascularity, irregular morphology and enhanced permeability.²³ Tumor tissue recovery of some substances from tumor interstitium into lymphatics is slow; this effect is observed for macromolecules, lipids and nanoparticles.^{22,23} Therefore, nanoparticles naturally stay within tumor tissue for a longer time-period, compared with other drugs, this is a well-known phenomenon called enhanced permeability and retention (EPR) effect.^{22,23} EPR is one of the reasons to explain why nanomaterials are intensively developed for cancer treatment.²⁴ Interestingly, NO has been linked to mediate the enhanced permeability. Indeed, NO scavenger and NOS inhibitor suppressed the EPR effect in mice with sarcoma solid tumor.^{23,25}

NO donors are a class of molecules capable to mimic NO flux conditions and modulate its concentration.^{3,17} Due to the NO instability, the use of NO donors has been successful used to exogenously delivery NO to a target site, in different biomedical applications.^{19,26} The most common classes of NO donors, are sodium nitroprusside, organic nitrite and nitrate, furoxans, benzofuroxans, diazeniumdiolates (NONOates), S-nitrosothiols (RSNOs), Roussin's black salt (RBS) and metal nitrosyl complexes.^{3,17,27-31} The molecular representations of commonly used NO donors are shown in Figure 1. NONOates and RSNOs are highlighted as the most used NO donors in oncological therapeutic applications due to NO release features and feasibility to be produced.^{3,32,33} NONOate releases NO only in the presence of protons and can be classified according to its secondary amine structure, which



varies its half-life.^{3,21,33} In RSNOs, NO is covalently bound to a sulfur group (RS); and NO is spontaneously released from the homolytic S-N cleavage.^{26,27} RSNOs is also involved in S-transnitrosation reactions that has been linked to be a relevant step on the downward signaling route created by NO.^{19,26,34,35,36} Another commonly used NO donor is the RBS, which is a metal-nitrosyl complex that releases NO after illumination.^{31,37}

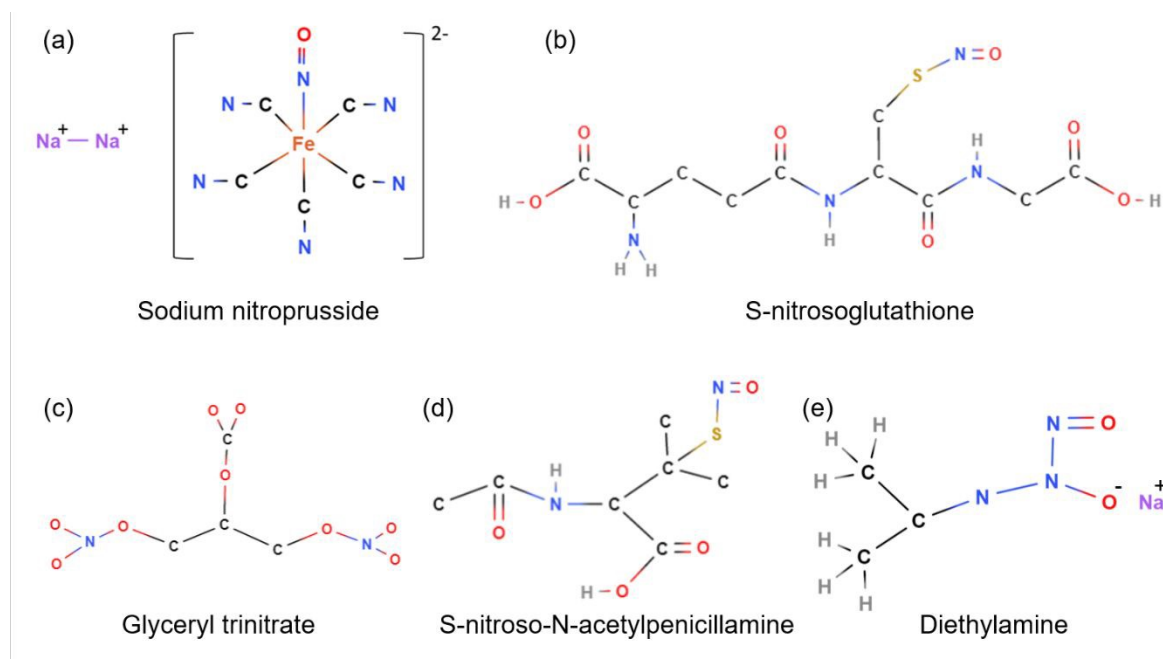


Fig.1. Chemical structure of selected commonly employed NO donors: (a) Sodium nitroprusside; (b) S-nitrosoglutathione (RSNO); (c) Glyceryl trinitrate; (d) S-nitroso-N-acetylpenicillamine; (e) Diethylamine (NONOate);

Although NO donors have allowed the use of exogenous NO in biomedical applications, these molecules have limitations regarding the NO concentrations spatially and temporally reach.^{26,27} In order to overcome this challenge, the combination of nanomaterials and NO has been extremely successful.^{3,27,32,38,39,40} Nanomaterials have been applied to cancer diagnosis and treatment with positive results.^{23,41,42} Cancer is a leading cause of death worldwide; its treatment usually involves surgical resection, radiation and chemotherapy.⁴³



Although several treatments are conventionally used with certain degree of success, there are some drawbacks such as collateral effects and multi-drug resistant cancers.^{3,18,22,30,40}

In this sense, the combination of nanomaterials and NO donors can be used alone or with chemotherapy or radiotherapy agents.^{3,27,43} This combination is cooperative; the nanoparticle is a carrier for NO allowing it to reach the target site at suitable concentrations. In addition, as a vasodilator, NO can increase tumor permeability allowing nanoparticle accumulation on tumor site.²³ All these features together can provide an alternative strategy to overcome setbacks of traditional cancer treatment.

In this scenario, the scope of this review is to point out the recent advances in the design of nanomaterials capable of releasing NO and their activity against cancer cell lines, highlighting their efficiency against multi-drug resistant tumor, *in vivo* results, and selective toxicity. We aimed to overview recent publications available on reliable platforms such as Web of Science and PubMed from the last five years (2016-2021), focusing on NO-releasing polymeric nanomaterials and/or polymer-coated nanomaterials.

2. Cytotoxicity of NO-releasing nanoparticles against cancer and non-cancerous cells

Since few years after NO was defined as the endothelium-derived relaxing factor (EDRF),^{7,44} NO was described as an important signaling molecule, involved in cytotoxic mechanisms, demonstrating relevant cytoprotective properties.^{5,45} Regarding its cell cytotoxicity, NO has been reported as a possible modulator of apoptosis, angiogenesis, invasion, metastasis, and also as a regulator of the cell cycle.⁴⁶ The cytotoxic effect of NO on tumor cells relays, mainly, in the suppression of DNA synthesis and cellular respiration, shifting iron metabolism, modulation of apoptosis by activating caspase family proteases, upregulation of p53 protein and other apoptosis-related proteins.⁴⁶ More recently, NO has also



been mentioned as a sensitizing agent, demonstrating promising cytotoxic effects against tumoral cells when allied to traditional therapeutic approaches (chemotherapy and radiotherapy).^{3,47} As previously mentioned, NO is a relatively unstable molecule, therefore NO donors have been employed as a strategy to promote an effective delivery. More recently, the combination of NO donors with nanoparticles has improved the use of NO as an antitumoral therapeutic strategy.³

In this scenario, NO has been allied to different kind of nanoparticles, ranging from metallic nanoparticles, as gold nanoparticles (AuNPs), silver nanoparticles (AgNPs), and quantum dots (QDs);⁴⁸ metal oxide nanoparticles, such as superparamagnetic iron oxide nanoparticles (SPIONs); zeolites and other metal-organic frameworks;⁴⁹ porous nanomaterials, as silica nanoparticles (SiO₂);⁵⁰ to polymeric nanoparticles.⁵¹⁻⁵⁴ Depending on the nature of the nanoparticles, they can have a direct cytotoxicity, or they can act as nanocarriers of active drugs, enhancing the intratumoral penetration, thus promoting a more efficient drug delivery.⁵⁵ Generally, the empty nanocarrier itself does not present toxic or cytotoxic effect, being only a nanovehicle for improving drug delivery. When compared to control cells or *in vivo* models, empty nanoparticles should demonstrate similar pattern, as no antitumoral effect should be promoted. For instance, poly(lactic-*co*-glycolic acid)-based nanoparticles (PLGA NPs), approved by the US Food and Drug Administration (FDA) for medical use, demonstrate promising potential to be combined with different drugs, other nanoparticles or molecules, since these nanoparticles do not demonstrate significant cytotoxic effects without the mentioned combinations.⁵⁶ On the opposite, there are some types of nanoparticles that present intrinsic properties that may lead significant cytotoxic potential, as well as contributing to the diagnosis, such as the theragnostic nanoparticles.⁵⁷ AuNPs, for example, exhibit unique optical and electronic properties that make them suitable for cell and/or tumor imaging, besides presenting size and shape-dependent toxicity against cancerous



and non-cancerous cells.^{58,59} AgNPs demonstrate higher cytotoxicity against cancer cells when compared to AuNPs, drastically reducing cell viability, as demonstrated for colon cancer cells, regulating redox processes and the cell cycle, mediating cell apoptosis and DNA disfunction.⁶⁰

Moreover, AgNPs may demonstrate a synergic toxic effect in combination with NO.⁵⁴ For instance, it is well-known that AgNPs may cause toxicity due to the ability to generate reactive nitrogen and oxygen species, leading to oxidative damage in mammalian cells and/or microorganisms.⁶¹ Similar to AgNPs, NO sub products, such as peroxynitrite (ONOO⁻) are also key players for increasing the oxidative stress and causing cellular damage.⁶² NO fast reacts with superoxide (O₂^{•-}) leading to the formation of the harmful peroxynitrite, described as following:



In this sense, combining functional nanoparticles, such as AgNPs, with NO releasing molecules consists in a promising strategy for increasing the generation of NOx species, such as peroxynitrite, increasing oxidative damage to cancer cell lines.

In this section, we aim to overview the recent progress in the cytotoxicity promoted by NO-releasing polymeric nanoparticles and/or polymer-coated nanoparticles and their interference in cellular mechanisms, which might be directly related to the NO delivered, or to the combination of the NO donor with the nanoparticle and/or other chemotherapeutic drugs.

2.1 Cytotoxicity of NO-releasing polymeric nanoparticles against tumoral and non-tumoral cell lines

Polymer-based nanoparticles have stand out in nanomedicine and drug delivery, mostly due to the synthesis facility, high biocompatibility, and the possibility of achieving different designs, such as polymeric nanocapsules and/or nanospheres, micelles, and



liposomes.⁶⁰ The last one stands out for being approved by FDA, being used for delivering the chemotherapeutic doxorubicin (DOX), improving its efficacy.⁶³ In recent years, NO has been combined to different polymeric nanoparticles in order to promote or potentiate cytotoxic effects against tumoral cells.⁴² PLGA NPs-containing the NO donor dinitrosyl iron complex were developed to promote a sustained NO release, regarding the concentration, localization, and duration.⁶⁴ Nanoparticles with 120 nm in size were responsible for promoting EPR effect in tumor cells/tissues. When comparing free NO and nanoencapsulated NO at a final concentration of 20 $\mu\text{mol L}^{-1}$, a more pronounced cytotoxic effect was observed for the free NO donor. Inferior cytotoxic of encapsulated NO was evidenced by 2-fold increase in the IC_{50} in comparison to free NO IC_{50} , resultant from a slow NO release in the cell media. The mentioned *in vitro* results are important to critically analyze the importance of evaluating different parameters (*i.e.* blood compatibility, NO life-time in blood circulation, targeting efficiency and tissue accumulation) when it comes to NO delivery. Regarding the cytotoxic effect of nanoencapsulated NO, it is usually expected an improved cytotoxicity against tumoral cell lines. Although, despite observing a higher IC_{50} for NO after encapsulation, a prolonged circulation of the encapsulated NO donor after intravenous administration was verified, with an outstanding 25-fold increase of the NO donor half-life and a higher accumulation in liver tumoral tissue, when compared to free NO donor. Similar pattern was observed for RSNO (1-10 mmol L^{-1}) encapsulated in poly(propylene sulfide) nanoparticles, in which no significant cytotoxicity was observed for the encapsulated molecule, but a 2-fold increase in the accumulation in the targeted tissue was verified *in vivo*, with no apparent signs of inflammation.⁶⁵

In contrast, other combinations have demonstrated potential cytotoxic effect against tumoral cell lines.^{30,51,66} RSNO encapsulated in chitosan nanoparticles (CS NPs), average hydrodynamic size of 108 nm, have demonstrated a sustained NO release for 10 h, at a



concentration of 50 mmol L⁻¹, in which NO should demonstrate significant cytotoxic effects.⁵¹

The potential cytotoxic effect of RSNO encapsulated in CS NPs was confirmed against different tumoral cell lines: hepatocellular carcinoma (HepG2), skin melanoma (B16-F10), chronic myeloid leukemia (K562), and vincristine resistant chronic myeloid leukemia (Lucena 1), compared with non-tumoral melanocyte (Melan-A) cells. A cell viability reduction was observed in all evaluated concentrations (5-40 µg mL⁻¹), although the resultant IC₅₀ demonstrated a higher toxicity against B16-F10 and HepG2 cell lines, when compared to non-tumoral Melan-A cells. Leukemic cells demonstrated to be less sensible to NO-releasing CS NPs. Lucena 1 exhibited the highest IC₅₀, which was expected as it is characterized as a resistant cell lineage derived from K562. When comparing the pair B16-F10 and Melan-A (both skin cells), a 2-fold selectivity for the tumoral cell-line reinforces the potential of NO-releasing CS NPs in the treatment of tumors. The reported cytotoxicity involved different mechanisms, such as caspase-dependent apoptosis, which was associated with oxidative stress promoted by NO, along with an increased superoxide production in the mitochondria and the oxidation of thiol containing proteins.⁶⁷ Interestingly, it was also observed tyrosine nitration and cysteine *S*-nitrosation in cellular proteins, demonstrating the involvement of the delivered NO in different cell mechanisms.

Similar results were reported for RSNO-loaded CS NPs functionalized with hyaluronic acid (HA).⁶⁶ Cytotoxic results were verified for all tested concentrations (5-200 µg mL⁻¹), achieving 0% of cell viability at the highest evaluated concentration. Interestingly, the HA did not contribute to the cytotoxicity, although it might promote a higher selectivity for cells that overexpresses CDD4 protein.⁶⁶ Another targeted nanomaterial was reported by Liu and coworkers, in which molecular imprinted nanoparticles (MIPs) were designed to target tumor that overexpresses sialic acid.³⁰ The cytotoxicity was evaluated against different tumoral cell lines: HepG2 cells, mammary cancer cells (MCF-7), and compared to non-tumoral



hepatocellular cells. The NO-releasing nanoparticles demonstrated selectivity for sialic acid overexpressing cells (HepG2 and MCF-7), evidenced by a higher cellular uptake and cytotoxicity against these cells when compared to non-tumoral hepatocellular cells, with low sialic acid expression. Interestingly, HepG2 cells that survived de NO-releasing MIPs were re-cultured and treated with the nanoparticles, and no acquired resistance was observed. This is an important result for future studies with NO-releasing nanoparticles, as it is directly related to the NO chemical biology. NO and its sub products are known to cause oxidative and nitrosative stress, DNA deamination, besides interacting with different proteins, comprehending a complex mechanism that may hinder the development of resistance mechanisms in tumoral cells.^{30,68}

Despite focusing on NO, other gasotransmitters also present important biomedical roles, including cytotoxicity against tumoral cells.⁶⁹ Indeed, a more recent strategy has demonstrated promising results by combining two different gasotransmitters: NO and hydrogen sulfide (H₂S), co-delivered by a polymeric nanoparticle based on carboxyl-functionalized mPEG-PLGH-thiobenzamide [(methoxy poly (ethylene glycol-b-lactic-co-glycolic-co-hydroxymethyl propionic acid)-thiobenzamide)], PTA copolymer.⁷⁰ H₂S is produced in mammalian cells mainly by three different enzymes: cystathionine-β-synthase (CBS), cystathionine-γ-lyase (CSE), and 3-mercaptopyruvate sulfurtransferase (MST).⁷¹ Biological pathways occur through sulfhydration, a post-translational modification of specific protein cysteines.⁶⁹ Regarding antitumoral properties, H₂S suppresses cellular bioenergetics, reduces the intracellular levels of antioxidant glutathione, and modulates p53 and nuclear factor-κB (NF-κB) pathways.⁷² When cell were treated with NO/H₂S-releasing nanoparticles, an enhanced angiogenesis was observed, resultant from the NO/H₂S crosstalk.⁷⁰ Moreover, these nanoparticles demonstrated high biocompatibility in different cell types. Thus, the combination of NO/H₂S in nanomaterials represents a new approach in biomedical



applications, and further studies are welcome. The crosstalk between NO and H₂S, and its biological responses, is under intensive investigation.⁷³

2.2 Cytotoxicity of NO-releasing polymer-functionalized nanoparticles against tumoral and non-tumoral cell lines

Polymer-coated metal or metal-oxide nanoparticles have also been reported as promising templates for delivering NO.^{22,48,74} The surface functionalization enables the delivery of therapeutics, such as NO or traditional chemotherapeutics, and also promotes a targeted delivery to cancerous cells.^{74,75} Among different nanoparticles, AuNPs have been one of the most employed in drug delivery.⁵⁰ Similarly to what was demonstrated for CS NPs, AuNPs were functionalized with hyaluronic acid for targeting CDD4 protein expressed by breast tumoral cells and the consequent lung metastasis. Furthermore, AuNPs were functionalized to deliver the chemotherapeutic paclitaxel (PTX), indocyanine green and NO, from a nitrate ester modified hyaluronic acid. The combined nanomaterial (AuNPs, PTX, indocyanine green and nitrate ester modified hyaluronic acid) exhibited the lowest IC₅₀ against breast cancer cell line (4T1) when compared to controls (nanoparticles without indocyanine green, and free PTX), evidencing a synergistic effect of PTX, indocyanine green, and NO delivered by AuNPs. The NO role was even more evident in apoptosis analysis, in which the necrotic and apoptotic 4T1 cells reached 52% when treated with AuNPs, PTX, indocyanine green and nitrate ester modified hyaluronic acid, in comparison to 40.9% for AuNPs without hyaluronic acid and NO coating, suggesting an important role in drug internalization combined with NO cytotoxic effects.⁵⁰

The apoptotic and necrotic effect of NO was also evident on osteosarcoma cells (MG63) when combined with a hybrid nanoparticle based on SPIONs and AgNPs.⁷⁴



Apoptotic and necrotic cells comprehended 25% of the cell population after 24 h treatment with hybrid nanoparticles based on SPIONs and AgNPs, coated with NO-releasing chitosan, at a concentration of 100 $\mu\text{g mL}^{-1}$, which corroborated with a pronounced cell viability reduction. Moreover, it was possible to observe the interference in the cell cycle, inducing a cycle arrest at S phase. Thus, it is evident that NO plays an important role against tumoral cells, combined or not with other therapeutics. Still, it is important to better comprehend the cytotoxic mechanism of NO against different cell lines, as well as the innovative proposed combinations with active nanomaterials and/or drugs.

3. Cytotoxicity of NO-releasing nanoparticles against multidrug resistant cancer cells

As reported in the previous section, when evaluating the potential cytotoxicity of NO-releasing nanoparticles against different cell lines, resistant cells demonstrated higher IC_{50} when treated with RSNO-CS NPs,⁵¹ compared with no resistant cells, confirming the necessity to employ higher dosages against these cell lines. We have recently published a review focused on the overview of recent innovative combinations of NO and nanomaterials, allied or not to chemotherapeutics, that represent potential approach to overcome resistance mechanisms.³ An illustrative scheme shown in Figure 2 describes possible resistance mechanisms that can be reverted by nanoparticles combined with NO donors.



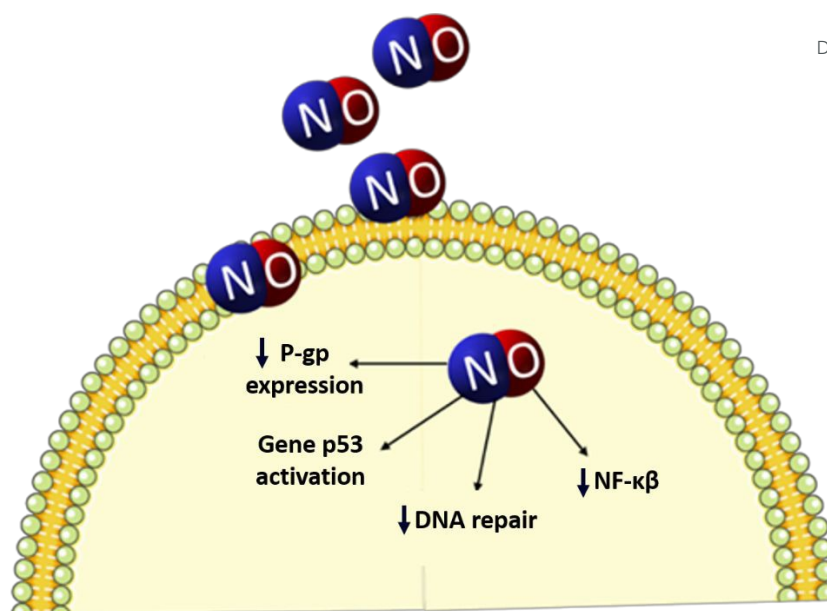


Fig.2. Schematic representation of NO interference in resistance mechanisms. NO has demonstrated to promote a decrease in the expression of NF- κ B, responsible for the expression of anti-apoptotic genes, in addition to promote a decrease in DNA repair and in the expression of proteins responsible for the efflux of chemotherapeutic agents, such as glycoprotein-P (P-gp).^{3,76}

Recent publications point to the increasing strategy of employing NO donors as a cell sensitizer agent for reverting resistance mechanisms.^{58,77-80} Important results were observed for a NONOate combined with pH sensitive liposomes and PTX, which facilitated tumor cell uptake of both compounds. *In vitro* experiments with adenocarcinoma cells (A549/T) confirmed a higher cytotoxicity for the designed combination when compared to controls. Some mechanisms have correlated NO release to the downregulation of P-gp protein through the inhibition in MDR-1 mRNA levels.⁷⁷ A similar design was reported by Wu and coworkers, combining an important RSNO, S-nitrosoglutathione (GSNO), with a vastly used chemotherapeutic, DOX, in polymeric block nanoparticles based on poly(ethylene glycol) and poly(propylene sulfide) (PEG-PPS NPs).⁸⁰ Even at the lowest evaluated concentration (1 μ g mL⁻¹ of DOX), a statistically significant increase in the cytotoxicity against HepG2 cells was



observed for the encapsulated drug combined with GSNO. When comparing tumoral to non-tumoral cells, the cytotoxicity of the nanomaterial was 37-fold higher, evidencing a high selectivity, this is of great importance when it comes to chemotherapeutic drugs. Through apoptosis analysis, it was evident that GSNO encapsulated in PEG-PPS NPs at a concentration of 25 $\mu\text{mol L}^{-1}$ already interferes in cell mechanisms and leads to a small percentage of apoptotic cells. Although, when combined with DOX and the PEG-PPS NPs, a synergistic effect was observed by reaching almost 100% of late apoptotic cells, in contrast with 23.6% for DOX encapsulated and 2.41% for GSNO encapsulated nanoparticles. With these data, it is clear that NO donor can sensitize the resistant cancerous cells, promoting a pronounced effect of the chemotherapeutic.

For a micelle nanoparticle with a similar design, combined with DOX, it was observed a pattern similar to the previously discussed when evaluated against MCF-7 cells.⁷⁸ Micelles presenting 130 nm were obtained from a biodegradable polycarbonate-based copolymer, tailored for NO release from a cyclic nitrate trimethylene carbonate monomer. Once more, NO was correlated to the decrease of P-gp protein expression in a dose-dependent manner, enhancing the chemotherapeutic efficiency. Inorganic nanoparticles, as silica nanoparticles (230 nm), loaded with NO and combined with DOX, reinforced the mechanism of P-gp expression decrease when employed against MCF-7 cells.⁵⁸ It is already clear that NO has an important involvement in the decrease in the expression of P-gp.

Different designs of nanoparticles, drug combinations, and component concentrations may lead to different cytotoxic effects and biochemical mechanisms. Some issues are not as clear as the decrease of P-gp expression and should be further investigated. Do these combinations initiate inflammatory processes? Are there any DNA damages? What is the ideal proportion for promoting apoptosis and/or necrosis? What is the redox balance in MDR cells treated with NO-releasing nanoparticles? Is there any influence in enzymatic activities?



Therefore, we expect to encourage researchers to further investigate the mechanism of NO in the MDR reversal/sensitization, as it consists in a promising advance in the area of chemotherapy.

3.1. Combination of NO-releasing nanomaterials with traditional anti-cancer therapies

Recently, in cancer treatment, the combination of chemotherapy or radiotherapy with NO donors is a promising strategy that might overcome drug resistance. Furthermore, the addition of nanomaterials allied to NO donors may enhance this positive effect. Nanomaterials are able to load either NO donors/generators or chemotherapeutic drugs. Interesting, the in clinical applications, administration of NO donors at subtoxic doses along with suboptimal doses of chemotherapeutics can lead to additive or synergistic effects, which are suitable for overcoming chemoresistance.⁴⁷ Such combinations (NO donors, nanomaterials and chemo/radio therapies) can also activate the anti-tumor immune response.

Chemotherapy remains restricted by poor drug delivery efficacy due to the heterogenous nature of tumor and to the development of tumor resistance.⁸¹ To overcome these issues, considering combined approaches, versatile nanomaterials have been prepared for cancer treatment. In particular, chemotherapeutic drugs can be allied to NO donors and nanomaterials. DOX and NO donor (RSNO) were loaded in mesoporous silica nanoparticles.²² The obtained nanomaterial enhanced tumor penetration allowing a localized released of DOX and NO. NO released reacts with superoxide anion yielding the powerful oxidant peroxynitrite, under pathological conditions. This process promotes protein nitration and oxidation, lipid peroxidation, DNA damage. Moreover, peroxynitrite activates pro-matrix metalloproteinases into active matrix metalloproteinases, which degrade collagen in the tumor



extracellular matrix. In other words, NO contributes to disintegrate tumor matrix collagen improving nanoparticle penetration.²²

A nanocarrier containing NO donor (N-NO moiety of a polymer) and paclitaxel was prepared.⁸² The polymeric micelles (hydrodynamic diameter of 137 nm) were able to spontaneously release NO, under physiological condition, and demonstrated toxic effects against MDR ovarian cancer cell line OVCAR-8/ADR. Higher cytotoxicity was found for micelles containing both NO donor and paclitaxel, compared with micelles containing only individual drugs. Moreover, these nanoparticles were found in tumor tissue for more than 48 h.⁸² Hyaluronan and keratin nanogels containing NO donor and DOX (average size of 60 nm) demonstrated significant and improved toxicity towards breast cancer 4T1 cell line, which expresses high levels of CD44 receptor.⁸³ The natural polysaccharide hyaluronic acid specifically binds to CD44 receptors, which are over-expressed on the cytomembrane of tumor cells. The nanomaterials increased intracellular NO levels, which in turn sensitizes cancer cells enhancing the efficacy of DOX. Thus, in addition of EPR effects, the presence of hyaluronic acid in nanomaterials enhances the tumor targetability.

In addition to chemotherapeutics allied to NO in nanomaterials, irradiation can also be employed. High energy ionizing radiation in radiotherapy treatment damages DNA and other biomolecules causing cell death through photon interaction-biomolecules interactions or by the generation of oxygen and nitrogen radical species, including hydroxyl radicals and nitrogen dioxide. However, as solid tumors are often oxygen deficient, tumor resistance to radiation can be observed. In this tumor hypoxic microenvironment, NO has been reported to act as radiosensitizer, enhancing radical damage of biomolecules.⁸⁴

Recently, NO-releasing (nitrosylated maytansinoid containing poly(lactide-*co*-glycolic)-block-poly(ethylene glycol) nanoparticles were used to sensitize non-small cell lung carcinoma to radiotherapy. Nanoparticles were efficiently delivered to tumors through the



EPR effect, where upon irradiation generated oxidative stress and NO release.⁸⁵ In addition, soft X-ray (45 kVp, 0.18–0.85 mGy) was used in combination with NaYF₄:Gd/Tb lanthanide scintillator nanorod as a light transducer for on-demand NO release (from Roussin's black salt) gas-sensitized cancer therapy.⁸⁶ This combined therapy can reach up to 3 cm in tumor tissue, making it suitable for solid tumors.

AuNPs were functionalized with nitroimidazole, a cell penetrating peptide (CPP) and poly(ethylene glycol) (PEG), for a combined cancer radiosensitization approach.⁴⁷ Nitroimidazole releases nitrite ions, NO_x species, while CPP induce nucleus internalization of the nanomaterial. Nitrite ions are reported to easily reduced to NO, especially in a hypoxic and/or acidic tumor microenvironment.⁸⁷ The nanomaterial acted in the sensitization of cancer cells upon radiation with clinically used X-ray (6 MeV X-rays). Interestingly, nitrite ion release is triggered by X-ray radiation, and no release was observed without radiation. *In vitro* studies with epidermoid carcinoma cell line A-431 demonstrated that such nanoparticles combined with radiation have enhanced toxicity. The improved radiotherapy effect can be associated with the action of both nitrite ion/NO in the oxidative damage and the actions of AuNPs themselves in the production of ROS.⁴²

Recently, soft X-ray luminescence nanotransducer (down to 0.9 mGy) integrating ZnGa₂O₄:Mn nanoparticles with Roussin's black salt (as light triggered NO donor) was prepared. The authors reported an efficient NO release even after 40 min after stopping the radiation with a deep tumor tissue penetration. Similarly, NaYbF₄:Tm@NaYF₄:Yb/Er upconversion nanoparticles containing Roussin's black salt able to release NO upon near-infrared radiation (980 nm) was reported.⁸⁸ This combined therapy is able to either release high amounts of NO (for direct toxic effects) or release low concentrations of NO for modulation of P-gp to overcome multi-drug resistance. Bismuth sulfide nanoparticle/bis-*N*-nitroso nanocomposites were prepared to release NO upon near-infrared radiation (808 nm).⁸⁹



Other versatile strategies have been developing in recent years to overcome drug resistance in combined therapies involving NO donors, nanomaterials and chemo/radio therapeutic agents. Overall, the combination of light irradiation with nanomaterials and NO donors facilitates the spatiotemporal trigger of drug release and allows a targeted therapy. These nanomaterials act as smart materials particular designed to target tumor cells/tissues. Thus, the tumor microenvironment is of fundamental importance for the design of these nanomaterials. In this sense, near infrared laser was used in combination with hyaluronidase-triggered sized shrinkable hyaluronic acid shells, containing NO donor and DOX.⁸¹ Upon systemic administration, larger size nanoparticles preferably accumulate in tumor site due to the EPR effect and CD44-targeting.⁹⁰ At the tumor site, small size dendrimeric produg of DOX and NO are formed via enzymatic degradation enhancing deep tumor penetration of the active drugs, increasing targetable-toxic effects (Figure 3).⁸¹

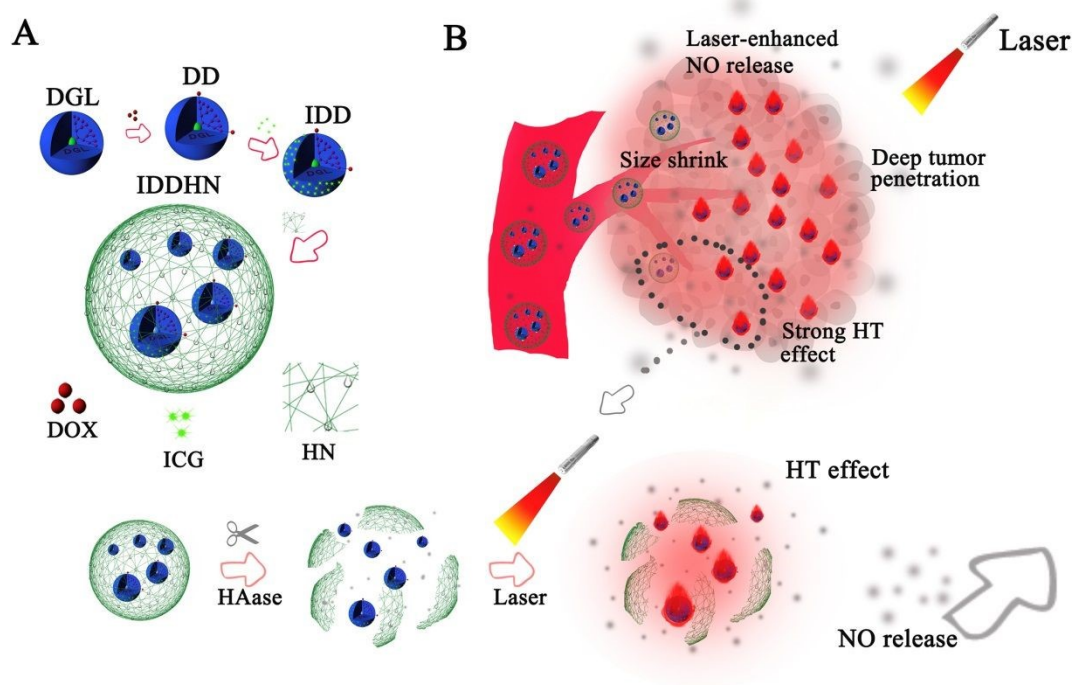


Fig.3. Schematic representation of the combination with hyaluronidase-triggered sized shrinkable hyaluronic acid shells, containing NO donor and DOX (A). B) Schematic



illustration of the synergistic effects upon laser irradiation for deep tumor penetration and therapy effects. Reproduced from reference 81 with permission from Elsevier.

NaYF₄:Yb,Er upconversion nanoparticles (75 nm) conjugated with the natural polymer chitosan and load with the photo NO donor Roussin's black salt and DOX were prepared.⁹¹ Under acid conditions, usually found in solid tumor microenvironment, the entrapped DOX is released from swollen nanomaterials. The enhanced toxic effects demonstrated on colorectal carcinoma cell line (CT26 cells) was attributed to the combined therapy of NO and DOX released from the nanomaterial. As expected the simultaneous release of NO and DOX promoted a synergistic antitumor effect. The concentration range of NO release was found to be up to 2 μmol/L. These effects were attributed to the fact that low doses of NO mediates P-gp increasing DOX uptake, while high doses of NO have a direct toxic effect in coordination with DOX.⁹¹ A similar approach was designed by combing NO-releasing platinum prodrugs and micelles in a photoresponsive therapy.⁹² Similar to DRX, platinum prodrugs, including cisplatin, have been clinical used as chemotherapeutic agents. Once internalized by cells, NO is controlled released upon light irradiation at concentrations require sensitization of cancer cells (human breast carcinoma cells, HCT-116 and MCF-7 cell lines). This process led to cleavage of photolabile hydrophobic groups releasing platinum (IV) prodrugs. Thus, NO enhanced the chemotherapy efficacy by inactivating P-glycoproteins and MDR-associated proteins, depleting glutathione (that inactivates cisplatin), impairing hypoxia-induced factors, inhibiting nuclear factor kappa B (NF-κB) overcoming drug resistance.⁹³

4. *In vivo* biocompatibility of NO-releasing NP or NO-producing NP



Concerning the published *in vivo* studies, two main strategies of NO release are currently described. The NP can release NO when designed from synthesized pro-drugs (mainly from RSNO). The NO can be produced by a biosynthesis based on NO synthases *via* *L*-arginine brought by NP or by a catalytic effect using copper NP on circulating endogenous RSNO. The claimed therapeutic indications are anticancer or antibacterial effects or the study of a new implanted medical device. The recent papers are reported and compared in **Table 1**.

View Article Online
DOI: 10.1039/D1MA00532D



Table 1. Analysis of the published work about *in vivo* biocompatibility and toxicity of NO-releasing NP or NO-producing NP from the five last years.

Mean of NO release	NP	Animal species	Administered dosage	<i>In vivo</i> toxicity	Ref.
From synthesized pro-drugs	NP made of NO-releasing <i>tert</i> -dodecane <i>S</i> -nitrosothiol encapsulated into polystyrene-maleic acid.	BALB/c female mice implanted with mouse 4T1 mammary carcinoma cells	Intra-tumor or intravenous NP (1 mg/kg each time) at day 0 day 8	General toxicity ^a : No toxicity	94
	SNAP loaded pegylated Liposomes	Pancreatic cancer cells (PSCs/PCs) implanted nude mice	NP injected intravenously (10 mg kg ⁻¹ SNAP equivalent)	General toxicity ^a : No toxicity Histopathological studies ^f : No major abnormalities	54
	Polyprodrug nanoparticles (reductive-sensitive NP releasing NO, ONOO- and cisplatin in the cytoplasm)	Adenocarcinomic human alveolar basal epithelial cells (A549) and cisplatin-resistant (A549/DDP) tumor-bearing mice	Intravenous injection every 3 days for a total of five injections with a dose of NP equivalent of 5 mg cisplatin/kg.	General toxicity ^a : No toxicity Histopathological studies ^f : No major abnormalities Biochemistry analyses ^{g, h, i, j} : minimal changes but an overall good biocompatibility and little side effects	95
	Sodium nitroprusside and docetaxel doped mesoporous Prussian blue NP	BALB/c mice bearing breast cancer (4T1) tumors	Intravenous injection of NP 100 μL, 5 mg/kg of docetaxel or equivalent dose) every two days	General toxicity ^a : no toxicity Histopathological studies ^f : No major abnormalities	96
	Nitrosylated maytansinoid loaded poly(lactide- <i>co</i> -glycolic)- <i>block</i> -poly(ethylene glycol) NP	Albino BALB/c mice	Intravenous administration of 260.8 nmol/kg of NPs equivalent to 0.2 mg nitrosylated maytansinoid/kg	General toxicity ^{a, b} : no toxicity Histopathological studies ^f : No major abnormalities Biochemistry analyses ^{g, h, i, j} : within normal values.	85



Phototriggered NO nanogenerators loaded with doxorubicin	BALB/c nude mice implanted with multidrug-resistant breast cancer (MCF-7/ADR) cells	Intravenous injection of a dose equivalent to doxorubicin of 5 mg kg ⁻¹ (100 μL)	General toxicity ^a : no toxicity	97
NP loaded with doxorubicin, indocyanine green and NO donor	BALB/c mice implanted with (4T1) breast tumor cells	Intravenous injection of equivalent of 2.0 mg indocyanine green kg ⁻¹ and 2.8 mg doxorubicine kg ⁻¹ , 300 mL) every four days for 4 cycles	General toxicity ^a : No toxicity Histological studies ^f : No major abnormalities	81
Polymer NP loaded in protoporphyrin (PpIX)-based NO donors	Multidrug-resistant breast cancer (MCF-7/ADR) tumor-bearing BALB/c nude mice	Intravenous injection of NP at a dose of 5 mg PpIX per kg, repeated every 3 days	General toxicity ^a : no toxicity Histopathological studies ^f : No major abnormalities Biochemistry studies ^{i,j} : within normal values	98
<i>S</i> -nitrosated human serum albumin dimer and albumin bound paclitaxel NP	BALB/c mice implanted with (SUIT2) pancreatic cancer cells	Intravenous injection of nab-paclitaxel (20 mg/kg) with dimer (1.95 mmol/kg)	General toxicity ^a : no toxicity	99
Hollow double-layer imprinted polymer NP loaded in <i>S</i> -nitrosothiols or RSNO loaded NP	Liver cancer (HepG2) bearing BALB/c mice	Intravenous injection of NP 5 mg/kg	General toxicity ^a : No toxicity except for the group treated with RSNO NP which showed a weight loss and a physical decline. Histological studies ^f : No major abnormalities except for RSNO NP treated mice with a slight inflammatory in the kidney, and a serious inflammatory and an	21



<i>S</i> -Nitrosocaptopril NP	Zebrafish embryos (Danio rerio, wild type, 5D-Tropical strain)	<i>S</i> -Nitrosocaptopril NP diluted from 0.016 to 250 ppm in fish water in 150 μ L	alveolar membrane thickening in the lung General toxicity ^c : No toxicity	100
GSH-responsive NO donor-modified NP loaded with 10-hydroxycamptothecin (HCPT)	Multidrug-resistant breast cancer (MCF-7/ADR) tumor-bearing BALB/c mice	Intravenous injection of 100 μ L of NP equivalent of HCPT:5mg/kg, NO:2.8mg/kg every four days	General toxicity ^a : no toxicity except for mice treated with unformulated HCPT Histopathological studies ^f : No major abnormalities except for the group treated with unformulated HCPT with serious damages of livers and kidneys	101
<i>S</i> -nitrosocompound loaded pluronic-stabilized, poly(propylene sulfide)-core NP	C57BL/6J mice	Intradermal injection of 30 μ L of NP	General toxicity: no local nor systemic inflammation due to the injection of NP Histopathological studies: Increase in lymph node size (but not for spleen) with SNO-NP but not with SNAP, explained by dramatic increase in resident immune cell frequencies. Biochemistry: hepatic function: unchanged levels of plasma alanine transaminase and aspartate transaminase	65





	Photothermally triggered nitric oxide nanogenerator targeting type IV pili	<i>P. aeruginosa</i> -infected BALB/c mice	Subcutaneous injection of 200 μ L, 80 μ g/mL of NP on day 1, 3 and 5,	General toxicity: no significant toxicity noticed Histopathological studies: no significant statistical difference in major organs (heart, liver, spleen, lung, kidney)	80
	Paclitaxel loaded modified <i>S</i> -nitrosoalbumin	BALB/c mice	Intravenously administrated with NP (200 μ L, Ptx: 2 mg/mL, NO: 2 mM) on days 0, 2, 4, and 6 for four total treatments.	Histopathological studies: no observable pathological abnormalities found in major organs Biochemistry: serum biochemical detection and whole blood analysis, platelet counts in whole blood and tail bleeding time showed no alteration	102
From biosynthesis based on NOS	Polyion complex micelles based on poly(ethylene glycol)-block-poly(L-arginine) and chondroitine sulfate	BALB/c mice, male injected with (C26) adenocarcinoma cells	Intravenous route of 16 mg/kg on arginine basis and up to 4 injection each 24h	General toxicity: no difference in the body weight even after four intravenous injections of the PIC micelles	103
	Erythrocyte membrane-enveloped proteinic nanoparticles with a biomimic nitric oxide synthase (NOS) (co-loading of L-Arginine (LA) and photosensitizer IR783)	Uterine cervical cancer cells (U14) tumor-bearing Kunming mice	Intravenous injection of 0.1 mL every two days and the dose of IR783 and LA equal to 0.6 mg/kg and 0.9 mg/kg	Histopathological studies: the analyses of the major organs (heart, liver, spleen, kidney, lungs) revealed no overt histological change and function damages	104
	NP composed of upconversion nanoparticles, porphyrinic MOFs doped with L-arginine	BALB/c mice infected with <i>S. aureus</i> in a wound	Circular wounds of 4 mm covered by membranes	General toxicity: no fluctuation of mice weight	105

and incorporated into matrices					
From a catalytic activity on RSNO	Coating of extra-corporeal circuits made of copper NP catalyzing NO release from GSNO	New Zealand white rabbits equipped with arteriovenous extracorporeal circuits	Extra-corporeal circulation with surfaces releasing NO with a flux of <i>ca</i> 1 to 10 x 10 ⁻¹⁰ mol cm ⁻² min ⁻¹	General toxicity: only copper nanoparticles combined with GSNO loop showed no clot formation. During the entire 4 h procedure, Cu GSNO loops maintained higher platelet counts compared to other test loops or both NO-releasing loops (GSNO and Cu GSNO), all 3 rabbits survived the 4 h procedure	106
	Oxygenation system via a veno-venous extracorporeal membrane based on PDMS hollow fibers embedded with copper NP and supplied with an infusion of the NO donor S-nitroso-N-acetyl-penicillamine	Miniature artificial lung (MAL) attached to Montadale sheep in parallel in a veno-venous extracorporeal membrane oxygenation circuit	Each device received a SNAP infusion of 0.12 l mol/min and catalytic generation of NO at 3 ± 0 x 10 ⁻¹⁰ mol cm ⁻² min ⁻¹ by Cu-PDMS fibers	General toxicity: mean arterial blood pressure and heart rate were stable and within normal ranges during the testings. Biochemistry analyses: Parameters of coagulation and inflammation remained stable during the testings	107
	Keratin/doxorubicin complex nanoparticles releasing NO from endogenous GSNO	Nude mice bearing (A549) tumors	Intravenous injection of 500 mg of NP /kg mouse	General toxicity: body weight of NP group displayed a slight decrease non-significant, interpreted as a non-severe toxic side effect Histopathological studies No significant histological modifications for the heart,	108





liver, and kidney
Hemolysis study: no
hemolysis induced

General toxicity includes measure of body weight^a, or general signs of toxicity (behavior, dizziness, respiratory distress)^b, or embryonic mortality, morphology modifications or behavior modifications^c, or general signs of toxicity on the cardiovascular function (heart rate and mean arterial blood pressure)^d, or hemolysis^e. Histopathological studies were performed on major organs (heart, liver, spleen, lung, kidney)^f and biochemistry analyses on blood^g, on the coagulation system^h, on the hepatic functionⁱ, on the renal function^j.

The main animal species used to study NO *in vivo* effects are mainly mammals and especially mice, except one study in which Zebrafish embryos were used.¹⁰¹ The mice usually bear tumors which are implanted before testing the NP. Tests on Zebrafishes are often used in the literature to assess the toxicity or the safety of compounds, drugs or even nanoparticles.¹⁰⁹ Moreover, the regulatory agencies, FDA and European Medicines Agency (EMA) accept these data for the approval of investigative new drug. Globally, the articles concerning the biocompatibility of NO releasing/producing NP reported a general good tolerance of the treatment by the animals.

Usually, besides the general signs of toxicity, an exploration of the possible disturbance of the biochemical parameters is explored. After the animal sacrifice, a histopathological study is often performed on main organs. The NO-releasing/producing NP are generally well-tolerated, only two articles reported a toxicity.^{21,63} The toxicity can be induced by the NP and/or by the release or the production of NO. NO, the gaseous transmitter with pleiotropic activities in the organisms, at uncontrolled concentration may induce a great variety of toxic side effects (inflammation, respiratory problems, modification in heart rate, in blood pressure).¹¹⁰ This can be counterbalanced by the very short half-life of NO and consequently, its limited action zone.¹⁰⁴ In parallel, after their parenteral administration, which is the most studied administration route, NP rapidly interact with immune cells and are distributed to reticuloendothelial organs (liver, spleen, lungs).¹¹¹ Combined, the properties of NO and NP explain why, besides general indicators of toxicity (body weight, general behavior of animals), other physiological and biochemical parameters must be explored to assess the potential systemic toxicity of the nanoarchitectures. The interaction with immune cells, with or without an observable inflammation, were observed with some particles loaded with a RSNO.^{21,63} In their work,²¹ Liu and colleagues explained their



observation by high release of high concentrations of NO in an immoderate manner, but the inflammatory effect could be also exacerbated by the nanoparticulate form.

All these *in vivo* works can be considered as very preliminary toxicological studies and lay the bases for a more complete work. Indeed, to go further into the development of a drug candidate for a human use in medicine, the regulatory agencies impose many constraints to ensure the final safety of the drug.¹¹² For example, the toxicology tests must be performed on rodent and non-rodent species according to the Good Laboratory Practices (GLP). The toxicity must be evaluated for a long term: The International Conference on Harmonization (ICH) guidance recommends 9-month chronic toxicity studies in nonrodents.¹¹²

5. Final remarks: Drawbacks, challenges and perspectives

As represented and discussed in the work, the recent progress in the design of various promising nanoplatforms of release controlled and therapeutic levels of NO at the desirable site of application have opened new avenues in this interesting research field. Intensive and fruitful research has made several advances in the preparation of smart and versatile nanomedicines able to release NO-on demand in biomedical applications highlighting NO-sensitized synergistic cancer therapy. NO-releasing nanomaterials can have a direct cytotoxic effect (for high NO concentrations) or can sensitize cancer cells (for low NO concentrations, combined with other therapy, such as chemotherapy or radiotherapy). The combined therapy significantly improved the response over monotherapy in solid tumors.⁴⁷ For instance, in radiotherapy, NO enhances DNA damage and inhibits DNA repair by acting as an oxygen-like radiosensitizer in hypoxic tumors.⁷³



The driving force to deeper evaluates the effects of NO-releasing nanomedicines in combination with traditional anti-cancer therapies is mainly based on the systemic toxicity of these traditional drugs and the increasing problem of MDR. NO-releasing nanomedicine is a promising candidate to mitigate the side effects of chemo/radio therapies. Much effort has been concentrated in the design of smart NO donors able to sensitively generate NO or NO-related species upon exogenous/endogenous stimuli at the desired site of application (tumor tissue), with minimum side effects to normal tissues.^{3,74} Undoubtedly, nanotechnology has significantly contributed to the preparation of a variety of smart and efficient multifunctional NO-containing nanostructures in several biomedical applications, including cancer biology. Although several advances have been achieved in this topic, as presented in this work, some issues still need to be further explored: (i) in-depth mechanism of NO inducing cell death, and more importantly, cancer cell sensitization should be investigated by using genetic and molecular approaches, (ii) development of nanomedicines stable at room temperature and able to release NO in a controlled manner upon and external or internal stimuli, (iii) further studies (*in vitro*, *in vivo* and clinical) of multitherapy by combining NO donors and/or traditional chemotherapeutic drugs, and/or radiotherapy and/or X-ray are still strongly encouraged to be developed, (iv) strategies to enhance deep penetration of NO and/or chemotherapeutic drugs still need to the further developed, by considering the tumor microenvironment.

Moreover, a great challenge in the biomedical applications of NO donors is still the ability to accurate measure and real-time monitor the NO generation from the nanomedicines at the target site. To this end, several important and different experimental techniques should be considered. The exactly controlled of the NO release profile from the nanomaterial is of fundamental importance to avoid a burst in the NO release and poisoning. Further *in vivo* studies



are required and the fate of each component in the nanomaterial should be monitored in the biological system, along with the studies of biocompatibility, biosafety and biodistribution prior the clinical applications. Finally, we expect that this work brings new avenues in the development of integrated nanostructures form combined therapeutic modalities allowing a successful and safely use of NO-sensitized synergist effects.

Acknowledgements

We have appreciated the support from CNPq (404815/2018-9, 313117/2019-5), FAPESP (2018/08194-2, 2019/07766-5, 2018/03646-2).

Author's contribution

All authors have contributed equally to writing – review & editing – Preparation, creation and/or presentation of the published work by those from the original research group, specifically critical review, commentary or revision – including pre- or post-publication stages.

Conflict of interest

The authors declare no conflicts of interest.

References

- 1 J. Hickok and D. Thomas, *Cur. Pharm. Design*, 2010, **16**, 381–91.
- 2 S. Habib and A. Asif, *Indian J. Clin. Biochem.*, 2011, **26**, 3–17.
- 3 J.C. Pieretti, M.T. Pelegrino, M.H.M. Nascimento, G.R. Tortella, O. Rubilar, and A.B. Seabra, *Biochem. Pharmacol.*, 2020, 113740.



- 4 M. Valko, D. Leibfritz, J. Moncol, M. Cronin, M. Mazur and J. Telser, *Int. J. Biochem. and Cell Bio.*, 2007, **39**, 44–84.
- 5 D.A. Wink, L. Ridnour, S. Hussain and C. Harris, *Nitric Oxide*, 2008, **19**, 65–67.
- 6 L.B. Kreuzer and C.K. Parel, *Science*, 1971, **173**, 47–47.
- 7 L.J. Ignarro, G.M. Buga, K.S. Wood, R.E. Byrns and G. Chaudhuri, *Proc. Natl. Acad. Sci. U. S. A.*, 1987, **24**, 9265–69.
- 8 T. Infante, D. Costa and C. Napoli, *Angiology*, 2021, **72**, 411-425.
- 9 J. Mintz, V. Rosete, K. Shah, G. Goldstein, J.M. Hare, R. Ramasamy and H. Arora, *Vaccines*, 2021, **9**, 94.
- 10 F. Lisi, A.N Zelikin and R. Chandrawati, *Adv. Sci.*, 2021, **8**, 2003895.
- 11 W. Hu, J. Shi, J. Zhang, Y. Wang, Y. Gua and Z. Zhang, *Adv. Therap.*, 2021, 100032.
- 12 D. Koshland, *Science*, 1992, **258**, 5090.
- 13 D. Zou, Z. Li, F. Lv, Y. Yang, C. Yang, J. Song, Y. Chen, Z. Jin, J. Zhou, Y. Jiang, Y. Ma, Z. Jing, Y. Tang and Y. Zhang, *Front. Oncol.*, 2021, **11**, 1–14.
- 14 S. Kobayashi, T. Homma and J. Fujii, *Biochemistry and Biophysics Reports*, 2021, **26**, 100942.
- 15 J. Scicinski, B. Oronsky, S. Ning, S. Knox, D. Peehl, M.M. Kim, P. Langecker and G. Fanger, *Redox Biol.*, 2015, **6**, 1–8.
- 16 C. Gokmenoglu, N. Ozmeric, C. Sungur, R. Bildik, I. Erguder and S. Elgun, *Arc. Oral Biol.*, 2018, **85**, 207–11.
- 17 R.Y.S. Cheng, D. Basudhar, L.A. Ridnour, J.L. Heinecke, A.H. Kesarwala, S. Glynn, C.H. Switzer, S. Ambs, K. Miranda and D.A. Wink, *Nitric Oxide*, 2014, **43**, 17–28.
- 18 B. Bonavida and G. Hermes, *Redox Biol.*, 2015, **6**, 486–94.
- 19 M.T. Pelegrino, A. Paganotti, A.B. Seabra and R. Weller, *Histochem. Cell Biol.*, 2020, 0123456789.



- 20 M.T. Pelegrino, J.C. Pieretti, G. Nakazato, M.C. Gonçalves, J. C. Moreira and A.B. Seabra, *Nitric Oxide*, 2021, **106**, 24-34.
- 21 Z.Q. Liu, J. Wang, P. Zhang, Z. Zhang, D. Guo and X. Yang, *Colloids Surf. B: Biointerfaces*, 2019, **173**, 356–65.
- 22 X. Dong, H.J. Liu, H.Y. Feng, S.C. Yang, X.L. Liu, X. Lai, Q. Lu, J.F. Lovell, Z. Chen and C. Fang, *Nano Lett.*, 2019, **19**, 997–1008.
- 23 H. Maeda, C. Noguchi, K. Sato and T. Akaike, *J. Cancer Res.*, 1994, **85**, 331–34.
- 24 Z. Fang, Y. Shen and D. Gao, *New J. Chemistry*, 2021, **45**, 4534-4544.
- 25 M. Feelisch and K. Olson, *Nitric Oxide*, 2013, **35**, 2–4.
- 26 M.G. Oliveira, *Basic. Clin. Pharmacol. Toxicol.*, 2016, **119**, 49-56.
- 27 A.B. Seabra and N. Durán, *Med. Chem.*, 2016, **17**, 216–23.
- 28 L. Keefer, *Cur. Topics in Med. Chem.*, 2005, **5**, 625 – 636.
- 29 Y. Lan, X. Zhu, M. Tang, Y. Wu, J. Zhang, J. Liu and Y. Zhang, *Nanoscale*, 2020, **12**, 7875-7887.
- 30 T. Liu, Z. Qiao, J. Wang, P. Zhang, Z. Zhang, D.-S. Guo and X Yang, *Colloids Surf. B: Biointerfaces*, 2018, **173**, 356-365.
- 31 L. Chen, H. Qianjun, L. Minyi, X. Liwei, S. Kun, T. Liwei, J. Zhaokui, W. Tianfu and Q. Zhiyong, *ACS Appl. Mater. Interfaces*, 2017, **9**, 36473–36477.
- 32 J.F. Quinn, M. Whittaker and T. Davis, *J. Control. Release*, 2015, **205**, 190–205.
- 33 B. Li, Y. Ming, Y. Liu, H. Xing, R. Fu, Z. Li, R. Ni, L. Li, D. Duang, J. Xu, C. Li, M. Xiang, H. Song and J. Chen, *Front. Pharmac.*, 2020, **11**, 923.
- 34 P. Ford and I. Lorkovic, *Chem. Rev.*, 2002, **102**, 993–1018.
- 35 S. Wynia-Smith and B. Smith, *Nitric Oxide*, 2017, **63**, 52–60.



- 36 J. Jahnová, L. Luhová and M. Petřivalský, *Plants*, 2019, **8**, 1–19.
- 37 A. Janczyk, A. Wolnicka-Glubisz, A. Chmura, M. Elas, Z. Matuszak, G. Stochel and K. Urbanska, *Nitric Oxide*, 2004, **10**, 42-50.
- 38 A.B. Seabra, G. Justo and P.S. Haddad, *Biotechnol. Adv.*, 2015, **33**, 1370–79.
- 39 H. Duong, Z. Kamarudin, R.B. Erlich, Y. Li, M.W. Jones, M. Kavallaris, C. Boyer and T. Davis, *Chem. Commun.*, 2013, **49**, 4190-4192.
- 40 P. Couvreur, *Adv. Drug Delivery Rev.*, 2013, **65**, 21–23.
- 41 D. Brambilla, P. Luciani and J.P. Leroux, *J. Control. Release*, 2014, **190**, 9–14.
- 42 A.B. Seabra, G.Z. Justo and P.S. Haddad, *Biotechnol Adv.*, 2015, **33**, 1370-9.
- 43 F. Liu, J. Lou and D. Hristov, *Nanoscale*, 2017, **9**, 14627–34.
- 44 L.J. Ignarro, *Nitric Oxide Biology and Pathobiology*, Academic Press, San Diego, 2000.
- 45 K.-D. Kröncke, K. Fehsel and V. Kolb-Bachofen, *Nitric Oxide*, 1997, **1**, 107–120.
- 46 S.K. Choudhari, S. Korde., M. Chaudhary, S. Bagde, A.R. Gadmail and V. Joshi, *World J. Surg. Onc.*, 2013, **11**, 118.
- 47 B. Bonavida, *Biochem. Pharmacol.*, 2020, 113913.
- 48 L. Tan, A. Wan and H. Li, *ACS Appl. Mater. Interfaces*, 2021, **13**, 18392–18392.
- 49 M. Neidrauer, U. K. Ercan, A. Bhattacharyya, J. Samuels, J. Sedlak, R. Trikha, K. A. Barbee, M. S. Weingarten and S. G. Joshi, *J. Med. Microbiol.*, 2014, **63**, 203-209.
- 50 B. Xiao, P. S. Wheatley, X. Zhao, A. J. Fletcher, S. Fox, A. G. Rossi, I. L. Megson, S. Bordiga, L. Regli, K. M. Thomas and R. E. Morris, *J. Am. Chem. Soc.*, 2007, **129**, 1203-1209
- 50 R. Liu, W. Xiao, C. Hu, R. Xie and H. Gao, *J. Control. Release*, 2018, **278**, 127–139.
- 51 M.T. Pelegrino, L.C. Silva, C.M. Watashi, P.S. Haddad, T. Rodrigues and A.B. Seabra, *J. Nanoparticle Res.*, 2017, **19**, 57.



- 52 M.C. Santos, A.B. Seabra, M.T. Pelegrino and P.S. Haddad, *Appl. Surf. Sci.*, 2016, **367**, 26–35.
- 53 W.R. Rolim, J.C. Pieretti, D.L.S. Renó, B.A. Lima, M.H.M. Nascimento, F.N. Ambrosio, C.B. Lombello, M. Brocchi, A.C.S. De Souza and A.B. Seabra, *ACS Appl. Mater. Interfaces*, 2019, **11**, 6589–6604.
- 54 X. Chen, F. Jia, Y. Li, Y. Deng, Y. Huang, W. Liu, Q. Jin, J. Ji, *Biomaterials*, 2020, **246**, 119999.
- 55 S. Rezvantalab, N. I. Drude, M.K. Moraveji, N. Güvener, E.K. Koons, Y. Shi, T. Lammers and F. Kiessling, *Front. Pharmacol.*, 2018, **9**, 1260.
- 56 V.S. Madamsetty, A. Mukherjee and S. Mukherjee, *Front. Pharmacol.*, 2019, **10**, 1264.
- 57 M. Enea, E. Pereira, J. Costa, M.E. Soares, D.D. da Silva, M. de Lourdes Bastos and H.F. Carmo, *Toxicol. In Vitro*, 2020, 105046.
- 58 J. Guo, K. Rahme, Y. He, L.-L. Li, J. Holmes and C. O’Driscoll, *Int. J. Nanomedicine*, 2017, **12**, 6131–6152.
- 59 S. Gurunathan, M. Qasim, C. Park, H. Yoo, J.-H. Kim and K. Hong, *Int. J. Mol. Sci.*, 2018, **19**, 2269.
- 60 K.M. El-Say and H.S. El-Sawy, *Int. J. Pharm.*, 2017, **528**, 675–691.
- 61 I. Inkielewicz-Stepniak, M.J. Santos-Martinez, C. Medina and M.W. Radomski, *Int. J. Nanomedicine*, 2014, **9**, 1677-87.
- 62 T.A. Heinrich, R.S. da Silva, K.M. Miranda, C.H. Switzer, D.A. Wink and J.M. Fukuto, *Br. J. Pharmacol.*, 2013, **169**, 1417-1429.



- 63 S.A. Abraham, D.N. Waterhouse, L.D. Mayer, P.R. Cullis, T.D. Madden and M.B. Bally, *Liposomes*, 2005, **391**, 71–97.
- 64 Y.C. Sung, P.R. Jin, L.A. Chu, F-F. Hsu, M-R. Wang, C-C. Chang, S-J. Chiou, J.T. Qiu, D-Y. Gao, C-C. Lin, Y-S. Chen, Y-C. Hsu, J. Wang, F-N. Wang, P-L. Yu, A-S. Chiang, A.Y-T. Wu, J.J-S. Ko, C.P-K. Lai, T-T. Lu and Y. Chen, *Nat. Nanotechnol.*, 2019, **14**, 1160–1169.
- 65 A. Schudel, L.F. Sestito and S.N. Thomas, *J. Biomed. Mater. Res. A*, 2018, **106**, 1463–1475.
- 66 M.T. Pelegriño, C. Baldi, A. Souza and A. Seabra, *J. Phys. Conf. Ser.*, 2019, 012019.
- 67 L.S. Ferraz, C.M. Watashi, C. Colturato-Kido, M.T. Pelegriño, E.J. Paredes-Gamero, R.B. Weller, A.B. Seabra, T. Rodrigues, *Mol. Pharm.*, 2018, **15**, 1160–1168.
- 68 E.M. Hetrick, J.H. Shin, N.A. Stasko, C.B. Johnson, D.A., Wespe, E. Holmuhamedov and M.H. Schoenfish, *ACS Nano*, 2008, **2**, 235–246.
- 69 C. Szabo, *Nat Rev Drug Discov*, 2016, **15**, 185–203.
- 70 J. Lee, C. Yang, S. Ahn, Y. Choi and K. Lee, *Biomater Sci.*, 2021, **9**, 5150-5159.
- 71 C. Szabo, *Nat. Rev. Drug Discov.*, 2007, **6**, 917–935.
- 72 C. Szabo, C. Coletta, C. Chao, K. Módis, B. Szczesny, A. Papapetropoulos and M.R. Hellmich, *Proc Natl Acad Sci USA*, 2013, **110**, 12474-9.
- 73 J.C. Pieretti, C.V.C. Junho, M.S. Carneiro-Ramos and A.B. Seabra, *Pharmacol Res.*, 2020, **161**, 105121.
- 74 J.C. Pieretti, M.C. Gonçalves, G. Nakazato, A.C.S. de Souza, A. Boudier and A.B. Seabra, *J Mater Sci: Mater Med*, 2021, **32**, 23.
- 75 A. L. Tessaro, A. Fraix, A. C. Pedrozo da Silva, E. Gazzano, C. Riganti and S. Sortino, *Nanomaterials*, 2019, **9**, 823.



- 76 E. Hays and B. Bonavida, *Antioxidants*, 2019, **8**, 1397–1406.
- 77 M. Chen, F. Song, Y. Liu, J. Tian, C. Liu, R. Li and Q. Zhang, *Nanoscale*, 2019, **11**, 3814-3826.
- 78 S. Gao, W. Zhang, R. Wang, S.P. Hopkins, J.C. Spagnoli, M. Racin, L. Bai, L. Li, W. Jiang, X. Yang, C. Lee, K. Nagata, E.W. Howerth, H. Handa, J. Xie, Q. Ma and A. Kumar, *ACS Nano*, 2020, **14**, 1468–1481.
- 79 A. Wilson, V. Menon, Z. Khan, A. Alam, L. Litovchick and V. Yakovlev, *Redox Biol.*, 2019, **24**, 101169.
- 80 W. Wu, M. Chen, T. Luo, Y. Fan, J. Zhang, Y. Zhang, Q. Zhang, A. Sapin-Minet, C. Gaucher and X. Xia, *Acta Biomaterialia*, 2020, **103**, 259-271
- 81 C. Hu, X. Cun, S. Ruan, R. Liu, W. Xiao, X. Yang, Y. Yang, C. Yang, H. Gao, *Biomaterials*, 2018, **168**, 64–75.
- 82 W. Fan, B.C. Yung and X. Chen, *Angew. Chem. Int. Ed.*, 2018, **57**, 8383 – 8394.
- 83 Z. Sun, Z. Yi, X. Cui, X. Chen, W. Su, X. Ren and X. Li, *Nanoscale*, 2018, **10**, 12109.
- 84 E.I. Azzam, J.P. Jay-Gerin and D. Pain, *Cancer Lett.*, 2012, **327**, 48.
- 85 S. Gao, W. Zhang, R. Wang, S.P. Hopkins, J.C. Spagnoli, M. Racin, L. Bai, L. Li, W. Jiang, X. Yang, C. Lee, K. Nagata, E.W. Howerth, H. Handa, J. Xie, Q. Ma and A. Kumar, *ACS Nano*, 2020, **14**, 1468–1481.
- 86 M. Jiang, Z. Xue, Y. Li, H. Liu, S. Zeng and J. Hao, *Nanoscale Horiz.*, 2020, **5**, 268-273.
- 87 A.B. Seabra, M. Oullet, M. Antonic, M.N. Chretien and A.M. English, *Nitric Oxide*, 2013, **35**, 116-122.
- 88 X. Zhang, G. Tian, W. Yin, L. Wang, X. Zheng, L. Yan, J. Li, H. Su, C. Chen, Z. Gu and Y. Zhao, *Adv. Funct. Mater.*, 2015, **25**, 3049–3056.



- 89 X. Zhang, J. Du, Z. Guo, J. Yu, Q. Gao, W. Yin, S. Zhu, Z. Gu and Y. Zhao, *Adv. Sci.*, 2019, **6**, 1801122.
- 90 M. Gotte and G. Yip, *Cancer Res.*, 2006, **66**, 10233e10237.
- 91 L. Tan, R. Huang, X. Li, S. Liu and Y.M. Shen, *Acta Biomaterialia*, 2017, **57**, 498–510.
- 92 S. Pramanick, J. Kim, J. Kim, G. Saravanakumar, D. Park and W.J. Kim, *Bioconjugate Chem.*, 2018, **29**, 885–897.
- 93 J. Kim, B.C. Yung, W.J. Kim and X. Chen, *J. Controlled Release*, 2017, **263**, 223–230.
- 94 H. Alimoradi, K. Greish, A. Barzegar-Fallah, L. Alshaibani and V. Pittala, *Int. J. Nanomed.*, 2018, **13**, 7771–7787.
- 95 C. Chu, X. Lyu, Z. Wang, H. Jin, S. Lu, D. Xing and X. Hu, *Chem. Eng. J.*, 2020, **402**, 126125.
- 96 T. Feng, J. Wan, P. Li, H. Ran, H. Chen, Z. Wang and L. Zhang, *Biomaterials*, 2019, **214**, 119213.
- 97 R. Guo, Y. Tian, Y. Wang, W. Yang, *Adv. Funct. Mater.*, 2017, **27**, 1606398.
- 98 X. Huang, F. Xu, H. Hou, J. Hou, Y. Wang and S. Zhou, *Nano Res.*, 2019, **12**, 1361–1370.
- 99 R. Kinoshita, Y. Ishima, V.T.G. Chuang, H. Nakamura, J. Fang, H. Watanabe, T. Shimizu, K. Okuhira, T. Ishida, H. Maeda, M. Otagiri and T. Maruyama, *Biomaterials*, 2017, **140**, 162–169.
- 100 B. Mordorski, R. Pelgrift, B. Adler, A. Krausz, A.B. da Costa Neto, H. Liang, L. Gunther, A. Clendaniel, S. Harper, J.M. Friedman, J.D. Nosanchuk, P. Nacharaju and A.J. Friedman, *Nanomed.-Nanotechnol. Biol. Med.*, 2015, **11**, 283–291.



- 101 X. Niu, J. Cao, Y. Zhang, X. Gao, M. Cheng, Y. Liu, W. Wang and Z. Yuan, *Nanomed.-Nanotechnol. Biol. Med.*, 2019, **20**, 102015.
- 102 Y. Xu, J. Liu, Z. Liu, H. Ren, J. Yong, W. Li, H. Wang, Z. Yang, Y. Wang, G. Chen and X. Li, *ACS Nano*, 2020, **14**, 9780–9795.
- 103 S. Kudo and Y. Nagasaki, *J. Control. Release*, 2015, **217**, 256–262.
- 104 Z. Ma, S. Liu, Y. Ke, H. Wang, R. Chen, Z. Xiang, Z. Xie, Q. Shi and J. Yin, *Biomaterials*, 2020, **255**, 120141.
- 105 J. Sun, Y. Fan, W. Ye, L. Tian, S. Niu, W. Ming, J. Zhao and L. Ren, *Chem. Eng. J.*, 2020, **417**, 128049.
- 106 M.E. Douglass, M.J. Goudie, J. Pant, P. Singha, S. Hopkins, R. Devine, C.W. Schmiedt and H. Handa, *ACS Appl. Bio Mater.*, 2019, **2**, 2539–2548.
- 107 A. Lai, C.T. Demarest, C.C. Do-Nguyen, R. Ukita, D.J. Skoog, N.M. Carleton, K.A. Amoako, P.J. Montoya and K.E. Cook, *Acta Biomaterialia*, 2019, **90**, 122–131.
- 108 Y. Li, J. Lin, X. Zhi, P. Li, X. Jiang and J. Yuan, *Mater. Sci. Eng. C*, 2018, **91**, 606–614.
- 109 C. Chakraborty, A.R. Sharma, G. Sharma and S.-S. Lee, *J. Nanobiotechnol.*, 2016, **14**, 65.
- 110 R.S. Ronson, M. Nakamura and J. Vinten-Johansen, *Cardiovasc. Res.*, 1999, **44**, 47–59.
- 111 N. Khlebtsov and L. Dykman, *Chem. Soc. Rev.*, 2011, **40**, 1647–1671.
- 112 M.M. Dotzel, *Federal Register*, 1999, **64**, 34259–34260.

