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REVIEW

Nanomaterials for Nanotheranostics: Tuning Their Properties According to Disease Needs

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ABSTRACT: Nanotheranostics is one of the biggest scientific breakthroughs in nanomedicine. Most of the currently available diagnosis and therapies are invasive, time-consuming, and associated with severe toxic side effects. Nanotheranostics, on the other hand, has the potential to bridge this gap by harnessing the capabilities of nanotechnology and nanomaterials for combined therapeutics and diagnostics with markedly enhanced efficacy. However, nanomaterial applications in nanotheranostics are still in its infancy. This is due to the fact that each disease has a particular microenvironment with well-defined characteristics, which promotes deeper selection criteria of nanomaterials to meet the disease needs. In this review, we have outlined how nanomaterials are designed and tailored for nanotheranostics of cancer and other diseases such as neurodegenerative, autoimmune (particularly on rheumatoid arthritis), and cardiovascular diseases. The penetrability and retention of a nanomaterial in the biological system, the therapeutic strategy used, and the imaging mode selected are some of the aspects discussed for each disease. The specific properties of the nanomaterials in terms of feasibility, physicochemical challenges, progress in clinical trials, its toxicity, and their future application on translational medicine are addressed. Our review meticulously and critically examines the applications of nanotheranostics with various nanomaterials, including graphene, across several diseases, offering a broader perspective of this emerging field.

KEYWORDS: *nanotheranostics, nanomaterials, cancer, solid tumor, liquid tumor, neurodegenerative diseases, autoimmune diseases, cardiovascular diseases, clinical trials, graphene*

In 2002, John Funkhouser, the PharmaNetics president and CEO, was credited by scientists for introducing the term theranostics (a portmanteau of Therapeutics and Diagnostics), which epitomes the development of nanoparticle (NP) systems for personalized medicine.[1,2] Theranostics (or theragnostics) refers to a comprehensive effort that integrates diagnostics and therapy in a single system/platform.[3,4]

With the emergence of nanotechnologies and nanomaterials, the concept of nanotheranostics was then introduced (Figure 1). Nanotheranostics was able to provide non-invasive imaging, targeting, and therapy at the disease sites, without affecting surrounding healthy cells.[3,5] Hence, the use of empirical treatment can be avoided (therapy given based on experience, usually without a prior definitive medical diagnosis and likely to cause infectious disease), greatly improve the prognoses, and subsequently expedite clinician's therapeutic decisions.

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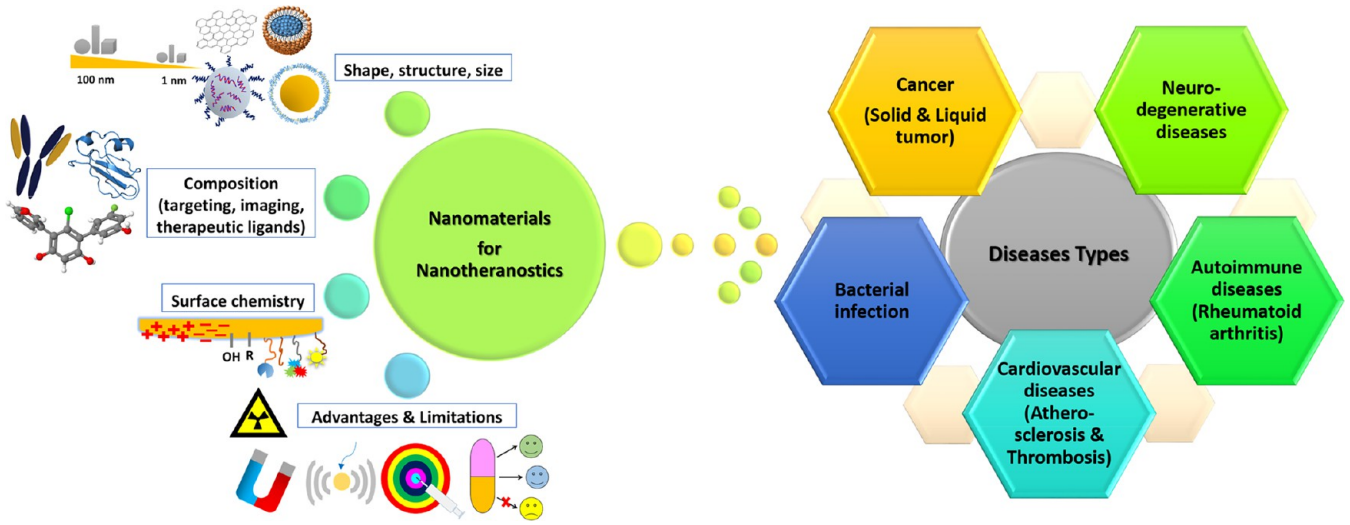

Figure 1. Nanotheranostics: The use of nanomaterials with integrated diagnostic and therapeutic properties across several diseases.

Therefore, early diagnosis will increase the patient's survival rate, and the optimized treatment will contribute to high therapeutic efficiency along with the best safety profile.[3,6] Furthermore, overdosing of drugs and cost of treatment can be effectively reduced. Nanotheranostics will also enable real-time monitoring of the drug release and its biodistribution in patients.[7]

Nanomaterials can be broadly categorized according to their composition, such as metal, carbon, and inorganic and organic NPs.[8,9] Generally, theranostic nanomaterials can be made up of different chemical constructs: targeting moiety (for specific cellular binding), therapeutic agents (for drug delivery), diagnostic agents (for non-invasive imaging), and polymer coating or matrix that imparts colloidal stability and provides functional groups for bioconjugation.[3,6] Some of the important advantages of nanomaterials are undoubtedly their small size and large functional surface area to volume ratio, in addition to interesting optical and electrical properties. These properties allow the diagnostic and therapeutic agents to be adsorbed, dissolved, or covalently attached to the surface, to form NP-drug/imaging/targeting complexes.[10] The complex can subsequently signal (diagnostics) and deliver the agents to the cancer cells or other targeted sites to perform the therapy.[11,12] Ideally, after the controlled release of encapsulated drug molecules, the residual NP will be safely degraded and excreted from the body.[10]

Recently, the application of nanomaterials with multiple physical imaging modalities and therapeutic capabilities has received increasing attention. There are several excellent review papers with similar topics made,[8,13−17] however, these papers are either focused on specific disease/cancer/illness or emphasized on the theranostic properties of a specific nanomaterial. In this review, we stratify the information on the basis of cancer- or disease-specific, enabling a comprehensive comparison of the nanomaterials for theranostics of up to three different diseases. Specifically, we focus on the nanotheranostics of cancer (including solid and liquid tumor) and several diseases: neurodegenerative, autoimmune, and cardiovascular diseases (see Table 1). The physiochemical properties of various nanomaterials, including graphene, a rising star in the 21st century, have been critically reviewed. We also discuss the physical and biological barriers that impede application of nanotheranostics *in vivo* and provide an overview of different nanomaterials that are currently in clinical trials. A future outlook of this rapidly growing field will be given as a conclusion. By putting this information together, this review may shed light on understanding nanomaterials for nanotheranostics while we are expecting continuous breakthrough in this field.

Physical and Biological Barriers That Impede the Application of Nanotheranostics *in Vivo*. The human body has multitiered physical, physiological, chemical, and biological barriers to protect it against foreign species/substances. Examples of the barriers that nanomaterials may encounter in biological systems are the skin, air−blood barrier in the lungs, reproductive system, circulation, and blood−brain barrier.[18,19] Nanomaterials must be precisely engineered to overcome these biological barriers and perform nanotherapeutics at the disease site.[20] While it is important to find a balance between therapeutic potential and toxicity of nanomaterials, their biological effects on human body are not fully understood due to the complexity of nanomaterial/biological barrier interaction.

In this section, we will discuss the interactions of nanomaterials with serum proteins and the mononuclear phagocyte system (MPS) in the tumor microenvironment and provide an overview of the barriers to the intratumoral delivery of therapeutic nanomaterials.

Interaction of Nanomaterials with Serum Proteins. When nanomaterials circulate throughout the body, they are exposed to a complex fluid containing blood, lymph, biomolecules, cytoplasm, *etc.*[21,22] Protein and other biomolecules such as albumin, transferrin, gamma globulin, and fibrinogen will compete for binding on the surface of nanomaterials. This will slightly change the secondary structure of the proteins and lead to the formation of both soft and hard protein corona.[22−24] Formation of protein corona on nanomaterials will affect the surface of nanomaterials and their subsequent interaction with biological molecules (biodistribution and penetrance) and cellular compartments.[18,25]

The composition, properties, and formation of protein corona are influenced by physiochemical properties (size, shape, surface area, charge, chemical composition, functionalization, colloidal stability, porosity, *etc.*) of nanomaterials.

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Table 1. A Summary of Functional Nanomaterials Developed for Different Cancer/Diseases/Illness

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
Cancer (Solid tumor)	Gold nanostructures	Diazirine-decorated Au@PEG-NH_2	20.5 ± 1.9	PTT	PAI	Female BALB/c mice	Light-addressable cross-linking at 405 nm laser irradiation	63
		AQ4N-Cu(II)-Apt_{Ce6}-GNPs	137.07 ± 4.26	PDT, PTT, chemotherapy	Optical	Male BALB/c-nude mice	Tumor microenvironment -triggered, programmed synergistic therapy at 670 nm laser irradiation	41
		SWNT@BSA@ Au-S-PEG-FA@DOX	20–30 (estimated thickness)	PTT, chemotherapy	Optical	Female nude mice	High drug loading ratio (150–590 %); 808 nm laser irradiation	67
		Stealth-AuNC NPs	80-100	PTT	Optical	BALB/c mice	850 nm laser irradiation; longer circulation half-life (> 4-fold)	46
		AuNR@Da NHs	130	PTT, chemotherapy	Fluorescence, PAI	Nude mice	Photothermal conversion (80 %); 27-fold higher internalized AuNR mediated by NHs; 6.6 times higher internalized ADR; 2.3 times higher tumor accumulation due to NIR-induced hyperthermia	73
	Other inorganic nanomaterials	MnO_2-SPs nanosheets	295 (average thickness = 2.0 nm)	PTT	MRI	BALB/c-nude mice	Ultra-sensitivity to endogenous tumor microenvironment and exogenous NIR irradiation; 808 nm laser irradiation; high photothermal-conversion efficiency (21.4 %)	80
		Anti-EpCAM-UPGs-MX	93.5	Chemotherapy, PDT	MRI, upconversion luminescence	Female BALB/c mice	MX loading level (12.5 wt %); 980 nm laser irradiation	82
		mNiO-TB-ART	310	PTT, radical-induced therapy	Optical luminescence, T_2-weight MRI	HeLa tumor mice models	T_2-weighted MRI, r_2 = 6.30 (mg $mL^{-1})^{-1}$ s^{-1}; NIR laser irradiation at 785 nm	81
		Pd@Pt-PEG-Ce6	80	PDT, PTT	Optical	4T1 subcutaneous tumor mice model	Laser irradiation at 660 and 808 nm; hypoxia modulation function with mild PTT effect	44
		BiP_5W_{30} NCs	1.5 (thickness of rGO)	Radiotherapy, PTT	Optical	HeLa tumor-bearing mice	Laser irradiation at 808 nm; increased radiation dose deposition within tumors; tumor microenvironment -manipulated	43
		CuS@BSA-MBA-cRGD	51.2 ± 2.46	PTT	Optical (infrared thermal)	EAC tumor-bearing mice	Laser irradiation at 808 nm; synergistic tumor-targeting delivery and PTT effects	77

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Table 1. continued

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
		TPGS-Cu_3BiS_3 NCs	15	Radiotherapy, PTT	Optical	Female BALB/c nude mice	Photothermal conversion efficiency at 1064 nm = ~67.29 %; 808 nm = ~18.27 %; 980 nm = ~61.06 %	87
		FA-QDs-FUA	220.28	Chemotherapy	Optical	Balb/c Nod/Scid mice	Zeta potential= -13.3 mV; drug-loading content = 36.85 % ± 1.61 % (n= 3)	84
		Gd-DTPA-coupled Ag_2Se quantum dots	4.08 ± 0.58	-	Optical, MRI	Female Balb/c mice	Contrast agents in *in vivo* dual-modality T_1-weighted MR imaging; NIR-IIb fluorescence imaging with high spatial resolution	85
		PHMNPs-S-S-PEG-LA@PFC(O_2)/EP	16.07	Chemotherapy	Optical, MRI	Nude mice	High etoposide/oxygen loading capacity, tumor-targeting capability and programmable intracellular agglomeration behavior	47
		Cu_3BiS_3 nanocrystals	12 ± 4	PTT, PDT	Optical, x-ray contrast	BALB/c nu/nu mice	Ultra-low NIR laser irradiation	70
		Co_3O_4 nanoprism	3.26 x 33.29 (thickness x length)	PTT, chemodynamic, chemotherapy	MRI, optical	Nude mice	Photothermal conversion efficiency, η= 60.07 %; MRI contrast, r_2= 5.42 $mM^{-1}s^{-1}$; significant hydroxyl radical generation; low toxicity; DOX delivery = 29.36 mg/g; low detection limit (50 nM), broad linear range (0-50 μM); high sensitivity and selectivity for H_2O_2	45
	Polymeric nanoparticles	SiNc-PNP, encapsulated in PEG-PCL	40	PTT, NPs-mediated image-guided surgery	Optical	Female athymic nude mice	Real-time intraoperative image-guided surgery; 785 nm laser irradiation; process can be tailored *via* photo irradiation dosage	90
		M-GEG NPs, M-EGFA NPs	105 (GEG NPs), 90 (EGFA NPs)	Chemotherapy	Optical	New Zealand albino rabbits, athymic mice models	Sustained and targeted drug release at the tumor site	89
		POCL nanoreactor	50	PDT	Chemiluminescence	BALB/c nude mice	Self-luminescing; tumor microenvironment activated; non-invasive	92

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Table 1. continued

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
		FUP cationic nanomicelles	30-150	Chemotherapy	Optical	-	Surface charge of zeta potential +20.1 mV; antitumor apoptosis mechanism might be related to the regulation of Fas/FasL and activation of caspase-8 and caspase- 3	93
		$Cu_{2-x}S$/PFBO@PLGA	123.7	HIFU	PAI	Balb/c nude mice	Core/satellite/shell sandwich structure; favorable biosafety; high PAI contrast capability with enhanced ablation efficacy under HIFU	95
		STD-NM_{drug}	25	Chemotherapy	Optical, AIE-based two-photon	BALB/c nude mice	Therapeutic effect monitoring by AIE signal 'switch on'; therapeutic property supported by gene analysis (RNA-seq)	97
	Lipid nanoparticles	HA/CPPs-10-HCPT-NPs	284.2 ± 13.3	Chemotherapy	Optical, ultrasound	BALB/c nude mice	Can undergo ADV and ultrasound-targeted microbubble destruction; triggered by LIFU; allow penetration into extracellular matrix, cellular membrane and nucleus	100
		Lipo@HRP&ABTS	100	PTT	PAI	Female BALB/c mice	Under 808 nm NIR laser irradiation; *in vivo* H_2O_2-responsive chromogenic assay; detection of inflammation; enable differentiation of metastatic lymph nodes	101
		DOX/SPIONs-loaded DFSLNs	132.1 ± 8.7	Chemo/magnetothermal combination therapy	Optical	BALB/c mice	Hierarchical and dual targeting for the oral delivery of dual-modality local therapy	98
		Lip/Ce6/TPZ NPs	162 ± 4	PDT, chemotherapy	Optical	MCF-7-beared mice	Light- triggered and hypoxia-responsive; good biocompatibility with little toxicity toward normal cells without irradiation	99
Cancer (Liquid tumor)	Metal nanoparticles	FA-IONPs	100	PTT	MRI	LnCaP cells	Specific targeting due to FA functionalization	127
		EMG-308 IONP	60	PTT	MRI	LnCaP cells	IONP aggregation prevention	128
		Cu-Au@F-Apt NSs	30	PTT	Optical	Male athymic BALB/c mice	Cu high thermal conductivity	129

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Table 1. continued

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
	Lanthanide-doped nanoparticles	antiCD33-LONp-PMI	5.6	Chemotherapy	Optical	Primary cells from patients with AML	Real time visualization of AML cells apoptotic events	131
	Polymeric nanoparticles	CCM-PEG	228	Chemotherapy	Optical	HL-60, HepG2, HEK293 T, HDF cells	Natural biocompatible material with anticancer activity	132
		pA20-36 Chitosan-HA-NPs	70	Chemotherapy	Optical	Balb/C nude mice	Multimodal imaging depending on the site of tumor	134
		PDI NP	60	PTT	PA and PET	U87MG tumor-bearing nude mice	Size dependent tumor accumulation effect	135
	Lipid nanoparticles	Lip/PEG/Tween 80/SPIONs-PVA/RTX	7-10	Chemotherapy	MRI	Athymic nude mice	Blood-brain barrier internalization	189
Neurodegenerative diseases	Dyes	DBA-SLOH	-	Chemotherapy	Optical	APP/PS1 transgenic (Tg) mice	NIR dye	141
	Multifunctional nanocomposite	CeNC/IONC/MSN-T807-MB	131	Chemotherapy	MRI	Male Sprague–Dawley rats	Synergistic therapeutic effect of CeNC and MB	142
	BTTA chelator	BTTA	-	Chemotherapy	Optical	C57BL/6J male mice	Fluorescent chelator	144
	Multifunctional upconversion nanoparticle	UCHQs	114	Chemotherapy	Optical	C57BL6 female mice	Tissue autoluminiscence circumvented by NIR excitation	145
Autoimmune diseases (Rheumatoid arthritis)	Polymer conjugate micelles	DS-*g*-MTX	104.4 ± 14.4	Chemotherapy	Optical	CIA mice	Targeting on SR-expressed activated macrophages	149
	Polymeric NPs (amphiphilic)	MTX-DSNPs	220	Chemotherapy	Optical	CIA mice	MTX loading efficiency (73.0 %); targeting on macrophages scavenger receptor class A	150
	Phase-transition NPs	OI-NPs	277.80 ± 22.49	PSDT	Optical	-	Exposed to LIFU, caused a sonodynamic reaction; laser irradiation at 808 nm	154
	Plasmonic NPs	MTX-Au/Fe/Au plasmonic NPs	135	PTT, chemotherapy	MRI, optical	CIA mice	NIR light irradiation at 808 nm; T_2 weighted MRI; magnetic targeted chemo-photothermal treatment; higher therapeutic efficacy with smaller MTX dosage (0.05 %)	153
	Inorganic NPs	$Cu_{7.2}S_4$NPs	120	PTT, PDT	Optical	CIA mice	NIR irradiation at 808 m, can prevent bacterial infection using intra-articular injection	156

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Table 1. continued

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
Cardiovascular diseases (Atherosclerosis)	Inorganic NPs	CuS-TRPV1	13 ± 1.2	PTT	PAI, optical	ApoE −/− mice	Targeting on TRPV1 signaling; NIR laser irradiation at 980 nm; showed no obvious *in vivo* toxicity	164
	QDs	SV40 VNPs	26 ± 1.2	Chemotherapy	Optical	ApoE −/− mice	Encapsulating NIR QDs, bearing atherosclerotic targeting peptides and anti-coagulant drug Hirulog; targeting on VACM-1, macrophages and fibrin	166
	Magnetic NPs	HDL-MNS	80-100	Reverse cholesterol transport	MRI	-	Serve as cholesterol efflux agents (4.8 %); show a 5 times higher contrast (r_2 relaxivity up to 383 $mM^{-1}s^{-1}$)	172
	Polymeric NPs	ICG-BM NPs	500	Antioxidant, anti-inflammatory	Fluorescence, ultrasound, photoacoustic	Balb/c male mice	Photoacoustic signal is detectable with low frequency ultrasound transducers; excellent antioxidant, anti-inflammatory, proangiogenic activities; pathological stimulus-activatable multiple contrast amplification	171
Cardiovascular diseases (Thrombosis)	Polymeric NPs	FTIAN	160	Chemotherapy	PAI, optical	$FeCl_3$-induced carotid arterial thrombosis mice model	Targeting on fibrin and elevated level of H_2O_2; intrinsic anti-oxidant, anti-inflammatory and anti-platelet activity; anti-thrombotic when loaded with antiplatelet drug tirofiban; irradiation of pulsed laser at 808 nm	165
	Inorganic NPs	T-FBM NPs	320	Chemotherapy	PAI, optical	$FeCl_3$-induced carotid arterial thrombosis mice model	CO_2 bubble generation and photoacoustic waves formation when exposed to ultrasonic transducer; H_2O_2-activatable ultrasound/photoacoustic signal amplification; antithrombotic effect	171
	Polymer nanobubbles	Fucoidan-MBs	2–6 μm	-	Ultrasound	Wistar male rats	Stable in suspension at 4 °C up to 2 months; exhibit high echogenicity; could completely burst under high destructive pulse	174

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Table 1. continued

Cancer/Disease /Illness	Type of nanomaterial	Formulation	Mean size (nm)	Therapeutics modality	Imaging modality	Animal model	Brief description/ Remarks	Ref.
Bacterial infections	Composite materials	MIL-100 (Fe) NPs	120	PDT	Optical	MRSA-bearing mice	H_2O_2-responsive MOFs assisted bacteria metabolic labelling strategy; incorporation of unnatural functional group into bacteria *in vivo*	181
		Se@PEP-RuNPs	78 ± 13	Antibacterial	Optical	BALB/cA -nude mice	High stability, excellent light stability; no obvious cytotoxicity, negligible hemolytic effect; could promote wound healing	178
		Au/AgNRs	104.9	Antibacterial	PAI	Wild-type male C57BL/6 mice	Strong bactericidal efficacy towards both MRSA (32 μM Ag^+) & *Escherichia coli* (8 μM Ag^+); PA signal increased by 730% pre- and post-etching; bacterial counts reduced by 1000-fold (log CFU/g= 4.15 *vs* 7.75) after treatment	187
	Inorganic NPs	CIP-LuPSi	17.3	Bacterial inhibition *via* drug release	Optical	SD male rats	High biocompatibility & drug-loading ability; silicon-based smart bandage in wound care and bioimaging	182
		SiO_2-Cy-Van	72.7 ± 3.2	Antimicrobial, PTT	Optical	MRSA-bearing mice	Activated by bacteria-responsive dissociation of the polyelectrolyte from silica NPs; rapid MRSA-activated NIRF imaging (4 hours post-injection, high sensitivity up to 10^5 colony-forming units); effective PTT upon 808 nm laser irradiation	183
		QA-AuNCs	2	Antibacterial	Optical	MRSA T144 mouse	Imaging-guided bacteria counting; discrimination of live/dead bacteria; non-toxic to mice at doses of up to 100 mg/kg	185
		PDA NP-Cip/GC hydrogel	30	PTT, antibacterial	Optical	BALB/c female mice	NIR laser irradiation at 808 nm; bacterial killing activity with wound healing ability	188
	Organic NPs	PEG-$W_{18}O_{49}$	18 x 5 x 1 (height x width x thickness)	PTT	X-rays, CT, MRI, ultrasound	Kunming mice	NIR laser irradiation at 808 nm; excellent colloidal stability, low cytotoxicity & neglectable hemolysis	175

Nanomaterials could exert both positive (act as carriers to immobilize enzyme, improve activity and stability of proteins) and negative impacts (induce potential toxicity to cells and organs) on proteins.[26] Supramolecularly built protein corona

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can also be exploited to shield nanomaterials' interaction with serum proteins and macrophages while retaining its targeting specificity *in vitro* and *in vivo*.[24]

Positively charged nanomaterials facilitate cellular uptake and improve lysosomal escape without induction of toxicity, showing more specific interaction with negatively charged biological membranes.[18] Single-layer and multilayered graphene oxide has been proven to exhibit different behaviors in cell culture medium.[27] The various types of carbon nanomaterials (fullerene, carbon nanotubes, graphene, and their derivatives) have particular effects on the structure or activity of the proteins. For instance, the graphene sheet has a stronger adsorption capacity for serum proteins than carbon nanotubes. Yet, the enzymatic degradation of graphene and fullerenes derivatives is much complicated than carbon nanotubes.[26]

The individual and in combination properties of nanomaterials play an important role in determining their path, biological effect, and immunological fate in biological systems.

Interaction of Nanomaterials with MPS. One of the factors for low drug-delivery efficacy to the tumor and low therapeutic outcomes is due to the MPS. The MPS mainly involves the liver, spleen, and lymph nodes. MPS serves as a delivery barrier for invading pathogens, particulates, and dead or damaged host cells.[28] Among the MPS, Kupffer cells are the major phagocytic cells (*e.g.*, macrophages) residing inside the liver sinusoid.[23] In principle, cationic nanomaterials have higher affinity for macrophages than neutral and anionic nanomaterials.[23] Attachment of surface protein, such as opsonins on the nanomaterials, may increase the chance of nanomaterials being recognized by the scavenger receptors on the Kupffer cells. This will result in opsonization and subsequent phagocytosis.[18,19,23] The nanomaterials will be ultimately taken up and cleared by macrophages. Generally, MPS cuts off more than 95% of the administered nanomaterials.[23]

Mammalian cells engulf intracellular contents using autophagosome, a double-membrane vesicle, fuse with lysosomes, and later degrade or recycle the autophagic contents. This process is known as autophagy.[25] Autophagy is vital in maintaining the homeostasis of cells. Dysregulation of autophagy in degrading overexpressed prions proteins may lead to neurodegenerative disorders, while active autophagy aids in chemotherapeutic treatments of cancer cells.[25] Fe_3O_4 NPs were found to have the ability to induce autophagy in human cervical carcinoma cells. Positive correlations between size/molecular weight of protein and adsorption of protein on a 20 nm Fe_3O_4 NPs were confirmed.[25] However, the higher the adsorption of protein on Fe_3O_4 NPs, the lower the cell uptake of NPs and consequently lower cell autophagy responses.[25]

An increase in the dosage of nanomaterials, on the other hand, raises toxicity concerns induced by the accumulation of nanomaterials in organs such as liver and spleen.[23] Solvents and chemicals involved during the synthesis of nanomaterials are one of the causes of toxicity *in vivo*.[17] Their long-term cytotoxicity and related immune response should be taken into consideration.

Four strategies (surface modification, tuning of physiochemical properties of nanomaterials, biomimetic design inspired by nature, and modulation of the MPS) have been identified to oppose uptake by the MPS, lower off-target rate, and enhance cancer therapeutic efficacy.[23] For instance, modifying the surface of nanomaterials with zwitterions, polyethylene glycol, carbohydrate moieties, and dysopsonic proteins allows the bypass of phagocyte-mediated cellular barriers, which in turn increases nanomaterials blood circulation time and theranostics efficacy.[24] Another interesting strategy to protect the nanomaterials from phagocytosis is by using the extracts of cell membranes from blood or tumor cells. The extracts can be used to coat the nanomaterials, camouflaging the nanomaterials from uptake by the MPS.

Barriers of Intratumoral Delivery. Tumor microenvironment is generally composed of tumor cells, the extracellular matrix, stromal cells, cells from the immune systems (macrophages, lymphocytes, natural killer cells), *etc.*[12,19] Macrophages act as immune cells to maintain immunohomeostasis. The failure of existing therapies is mainly attributed to the tumor microenvironment limiting drug access to the tumor cells.[12,29] This is because upon entering through the blood vessel leakage, nanomaterials would interact with the microenvironment factors.

The intratumoral microenvironment serves as a physical and biological barrier for the delivery of therapeutic nanomaterial to the solid tumor (*e.g.*, pancreatic cancer).[18] In normal tissues, the extracellular matrix is loose and elastic, with sufficient oxygen supply, and the overall redox environment is homeostasis.[30] In contrast, the basement membrane in the tumor is thicker, with higher cross-linked extracellular matrix, hypoxic, acidic and has a harsh redox environment.[31,32] Differentiated macrophages, named as M2-type tumor-associated macrophages, will trap and degrade the functional nanomaterials delivered into the tumor.[30] High tumor interstitial fluid pressure will also force the nanomaterials back to blood circulation, further preventing them from reaching the tumor sites.[30] These pathophysiological properties greatly impede intratumoral delivery of nanomaterials.

Dissolution (or generation of metal ions in target organs and cellular barriers) is another common phenomenon in metal and metal oxide nanomaterials in biological systems due to their high surface area and reactivity.[18] Different strategies, such as the use of stromal depletion molecules, targeting of transforming growth factor-beta (TGF-β) and interleukin-6 (IL-6) pathways, *etc.* have been studied to overcome the stromal barrier.[18,33,34] Pei *et al.* (2019)[29] also demonstrated that simultaneous targeting of both TGF-β signaling and KRAS mutation attenuates the dense stroma barrier, enhances tumor blood perfusion, and improves therapeutic efficiency in pancreatic cancer.

In short, it is important to understand the interaction between nanomaterials and tumor microenvironmental factors before constructing functional nanomaterials that are expected to be able to overcome the above-mentioned challenges.

CANCER

Cancer is a broad name given to the diseases featured with uncontrolled rapid cell division that may form growths called tumors. Nobel Laureate Otto Warburg discovered that low oxygen was a hallmark of cancer cells. Cancer cells "reprogram" themselves under stressful conditions (lack of oxygen, limited nutrient resources, or energy, *etc.*), with a faster growth rate than the rate of new blood vessel formation.[35,36]

Cancer can be further classified into solid and liquid tumors, each with differences in terms of their tumor vascularity and heterogeneity, thus requiring different diagnostic and targeting strategies.[37] For centuries, surgery, chemotherapy, and radiation therapy remain as the most common cancer therapies. However, these few alternatives often come with

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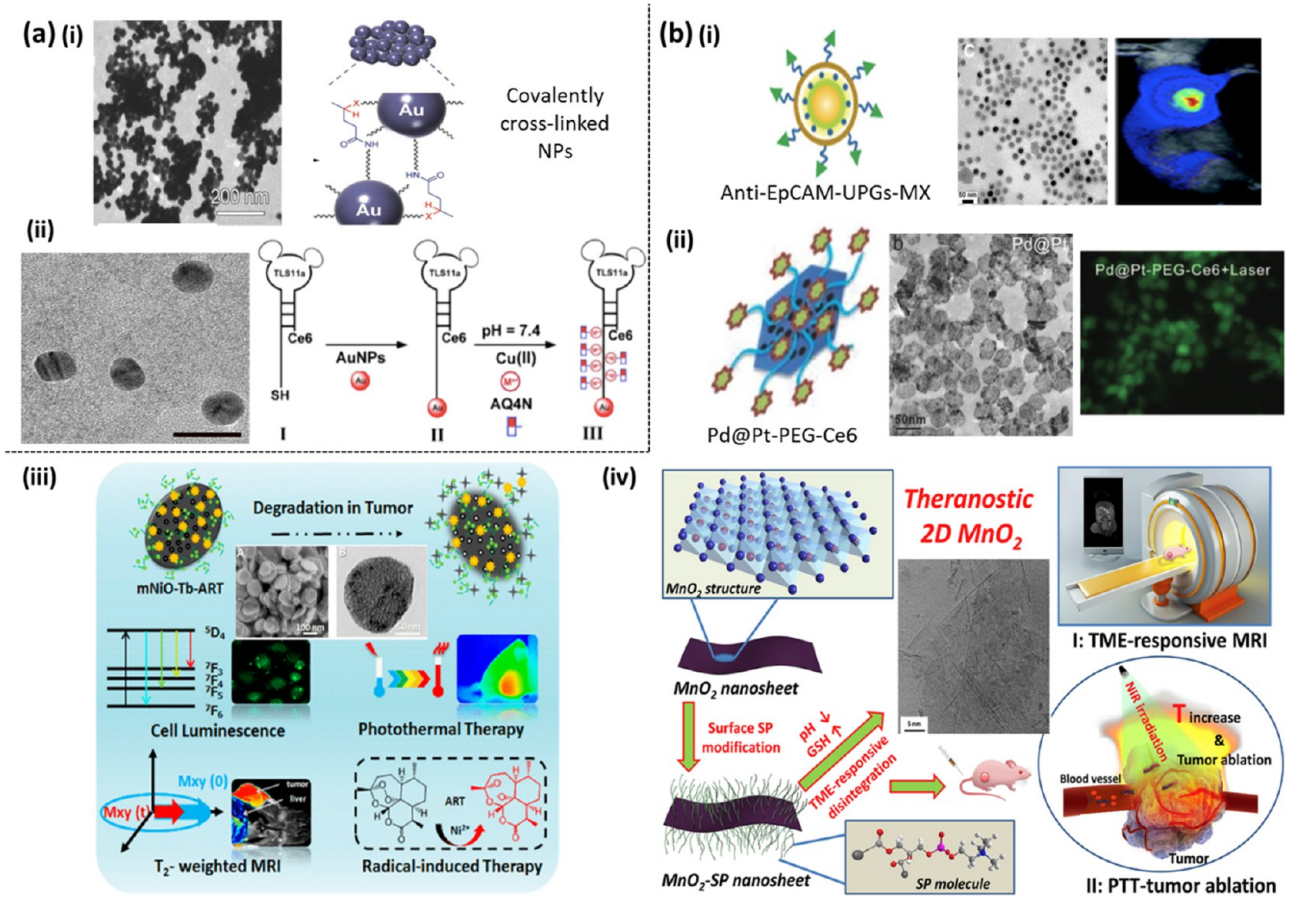

Figure 2. Brief overview of nanomaterials used for solid tumor theranostics, with their respective TEM images. (a) Gold nanoclusters: (i) The photo-cross-linkable Au NPs for PTT and photoacoustic imaging of tumors *in vivo*. Adapted with permission from ref 42. Copyright 2019 Ivyspring International Publisher. (ii) Preparation of the smart Cu (II)-aptamer complex-based gold nanoplatform for synergistic PDT/PTT/chemotherapy of hepatocellular carcinoma. Adapted with permission from ref 41. Copyright 2017 Ivyspring International Publisher. (b) Inorganic nanomaterials: (i) The structure of PEGylated upconversion-based micelles which permits dual-modality magnetic resonance/upconversion luminescence-guided synergistic chemotherapy and PDT in hepatocellular carcinoma. Adapted with permission from ref 82. Copyright 2018 Royal Society of Chemistry. (ii) A photosensitizer-Pd@Pt nanosystem (Pd@Pt-PEG-Ce6) in enhancement of tumor-specific PDT. Adapted with permission from ref 44. Copyright 2018 John Wiley and Sons. (iii) The artemisinin-loaded mesoporous nanoplatform for synergistic photothermal and radical-induced tumor theranostics. Adapted with permission from ref 81. Copyright 2018 American Chemical Society. (iv) Overview of 2D ultrathin MnO_2 nanosheets in magnetic resonance imaging and ultrasensitive stimuli-responsive PTT. Adapted with permission from ref 80. Copyright 2018 Elsevier.

the possibility of recurrence after the treatment (since not all cancer cells can be completely removed by surgery), severe toxic side effects (chemotherapy and radiotherapy), and limited specificities to cancer cells.[38,39] Due to their low molecular weight, conventional chemotherapeutic drugs generally have low half-lives in the blood and are rapidly distributed in healthy tissues and organs, limiting their therapeutic efficacy.[40] Furthermore, the use of centralized diagnostic platform in most of the cancer management can be complex, time-consuming, and not tailored to patients and malignancies.[37]

Theranostic nanomedicine possesses the ability for specific cancer biomarker detection and concurrent cancer cells ablation, in a simple and non-invasive way, making them suitable candidates for nanotheranostics.[37] For instance, the nanomedicine can be delivered and accumulated at the tumor sites to perform therapeutic action. Yet, the drug delivery is still limited in poorly vascularized regions, and some cancer cells are able to continue proliferating.[10,39] In contrast, liquid tumors (such as leukemia and lymphoma) are spread throughout the bloodstream, and the diagnostics and therapies are often challenged by poor selectivity, low therapeutic efficacy, multidrug resistance, and long-term side effects.[37] Tumor microenvironment varies between cancer types of different or the same anatomical region.[12] The discovery of the right diagnostics and therapeutics intervention is highly important in cancer treatments.

Continuous research efforts in nanotheranostics from drug delivery vesicles to imaging of contrast agents and targeting modalities have rapidly driven nano-oncology toward an all-in-one, localized early detection and treatment. This section will comprehensively review the recent advances regarding the development of different therapies (besides chemotherapy) and imaging modalities (such as optical, photoacoustic imaging, magnetic resonance imaging (MRI)) for solid and liquid tumors diagnosis and treatment, using functional nanomaterials.

Solid Tumor. A solid tumor is an abnormal mass of tissues and may be benign (noncancerous) or malignant (cancerous). Examples of solid tumors are carcinomas (tumors formed in

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epithelial cells) and sarcomas (tumors in blood vessels, bones, fat tissues, muscles, *etc.*).

Hypoxia, a condition in which the body tissues are deprived of oxygen, mainly due to the disorganized vasculature and poor blood circulation, is an important characteristic of solid tumors.[41,42] The hypoxia microenvironment may confer the resistance of tumors to cancer treatment,[31] especially photodynamic therapy (PDT), an externally activable and oxygen-dependent therapeutic modality.[38] PDT works by using cytotoxic oxygen species (such as singlet oxygen or reactive oxygen species (ROS)) generated from photosensitizer molecules upon light exposure, which destruct tissue structure and subsequently kill cancer cells.[41] Solid tumors are also 2−3 times more radio-resistant than normoxic tumors.[43] Hence, the hypoxic and radio-resistance nature of solid tumors causes the cancer treatment to be even more challenging.[44]

Intracellular environment of tumor cells is also rich in hydrogen ions (H^+) and hydrogen peroxide (H_2O_2) due to rapid glycolytic metabolism and superoxide dismutase overexpression.[45] This contributes to the weakly acidic extracellular pH (pH 6.0−6.8) in tumors, in contrast to weakly basic normal tissues (pH 7.2−7.4).[5,41] Hence, an ideal solid tumor theranostic nanomaterial should be sensitive enough to respond to the minute difference in extracellular pH between blood and tumors.[46] Other common cancer phenotypes are high abundance of antioxidants and elevated glutathione (GSH) level (about 4-fold higher than normal cells).[5,39,42]

In addition, the original size of the nanocarrier should be maintained below 160 nm for optimum deposition on the tumor tissues and to exploit the enhanced permeability and retention (EPR) effect.[47] EPR is a phenomenon where nanomedicine leaks preferentially into tumor tissues, through the permeable tumor vasculature. The nanomedicine will be retained in the tumor bed owing to the reduced lymphatic drainage.[36,48] EPR effect aids in the delivery (with a relatively modest effect of less than a 2-fold increase) and accumulation of nanomedicine at the solid tumors and subsequently improves the therapeutic efficacy.[23,32,49] The potential side effects are greatly reduced, since there is very low accumulation of nanomedicine within the normal tissue.[36] The ability of the NPs to cluster into large size aggregates after successful cellular internalization could prevent the lysosomal exocytosis, which may minimize the loss of their therapeutic activity.[47] Nevertheless, the drug delivery remains limited in poorly vascularized regions of the tumors, and some cancer cells are still able to survive.[10,18,32] Also, the efficiency of EPR effect is highly dependent on cancer type.[18]

Researchers have been putting efforts in designing and tailoring different stimuli-responsive nanomaterials to overcome multiple biological and physiological barriers in drug delivery and simultaneously serve as a nanotheranostic platform for cancer. The following section provides a comprehensive review on the nanotheranostic features of each nanomaterial, together with their advantages and limitations.

Gold Nanostructures. A gold (Au) nanostructure is a collective term given to different shapes of gold nanoparticles (AuNPs). It has received increasing attention for being able to provide a versatile and multifaceted platform for biomedical applications.[38,49−51] Apart from having excellent biocompatibility and facile surface chemical features, Au nanostructures are able to act as photothermal transducers. They are capable of absorbing visible or NIR radiation and then converting it into heat with high efficiency to destroy nearby biological structures (coined as photothermal therapy, PTT).[31,41,42,45,47] The potential side effects of using Au nanostructures for cancer treatment can be reduced to a minimum by controlling the intensity of light and amount of injected nanomaterials, making it a highly selective material in cancer treatment.[17,52−55]

Hepatocellular carcinoma (HCC), a type of solid tumor, is the most common primary liver cancer.[56] As the third leading cause of cancer death worldwide, HCC has often been chosen as the focus of many clinical research.[57,58] HCC tumors, like other solid tumors, have scant stroma and necrosis in the central area due to poor vascularization. HCC is nodular and can either appear as a single solitary tumor with a large mass or as multiple small tumors.[56] A tumor microenvironment responsive and triple-synergistic therapeutic nanoplatform based on AuNPs with Cu (II)-aptamer complexes has been developed for HCC treatment [Figure 2a(ii)].[41] An aptamer is a small and easy to synthesize secondary structure ligand made up of a single DNA or RNA sequence. Aptamers confer lower immunogenicity and have high targeting affinity to cell surface receptors,[59] whereas chlorin e6 (Ce6) is a widely used photosensitizer.[38,60] Possessing high singlet oxygen generation capability, Ce6 labeled aptamer has been chosen to specifically target the HCC cells and activate PDT. The binding of Ce6 labeled aptamer onto AuNPs not only avoids rapid clearance of AuNPs from the body but also serves as a cargo for the Cu (II) coordinated chemotherapeutic prodrug AQ4N (or banoxantrone, a hypoxia activated prodrug to enhance antitumor effects). The high level of intracellular GSH and acidic extracellular pH in cancerous cells induces the release of the AQ4N. The electrostatic aggregation of AuNPs induced by the free Cu (II) also switches on the PTT effects to ablate solid tumors. This system successfully permits the synergistic PDT/PTT/chemotherapy of HCC by single laser irradiation at 670 nm.[41] However, this approach has some limitations especially when selecting AQ4N as the prodrug. Since AQ4N has an ultrahigh aqueous solubility (260 mg/mL), large doses and multiple dosing (≥100 mg/kg) are required during combination therapy.[61] Although the potential side effects of AQ4N loaded nanomedicines have not been reported thus far, low AQ4N loading content and encapsulation efficiency, nonspecific release, and short-term *in vivo* retention time (half-life *in vivo* ≤ 6 h) are some of the concerns.

On the other hand, it is technically difficult to keep photoirradiation localized only on cancer cells due to uncontrollable distribution of the photothermal agents in the intracellular microenvironment.[62] Alternatively, a laser beam allows precise focusing to a tiny region of tumor cells. It has therefore been used as a stimulus to cross-link photothermal AuNPs covalently with the surface diazirine groups of polyethylene glycol (PEG) ligands [see Figure 2a(i)].[63] Upon 405 nm laser irradiation, diazirine groups generate a highly active carbene intermediate that can form covalent bonds with ligands within close proximity of AuNPs. The interparticle cross-linking of AuNPs has significantly improved photothermal ablation effects, with an optical-thermal conversion efficiency of about 78.8% as compared to 21.6% for the non-cross-linked AuNPs. This innovative approach has effectively shifted the surface plasmon resonance of 20.5 nm AuNPs to NIR region. It was also noted that the as-synthesized photo-cross-linked AuNPs have a longer blood circulation time and shorter biological half-life than particle aggregates.[63] Nevertheless, the penetration depth of 405 nm laser remains

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limited. In fact, for *in vivo* imaging application, the chosen NPs need to have the ability to be imaged at a greater tissue penetration depth (including thick bone penetration for imaging of brain tumors, air-filled cavities for imaging of lung tumors, *etc.*), without compromising the spatial resolution.[17,39,64] NIR shows better penetration depth in the tissue than visible light, yet, its clinical utility is still hindered due to autofluorescence, potential blink, scattering, and photobleaching effects in various tissues.[54,59] In fact, it is difficult to compare and evaluate the efficacy of different Au nanostructures in nanotheranostics, as their behavior is highly dependent on various parameters, such as size, shape, and surface functional group.[65] Au nanocages, with cubic shape, are particularly attractive as photothermal transducers for nanotherapeutics, owing to their interesting features such as flexible tuning of the localized surface plasmon resonance (LSPR) peaks to any wavelength of interest (in the range of 600−1200 nm) and a large NIR absorption cross section (5 orders of magnitude greater than the conventional organic dyes). With a compact size of about 40 nm, the hollow and porous structures of Au nanocages permit drug encapsulation with controlled release upon irradiation with NIR light.[52] In another study, it was reported that cationic NPs exhibit superior cellular internalization, but inferior systemic circulation compared to their anionic and neutral counterparts.[46] In view of this, the idea of integration of photothermal Au nanocages with zwitterionic stealth ligand has been proposed. As aforementioned, zwitterionic medication endows NPs with surface properties resistant to aggregation, binding plasma proteins and macrophage uptake, prolonging blood circulation time.[59] Zwitterionic polymers coated on Au nanocages have successfully extended the NPs' systemic circulation lifetime by 4-fold, without compromising its cellular internalization, breast tumor targeting ability, and PTT efficacy. Sensitive to the changes in cell's extracellular pH, the zwitterionic ligands on Au nanocages switch from "zwitterionic" at physiological pH (7.0−7.4) to "cationic" at acidic pH (≤6.5). Triggering of this charge reversal makes the NPs attach to the surface of cancer cells, leading to targeted accumulation within tumors.[46]

Cervical cancer is the fourth most common cancer in women and has the fourth highest mortality rate (among cancers in women).[66] Additionally, it is a solid tumor associated with the human papillomavirus infection.[66] An example of synergistic PTT and drug delivery for cervical cancer is the use of multilayered single-walled carbon nanotubes, termed SWNT@BSA@Au-S-PEG-FA@DOX, which was prepared using a facile layer-by-layer assembly process.[67] Carbon nanotubes display hemodynamic properties, as their shape greatly affects its circulation time and biodistribution.[68] For example, the needle-like morphology of nanotubes contributes to an increased specific area for interaction with plasma proteins and cells, permits cell penetration *via* both endocytosis and diffusion across the plasma membrane, and allows longer circulation time (up to 10 times longer) in blood, as compared to spherical nanomaterials.[69] Coating of bovine serum albumin (BSA) on oxidized and cut-single-walled carbon nanotubes (SWNTs) provides abundant active sites for the nucleation of Au seeds, subsequently converting Au into AuNPs by *in situ* reduction. Possessing ideal photothermal properties, the SWNT@BSA@Au was further modified with folic acid terminated-polyglycol (FA-PEG-SH), which endows the material with high water dispersibility, biocompatibility, and selectivity toward human cervical cancer cells. Doxorubicin (DOX) was subsequently loaded onto the system, with a high loading ratio of up to 590%. The resulting complex exhibited high efficacy, especially when combined with PPT (irradiation of the tumor with a 808 nm laser, 1 W/cm^2 or 5 min, 24 h after systemic injection of the nanomedicine). Release of DOX is also induced by the pH value and temperature in the tumor microenvironment, adding selectivity to the system. The system completely eradicated tumors *in vivo* without systemic toxicity, as substantiated by several hematological and biochemical parameters and histopathological analysis.[67] However, it is of utmost importance to note that the usage of high laser irradiance (1−48 W/cm^2) is practically not applicable for clinical treatment of tumors, as they exceed the skin tolerance threshold values (maximum permissible exposure of skin at 808 nm is 350 mW/cm^2, with an exposure time of 10−1000 s).[70] Future studies can be focused on the interactions between SWNTs and actual biological environment such as blood, since the presence of protein corona in the biological fluids might affect the BSA coatings on SWNTs and subsequently modulate their biological fate.[69]

Gold nanorod (AuNR) is an excellent photothermal agent owing to their adjustable longitudinal surface plasmon resonance and high light-to-heat conversion efficiency.[71,72] These rod-shaped NPs allow prolonged blood circulation time and facilitate deeper mammary tumor penetration than nanospheres with the same diameter.[40,71] Dendrimers are inherent polymeric scaffolds for encapsulation of small inorganic NPs (2−20 nm) used to further increase blood circulation time, solubility, and dimensional stability of nanohybrids.[73] A smart nanohybrid, termed Au nanorod/dendrimer-assembly nanohybrids (AuNR@Da NHs), with size of about 130 nm, has been constructed by supramolecular encapsulation of 83.0 w/w% AuNR into dendrimer assemblies.[73] The amphiphilic dendrimer assemblies are composed of PEGylated and antitumor adriamycin (ADR)-decorated dendrons, containing tumor microenvironmental matrix metalloproteinase (MMP)-cleavable linkages, intracellular GSH-degradable disulfide bonds, and pH-breakable hydrazone bonds that are highly responsive toward tumor microenvironment. Li *et al.* (2018)[73] investigated the biological adapting ability of the nanohybrids under different biomimetic stimulations. The group proved that AuNR@Da NHs could adapt sequential biological barriers through triple-responsive features, enzyme/redox/pH, to facilitate deep tissue penetration and high internalization in tumors, particularly in human ovarian tumors that are deep within the abdominal cavity and most of the time difficult to palpate.[74] The permeability of nanohybrids in ovarian tumors is further improved due to the efficient photothermal properties of AuNRs in AuNR@Da NHs (about 70%, as compared to single AuNRs about 60%). The amount of internalized AuNR and ADR mediated by nanohybrids was about 27-fold and 6.6 times higher, respectively, than individual AuNR-treated. Furthermore, the nanohybrids were capable of generating hyperthermia (up to 67 °C), with tumor accumulation of more than 2.3 times higher. NIR-induced hyperthermia subsequently induces the rupture of the lysosome, accelerates the endosomal release of ADR/AuNRs, and thus inhibits the human ovarian tumor cells *in vivo*. In brief, AuNR@DA NHs with laser irradiation offered strong curative effects, with an inhibition rate of 80.7%, on synergistic chemo-photothermal treatment for combating multidrug resistance.[73]

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Overall, targeting and therapeutic efficacy of Au nanostructures can be enhanced by tuning its physiochemical properties such as size, surface chemistry, and shape. On the other hand, tumor pathological characteristics also play an important role in penetration of nanomedicines in tumor, as tumor microenvironment is highly heterogeneous between different types of tumors. Hence, characterization of both Au nanostructures and pathological properties of tumors is equally important in the design of nanomedicine with nanotheranostic properties.

Other Nanomaterials. Inorganic nanomaterials are multifunctional NPs platform synthesized from metals, metal oxides, and metal sulfides. Inorganic nanomaterials are relatively stable over large ranges of pH and temperature,[10] resistant to enzymatic or photochemical degradation,[70] and thus suitable for nanotheranostics in tumor microenvironment.[70,75]

Copper sulfide (CuS) NPs are featured with several properties compared to other commonly used NPs, such as prominent absorbance, effective heat conversion, small particle size, easy modification, and facile synthesis.[76] A tumor-targeting nanocomposite (CuS@BSA-MBA-cRGD) with photothermal effect for targeting of liver-intestinal metabolism pathway was synthesized recently.[77] The biocompatibility and stability of CuS NPs were improved *via* the capping effect of BSA. Then, NIR fluorescence probe (MBA) and tumor-targeting ligand cyclic arginine-glycine-aspartic acid (cRGD) peptide were further conjugated on the surface of CuS@BSA. Peptides are another commonly used ligand targeting moiety, with advantages in terms of chemical stability, ease of synthesis, and reduced immunogenicity.[59] cRGD can target the cell-adhesion molecule, $\alpha_v\beta_3$ integrin, that is overexpressed on tumor new-blood vessels and some tumor cells.[78] The as-synthesized CuS@BSA-MBA-cRGD served as an infrared thermal imaging contrast agent for infrared thermal imaging and as a photothermal agent for tumor ablation *via* PTT. However, the obtained nanocomposite has a mean diameter of about 51.2 nm,[77] raising concerns regarding its uptake by reticuloendothelial system (RES) organs that may cause slower elimination from the body and potential toxicity after effective treatment.[79]

Generally, most of the nanomaterial-based PDT requires an additional photosensitizer or high-power laser source for effective therapy. However, the high concentration of NPs and laser irradiation with long irradiation time may lead to a heat generation during NIR therapy. The rise in temperature will subsequently lead to cell death rather than ROS generation for PDT. Veeranarayanan *et al.* (2018)[70] proposed copper bismuth sulfide (Cu_3BiS_3) nanocrystals as an innovative human breast tumor treatment alternative, after showing the potential of Cu_3BiS_3 inducing PDT without any photosensitizer, at safe laser zone (808 nm, 10 mW/cm^2, 10 min), and in the deep tissue penetrative NIR region. Bi, with high X-ray attenuation, could serve as an efficient X-ray contrast probe, while Cu ions, with broad NIR absorption, could serve as NIR-responsive PDT and PTT agents. Upregulation of Cu ion leaching upon irradiation coupled with Bi efficiently capturing more photons is believed to contribute to the realization of Cu_3BiS_3 in exceptional PDT effects at low laser power.[70] Although the group has shown that the as-synthesized Cu_3BiS_3 nanocrystals are highly biocompatible without any genotoxic effects, yet, the uptake of this 12 nm nanocrystal by RES organs, their *in vivo* degradation behavior and clearance after PDT still require further investigation. The influence of Cu_3BiS_3 nanocrystals on the biogenesis and activity of cellular organelles also requires further understanding as organelle dysfunctions will lead to dramatic consequences on human health.

A photosensitizer-Pd@Pt nanosystem has been designed for highly efficient PDT in human breast tumors [see Figure 2b(ii)].[44] Palladium (Pd)-based nanomaterials have good catalase-like activity, which can decompose H_2O_2 to produce oxygen and water. This subsequently improves the hypoxic environment of solid tumor.[44] However, like other inorganic nanomaterials, Pd has a chemically/biologically inert framework, which raises concerns over low biodegradation and biosafety issues.[10] Functional inorganic two-dimensional (2D) biomaterials, MnO_2 nanosheets, have been introduced recently for improved theranostic performance [see Figure 2b(iv)].[80] Preliminary studies demonstrate its biocompatibility, as manganese (Mn) is one of the necessary trace elements in the human body. The ultrathin MnO_2 nanosheets structure, with an average thickness of 2 nm, is highly sensitive toward the endogenous (acidic and reducing) tumor microenvironment.[80] It was found that the MnO_2 nanosheets started to disintegrate and release Mn^{2+} only within 3 min in acidic (pH 5.0) and reducing ([GSH] = 5.0 mM) solutions, with a longitudinal relaxitivity (r_1) of 5.45 mM^{-1} s^{-1} and 4.81 mM^{-1} s^{-1}, respectively. The r_1 of MnO_2 nanosheets in neutral solution was only 0.87 mM^{-1} s^{-1}. High values of r_1 coupled with various direct photographic images demonstrated the potential of MnO_2 nanosheets structure as the contrast agents for MRI, since the higher accessibility of the released Mn^{2+} to water molecules could enhance the brightening effect of MRI signal. MnO_2 nanosheets also possess high intrinsic photothermal-conversion capability for PTT. Furthermore, surface modification of the MnO_2 nanosheets with soybean phospholipid improved the stability of the nanosheets in physiological condition.[80] Mesoporous NiO (mNiO) NPs also appear as a photothermal conversion agent for cancer PTT [see Figure 2b(iii)].[81] Artemisinin (ART) is a traditional Chinese medicine that is believed to inhibit tumor growth. Attachment of mNiO NPs and terbium complexes bestow mNiO with luminescence imaging features. The mNiO-Tb serves as a MRI contrast agent, a luminescence imaging probe, and a vehicle for ART. Synergistic PTT and radical-induced therapy of cervical tumors was achieved using this ART-loaded mNiO nanoplatform.[81] Nonetheless, the selective damage mechanism of ART to cancer cells remains elusive, and the toxicity of ART derivatives to normal cells needs to be explored.

Perfluorocarbon (PFC) is a chemically inert molecule with high oxygen-carrying capacity and good biocompatibility for *in vivo* application.[47] Owing to the intrinsic hydrophobic nature of the PFC compounds, their clinical application usually involves encapsulation by a carrier matrix. Porous hollow magnetic Fe_3O_4 NPs (PHMNPs) have a large central cavity for the loading of small molecules and/or the therapeutic cargo, while retaining favorable biological properties of conventional iron oxide NPs (intrinsically superparamagnetic, as a contrast agent for MRI). In view of this, PFC and etoposide (EP) were loaded onto PHMNPs. Oxygen was released at a moderate rate from the PHMNPs over an extended period of time, effectively reducing the hypoxia-induced EP resistance of liver tumor cells and facilitating concurrent chemotherapy. Modification of the surface of PHMNPs with lactobionic acid (LA)-containing amphiphilic polymers (LA-PEG-S-S-C18PMH), through hydrophobic interaction, facilitates selective targeting of LA

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against the asialoglycoprotein receptor present on the plasma membrane of hepatocytes.[47] The intracellular agglomeration of the nanocarriers after GSH-triggered removal of the hydrophilic LA-PEG segment could also significantly enhance intracellular accumulation and improve therapeutic efficacy.[47]

In addition, the upconversion NPs (UCNP)-based theranostic micelles have been proposed for dual-modality imaging and PDT in HCC [see Figure 2b(i)].[82] Loading of mitoxantrone (MX) and antiepithelial cell adhesion molecule (anti-EpCAM) onto PEGylated UCNP micelles has improved the biocompatibility and synergistic antitumor efficiency of the system, without any noticeable systemic toxicity.[82] Like other commonly used UCNP-based therapeutic approaches, the as-synthesized 23.4 nm UCNPs are difficult to fabricate in ultrasmall (<15 nm diameter) sizes. The quantum yield of these UCNPs was not reported. Since water has an absorption peak around 980 nm, laser excitation at 980 nm will result in unnecessary tissue heating during PDT. It is of interest to develop UCNPs which can be excited by other NIR wavelengths and allow deeper tissue penetration. Lastly, overall understanding of nanotoxicology of UCNPs (NPs distribution, excretion, metabolism, pharmacokinetics *etc.*) in animal models is of utmost importance.[83]

Quantum dots (QDs) are a luminescent inorganic nanomaterial with rich surface chemistry and optical properties. The application of QDs in biomedical field has been challenged by its nonspecific internalization and toxicity.[84] Shi *et al.* (2018)[84] covalently coupled folic acid (FA) and 5-fluorouracil acetic acid (FUA) on the surface of QDs to produce a HCC targeted therapy system, named FA-QDs-FUA. FA is responsible for the specific targeting of the system to the hepatocarcinoma cells, while QDs act as the delivery vehicles and imaging agent. FUA, which interferes with nucleic acid synthesis, has been chosen as the therapeutic agent. PEG has been selected as the linker chain to facilitate attachment of FUA to the QDs' surface and dramatically suppress the nonspecific interaction of QDs. The optimal proportion of FA:PEG-QDs:FUA = 10:1:100 was used. Noteworthy, the content of FA in the system is controlled within 10%, since excess FA may promote undesired tumor cell growth. The system was observed to exert reduced toxic side effects and better antitumor efficacy.[84] Nevertheless, the particle size of FA-QDs-FUA was about 220.28 nm, which is bigger than 160 nm, raising concerns about the cellular uptake and accumulation of the FA-QDs-FUA at tumor sites. Another similar work has been reported by Ma *et al.* (2018).[85] The group coupled second near-infrared window fluorescent (NIR-II) Ag_2Se QDs with gadopentetate dimeglumine injection (Gd-DTPA) for dual-modality: T_1-weighted MRI and fluorescence imaging. Excellent temporal resolution and high tissue penetration depth were achieved by fluorescence imaging, further supporting the potential of QDs as multifunctional contrast agents for multimodal imaging in clinical diagnosis.[85]

Magnetic metal oxide nanomaterials (MMONPs) are negative contrast agents for T_2-weighted MRI. In response to intratumoral oxidability and acidity, MMONPs degrade and release corresponding metal ions that can serve as highly efficient positive T_1-weighted contrast agent. The ratio of increase of T_1 signals against decrease of T_2 signals (T_1/ T_2) from MMONPs is known as ratiometric MRI, which is highly selective for solid tumor imaging.[45] Cobalt oxide nanoprism (Co_3O_4), a type of MMONPs, has been selected and tuned for selective ratiometric MRI tumor imaging and synergistic cancer theranostics (PTT, chemodynamic and chemotherapy). The as-prepared Co_3O_4 nanoprism is cuboidal, with a thickness of 3.26 nm and a length of 33.29 nm, instead of a triangular structure. This could be due to the presence of a high concentration of surfactant used during the synthesis which subsequently inhibited nanomaterial growth in specific spatial directions.[45] It is interesting to note that although the sharp vertices of the triangular nanoprism may lead to stronger near-field enhancements for plasmonic applications, unfortunately, its high surface energy vertices most likely will make the nanoprism highly unstable and readily degradable.[86] Nevertheless, the Co_3O_4 nanoprism possesses significant photothermal conversion efficiency (η= 60.07%), outstanding MRI contrast (r_2= 5.42 mM^{-1} s^{-1}), and good DOX delivery (29.36 mg/g), with a low detection limit (50 nM) and broad linear range (0−50 μM).[45] In turn, the cuboidal structure and fast degradation property of the as-prepared Co_3O_4 nanoprism could contribute to enhanced drug delivery and controllable drug release.

Radiotherapy is another major modality of cancer therapy. However, radio-resistance, one of the intrinsic features of solid tumors, often gives rise to unsatisfactory therapeutic outcome and subsequent tumor relapse.[13,43] Du *et al.* (2017)[87] constructed a multifunctional theranostic agent, with a mean diameter of 15 nm, integrating radiation therapy with high-depth PTT. Functionalization of amphiphilic D-α-tocopherol PEG 1000 succinate (TPGS-Cu_3BiS_3) with bimetallic chalcogenide nanocrystals (NCs) increased the deposition of X-ray irradiation energy within cancer cells and triggered radiation damage *in vivo*. Moreover, conversion of NIR light (1064 nm) into heat greatly improved tumor oxygenation *via* increasing the blood flow, overcoming the hypoxia-associated radio-resistance of the tumor. The presence of copper ions is capable of catalyzing the conversion of endogenic H_2O_2 into highly reactive hydroxyl radicals and increase the level of oxygen radicals, hence further destroy the cancer cells. The as-synthesized NCs also have strong absorption in the second NIR window (1000−1400 nm), allowing a deeper tissue penetration ability, with low scattering and energy absorption by tissues, than in the first NIR window (650−950 nm).[87] High atomic number NPs such as platinum, gold, and bismuth are high electron emitters. These elements can act as radiosensitizers and amplify the effects of radiation.[88] Bismuth heteropolytungstate (BiP_5W_{30}) nanoclusters have also been explored as radiosensitizers for radiotherapy enhancement.[43] Owing to the electron structure and multielectron property, BiP_5W_{30} nanoclusters deplete GSH *via* redox reaction and catalyze the decomposition of H_2O_2 to HO• (about 1.3-fold) to enhance ROS generation upon X-ray radiation. The coupling of BiP_5W_{30} nanoclusters with reduced graphene oxide (rGO) formed a heterostructure that not only promotes electron−hole separation to improve radio-catalytic activity (about 4-fold) but also improves the oxygen level within tumors since rGO can promote a mild photothermal effect.[43]

Overall, inorganic nanomaterials serve as a platform for biomedicine, yet the often-neglected characterization and fairly weak fundamental understanding of its structure−function correlations often limits its predictive capabilities in nanotheranostics.

Polymeric Nanoparticles. Polymeric NP is a collective term given for any type of polymer NPs, but specifically for nanospheres and nanocapsules built from synthetic polymers (*e.g.* poly(organophosphazene) (POP), poly(ethylene glycol)

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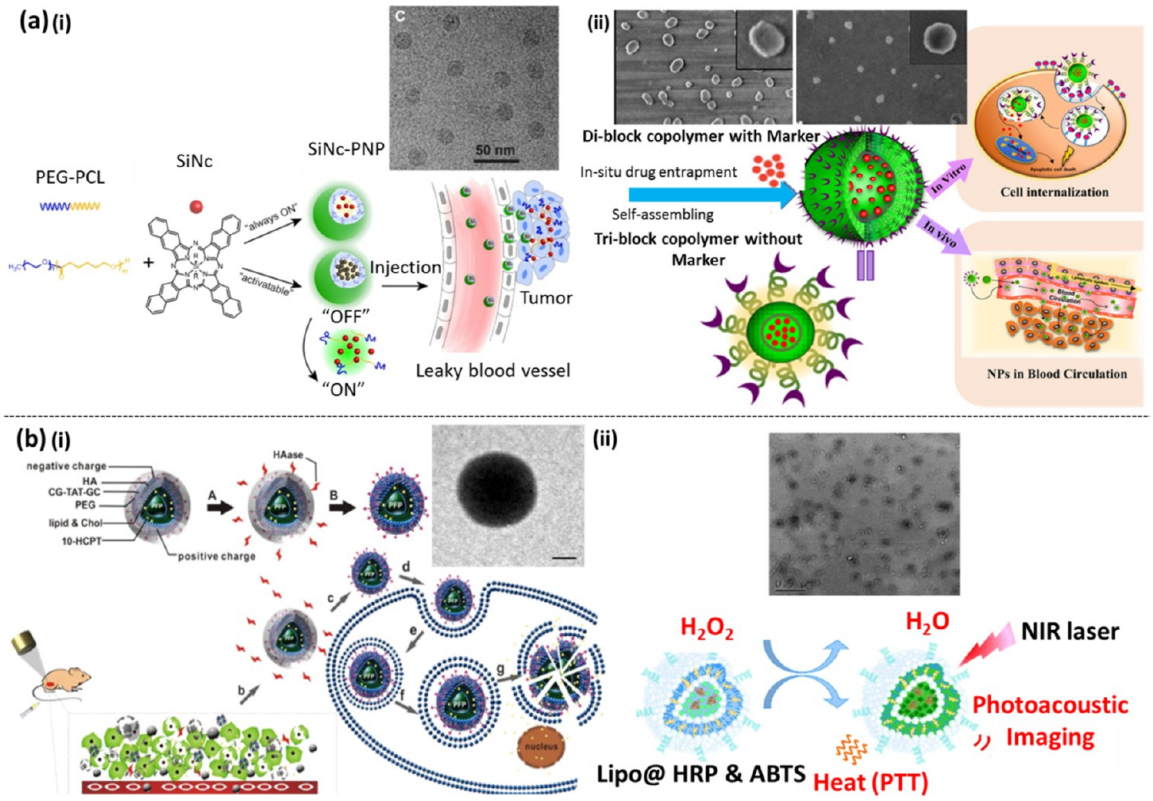

Figure 3. Brief overview of nanomaterials used for solid tumor theranostics, with their respective TEM images. (a) Polymeric NPs: (i) Illustration of a tumor-activatable SiNc encapsulated in a copolymer, PEG-PCL NPs, that permits NIR fluorescence-guided surgery and combinatorial phototherapy of ovarian cancer tumors. Adapted with permission from ref 90. Copyright 2018 Ivyspring International Publisher. (ii) Overview of block copolymer (PEG and PGA)-based NPs in passive and active theranostic intervention of cervical cancer. Adapted with permission from ref 89. Copyright 2017 American Chemical Society. (b) Lipid NPs: (i) A multifunctional ultrasound molecular probe (cell-penetrating peptide-modified targeted drug-loaded phase-transformation lipid NPs) with low-intensity focused ultrasound in hepatocellular carcinoma. Adapted with permission from ref 100. Copyright 2018 Ivyspring International Publisher. (ii) A H_2O_2-responsive liposomal nanoprobe capable for photoacoustic inflammation imaging and PTT of early stage of small tumors and metastatic lymph nodes. Adapted with permission from ref 101. Copyright 2017 U.S. National Academy of Sciences.

(PEG), *etc.*) or natural polymers (*e.g.* chitosan, gelatin, *etc.*).[10] The highly electron-delocalized structures, excellent light-harvesting and light amplifying properties, versatile surface modification, excellent photostability, and biocompatibility of polymeric NPs contribute to their rapid advancements in solid tumor theranostics. With the size range between 10 and 1000 nm, polymeric NPs have also proven to be viable carriers of therapeutic agents.

Encapsulation of methotrexate (MTX), a chemotherapeutic agent, in polymeric NPs is crucial in controlling its toxicity and side effects.[89] Two different block copolymers (poly(ethylene glycol)-*b*-poly(glutamic acid)-*b*-poly(ethylene glycol) (GEG) and poly(ethylene glycol)-*b*-poly(glutamic acid) (EG) conjugated with FA have been designed and used to encapsulate MTX. Both NPs, named M-GEG and M-EGFA NPs, are employed for passive and active targeting of cervical carcinoma, respectively [see Figure 3a(ii)].[89] FA has been used as a homing device to actively target and direct M-EGFA NPs toward the tumor, facilitating targeted drug release at the tumor site. On the other hand, M-GEG NPs passively target and accumulate at the cancer cells, by exploiting the EPR effect. Subsequently, M-GEG NPs release MTX inside the cytoplasm at a controlled rate to induce cell apoptosis. This mechanism of M-GEG NPs allowed long-term cytotoxicity action on the tumor cells while minimizing side effect to healthy tissues.[89] The entrapment efficiency for both polymeric NPs was found to be about 93−96%, with drug-loading content of about 38−47%. Both polymeric NPs have improved the systemic circulation and intracellular delivery of MTX. The potential of these polymeric NPs as alternative to conventional chemotherapy for human cervical carcinoma is supported by their complete biological evaluation in terms of cytotoxicity, intracellular drug uptake and release, as well as induction of apoptosis.[89] Future research can be expected on fabrication of stimuli-responsive block copolymers, for specific targeting and precise control of the drug-release and versatility in clinical applications.

On the other hand, poly(ethylene glycol)-*b*-poly(ε-caprolactone) (PEG-PCL) is a biodegradable and biocompatible block polymer.[90] PEGylation delays renal filtration, prolongs plasma circulation, and reduces nonspecific uptake of nanomaterials by macrophages.[18,19,91] Encapsulation of silicon naphthalocyanine (SiNc), a photostable fluorescence molecule, within the hydrophobic core of the PEG-PCL NPs serves as a real-time activatable theranostic nanoplatform [see Figure 3a(i)].[90] The as-synthesized nanoprobe is predominantly fluorescent at the tumor/cancer site (quantum yield at about 11.8%). This is mainly because the poor water-soluble SiNc (<1 ng/mL) in the PEG-PCL NPs tends to aggregate in an aqueous environment and leads to fluorescence self-quenching. However, once SiNc infiltrated into the core of the solid tumor, the complex acidic intracellular environment (pH 6.5−

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6.8) and the interior of the endosome/lysosome (pH 4.5−6.5) will disrupt the structural integrity and trigger the leaching of SiNc from the nanoprobe, leading to NIR fluorescence recovery.[90] The nanoprobe reveals high cancer-to-normal tissue contrast ratio (about 1.6−1.9-fold) specifically at the tumor sites, with none or minimal fluorescence signal in healthy organs.[90] This highly sensitive fluorescence switching nanoplatform successfully broadens the imaging and treatment window, making it highly promising for further clinical studies. The group also validated that heat can be efficiently generated by the nanoprobe up to 12 mm deep within tumors from the point of NIR light (1.3 W/cm^2) for PTT, which is beneficial for nanotheranostics of ovarian cancer which usually starts in one or both ovaries or fallopian tubes located in the female pelvis. Moreover, the chemistry involved in the SiNc-mediated combinatorial phototherapy can be easily tailored *via* photoirradiation dosage.[90] On the other hand, self-assembly of PEG-PCL with folate-PEG-cholesterol micelles forms a spherical and self-luminescing nanosystem (called POCL nanoreactor) with a diameter of about 50 nm.[92] POCL encapsulates bis[3,4,6-trichloro-2-(pentyloxycarbonyl) phenyl]oxalate (CPPO, a chemical power source with high reactivity to H_2O_2), poly[(9,9′-dioctyl-2,7-divinylene-fluorenylene)-*alt*-2-methoxy-5-(2-ethyl-hexyloxy)-1,4-phenylene] (PFPV, a chemiluminescence converter), and tetraphenylporphyrin (TPP, a photosensitizer with NIR emission and singlet oxygen. The folate ligand on the POCL surface allows specific targeting at the tumor site. Upon trigger by the high level of H_2O_2 at the tumor site (10^{-6} M, normal condition = 10^{-7} M), POCL can be used for chemiluminescence imaging and PDT *via* a series of intraparticle relayed resonance energy transfer. The tumor cells are converted to a "light on" state and subsequently destroyed by the generated singlet oxygen. With such an excellent NIR light emission and singlet oxygen generation abilities, POCL showed a high image contrast in fluorescence imaging with a high antitumor effect and low systemic toxicity.[92]

Ursolic acid (UA), a pentacyclic triterpenoid extracted from *Hedyotis diffusa* Willd, has shown great potential in cancer therapy, but its efficacy is extremely hindered by limited water solubility and poor pharmacokinetics *in vivo*. Yan *et al.* (2018)[93] has employed cationic nanomicelles derived from pluronic F127 as a delivery vehicle of UA for colorectal cancer treatment. Pluronic F127 is a widely used biocompatible polymeric drug delivery vehicle, comprising of poly(ethylene oxide)-polypropylene oxide-poly(ethylene oxide) (PEO-PPO-PEO) chains. The PPO segment of pluronic F127 allows incorporation of lipophilic drugs, while hydrophilic segment of F127 prevents adsorption and aggregation with other biomacromolecules. Since the positively charged NPs have a stronger affinity with negatively charged cell membranes, a cationic polymer of stearoyl chloride grafted polyethylenimine copolymer (C_{18}−PEI) was functionalized to increase UA uptake by colorectal cancer cells.[93] This UA loaded cationic nanomicelle, termed as FUP, was fabricated through simple self-assembly of UA, F127, and C_{18}-PEI in ethyl alcohol. FUP can effectively block colorectal cancer cell proliferation by interfering cell cycle arrest at the G1 checkpoint and inducing a cell apoptosis mechanism.[93] Nonetheless, further studies on the degradation behavior and clearance of NPs after performing therapy are necessary.

Photoacoustic imaging (PAI) is a biomedical imaging modality combining the high contrast of optical imaging with the high spatial resolution of ultrasound imaging.[5,42,45,72] PAI can also be defined as the nonradiative conversion of light energy into sound energy.[17] Based on the use of non-ionizing laser pulses, PAI non-invasively visualizes anatomical structures with greater penetration depth (several cms) and specificity than conventional optical imaging, suitable for imaging superficial tumors at breast and skin.[94] On the other hand, high-intensity focused ultrasound (HIFU) is a minimally invasive therapeutic modality. HIFU concentrates multiple intersecting ultrasound beams into the targeted tumor region. Subsequently, it generates hyperthermia and mechanical effects to destroy the affected areas.[95] A multifunctional poly(lactic-*co*-glycolic acid) (PLGA) nanocapsule, termed $Cu_{2-x}S$/PFBO@PLGA or in short CPPNs, encapsulating PAI contrast copper sulfide nanodots ($Cu_{2-x}S$ NDs) and a typical HIFU synergistic liquid, perfluorooctyl bromide (PFOB), has been constructed using emulsion solvent evaporation strategy.[95] The high performance of $Cu_{2-x}S$ NDs in the absorption and conversion of NIR confers high PAI contrast capability to the CPPNs, by which the location of the CPPNs within a tumor can be monitored successfully under PAI. Shifting absorption from the first to the second NIR-window could enhance PAI contrast in the imaging of deep-lying living structures *in vivo*.[17] Due to the encapsulated PFOB, the cavitation effect in CPPNs is improved, thus enhancing the ablation efficacy under HIFU exposure. With a particle size of 123.7 nm, CPPNs show its potential as a theranostic agent for future photoacoustic image-guided HIFU synergistic therapy of breast cancer.[95] However, high levels of ultrasound energy (usually more than 100 W/cm^2) may cause damage to healthy tissues, especially along the path of ultrasound propagation, hence leading to severe side effects.[96]

Aggregation-induced emission (AIE) is a concept originated from the phenomena that a class of fluorogens are non-emissive as free molecules but luminescent as aggregates.[57,97] AIE-based bioprobes are suitable to use in real-time imaging probes due to their low background, high sensitivity, and resistance to photobleaching. A smart nanodelivery system, named STD nanomicelle (STD-NM), with ST and TD peptide functionalization and AIE "switch on" characteristics has been presented for precise theranostics and apoptosis monitoring of colon cancer.[97] Comprising of pH-triggered targeting peptide STP (sequence: SKDEEWHKNNFPLSPG), a caspase-3 responsive peptide linker (sequence: DEVD) and an AIE molecule tetraphenylethylene (TPE), ST could recover the fluorescence of the nanocarrier during apoptosis. Meanwhile, TD, a tumor acidity-activated peptide made up of the cell-penetrating peptides TAT and 2,3-dimethylmaleic anhydride, maintained the "stealth" stability of the nanocarrier in the physiological environment.[97] Upon exposure to tumor microenvironment, STP and TAT were switchably stimulated and activate the peptides to penetrate through the colon cancer cells and subsequently release the anticancer drugs (*cis*-platinum and DOX) into the tumors. The AIE signal will then be "switched on". Gene analysis by RNA-seq has also been performed, supporting the superior therapeutic effect of anticancer drug-loaded STD-NM treatment.[97]

Generally, poor spatial resolution, shallow tissue penetration, and relatively low quantum yield of NIR-emissive polymeric NPs than other common fluorescent imaging probes are some of the concerns for polymeric NPs in theranostics. The interaction between light-induced charge transfer of polymeric

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NPs with other biological activities requires further detailed study.

Lipid Nanoparticles. Solid lipid NPs are made up of rigid core of hydrophobic lipids surrounded by a monolayer of phospholipids. This structure improves their biocompatibility and stability in a biological environment, making them suitable as a carrier system.[98]

A multifunctional hypoxia-responsive theranostic liposome co-encapsulating a photosensitizer Ce6, hypoxia-activated prodrug tirapazamine (TPZ), and gene probe miRNA-155 was designed for synergistic PDT-chemotherapy of breast cancer.[99] The liposome was fabricated using an innovative hypoxia-responsive 2-nitroimidazole derivative conjugated PEG amphoteric polymer. The gene probe is a molecular beacon probe with the loop sequence complementary to the target miRNA-155. In the absence of a target, the fluorescence of the gene probe is switched off, and upon hybridization with the target, the fluorescence is switched on and effectively used for detection and diagnosis of intracellular oncogenic miRNA biomarker in breast cancer.[99] Subsequent laser irradiation (670 nm, 0.48 W/cm^2, 10 min) induced Ce6-mediated PDT by consuming oxygen to generate intracellular ROS, such as singlet oxygen, which causes severe hypoxia. The PDT-induced hypoxia led to the disassembly of the liposome, intracellular TPZ leakage to cell nucleus and induce DNA damage and cell apoptosis.[99] A detailed nanotoxicology study of the as-produced liposome system is imperative for possible clinical application, as TPZ is currently under Phase III clinical trial.

An ultrasound molecular probe based on lipid NPs has been introduced for precision theranostics at an early stage of HCC [see Figure 3b(i)].[100] As common lipid NPs lack specific targeting ability, hyaluronic acid (HA) has been chosen as a ligand to actively target the overexpressed CD44 cell adhesion factor on HCC. Cysteine-flanked cell-penetrating peptide (CPP), CG-TAT-GC, has been selected to improve the delivery of macromolecular substances into the nucleus without causing cytotoxicity.[100] The as-synthesized lipid NP is known as HA-mediated cell penetrating peptide-modified with 10-hydroxycamptothecin-loaded on a phase-transformation lipid NPs (HA/CPPs-10-HCPT-NPs). Upon trigger by low-intensity focused ultrasound (LIFU) sonication, the NPs in tumor tissue and cells undergo acoustic droplet vaporization (ADV) and are transformed into microbubbles.[100] The resultant microbubbles are not only able to provide significant contrast enhancement in tumor-site imaging but also increase permeability of NPs into tumor blood vessels and cell membranes.[96] Since the acoustic intensity of LIFU sonication is usually low, no more than 3.2 W/cm^2, it is less likely to cause tissue necrosis as compared to HIFU.[96] This fascinating mechanism successfully induces local release of antitumor drug in the cytoplasm and nucleus.[100] However, there are some concerns with this approach. Although the ligand-mediated active targeting has been used to improve the targeting efficiency, it is important to fully understand and avoid the adverse side-effects due to off-target distribution of the CPP and its cargo which might induce mutations, cytotoxicity, or initiate immune responses in the host. Second, the pharmacokinetics, stability, and circulation time of the system in bloodstream should also be further investigated. In addition, since the effect of ultrasound is highly localized, its applicability in tumor metastasis is highly compromised.

On the other hand, abnormal levels of H_2O_2 (about 50−100 μM) often correlate with physiological and pathological conditions like inflammation and cancers. Generally, the concentration of H_2O_2 in physiological environments should be below 50 μM.[101] Liposomal nanoprobe loaded with horseradish peroxidase (HRP) and its substrate, 2,2-azino-bis(3-ethylbenzothiazoline-6-sulfonic acid) (ABTS), has been presented for *in vivo* detection of inflammation, photoacoustic detection, and imaging of H_2O_2 (down to sub/micromolar concentrations) [see Figure 3b(ii)].[101] In the presence of endogenous H_2O_2, HRP loaded in liposomes would catalyze ABTS (colorless) into its oxidized form (greenish) and show strong NIR absorbance (700−900 nm), allowing sensitive PAI of early stage tumors (as small as 2 mm in size). Meanwhile, based on the difference in H_2O_2 contents, the nanoprobe also allows diagnosis and imaging of LPS- (a lipoglycan that triggers inflammation) and bacteria-induced inflammation, orthotopic brain tumors, breast tumors, and metastatic tumors. These spherical shape liposomal NPs with an average diameter of about 100 nm concurrently also achieve selective PTT of tumors with high efficacy and minimal nonspecific heat damage to surrounding normal tissues.[101] However, the loading capacity of ABTS and HRP was found to be limited at about 23.17 and 5%, respectively. This could be due to premature release of the drug from the lipid matrix, as changes in temperature during administration may cause polymorphic transitions of the lipid matrix.[10] The depth-dependent light attenuation and interference of unwanted background signals remain challenging for the clinical application of PAI.

Superparamagnetic iron oxide NPs-loaded solid lipid (SPIONs) is made from iron, one of the most abundant metals present in metabolism. SPIONs have a big potential as theranostic agents, as they display interesting cellular and *in vivo* interactions with no dramatic toxicity.[69,102,103] A smart nanovehicle with DOX and SPIONs delivery system, in short DOX/SPIONs-loaded DFSLNs, has been constructed for oral chemo/magnetothermal combination therapy of colon cancer.[98] Despite the system combined both DOX chemotherapy and hyperthermia therapy (generated from SPIONs) with high frequency magnetic field (HFMF), its therapeutic efficacy is still limited by the systemic drug absorption into blood circulation. Thereby, the group innovatively coated folate (FA) and dextran on the surface of the NPs in a sequential layer-by-layer manner.[98] Although the fabrication of SPIONs can be relatively easy and reproducible, biocompatible polymer layer, such as PEG and poly(vinyl alcohol) (PVA), is normally coated on the SPIONs surface to improve their biocompatibility and stealthiness for specific targeting. This is because naked SPIONs tend to sediment and aggregate at physiological conditions, resulting in an increased risk of toxicity.[69] Coating of the polysaccharide dextran shell layer on the NPs surface not only evaded the cellular transport and systemic absorption by at least 2-fold but also enhanced the particle accumulation at the tumor sites by specific association with dextranase present only in the colon. The subsequent enzymatic degradation and removal of dextran coating led to the exposure of the FA residues which further facilitate cellular level targeting and uptake of the system by receptor-mediated endocytosis. The preliminary results demonstrated prominent therapeutic efficacy (a 15-fold decrease in tumor mass of mice than the PBS control) of DOX/SPIONs-loaded DFSLNs for the oral administration, with no apparent systemic side effects or toxicity.[98] The particle size of DOX/SPIONs-loaded DFSLNs is approximately 132 nm. In fact, the optimal size of the nanomaterials designed for colorectal cancer should be

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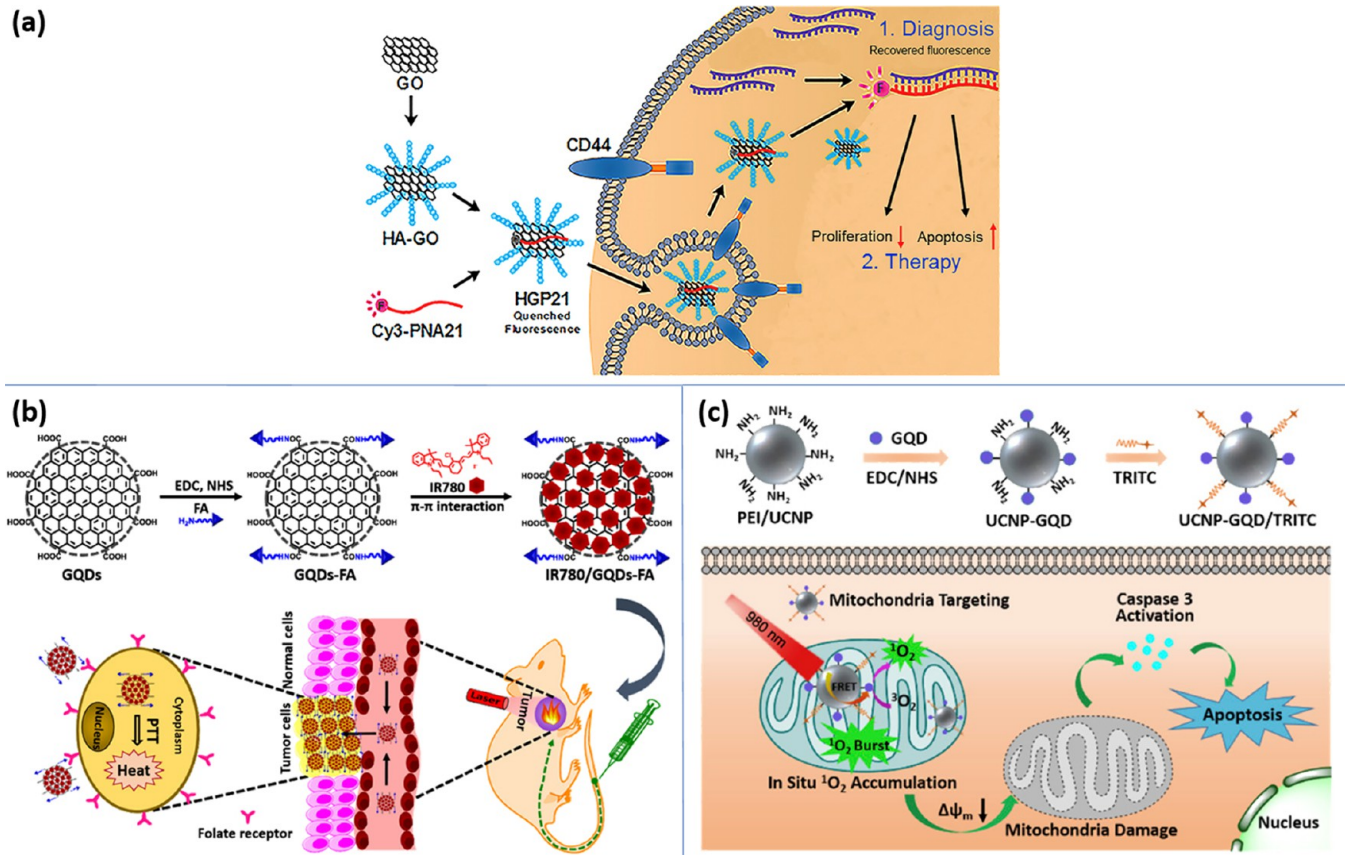

Figure 4. Brief overview of graphene for nanotheranostics. (a) Illustration of HA-coated graphene oxide synthesis and its theranostic effect by targeting oncogenic miR-21. Reprinted with permission from ref 110. Copyright 2017 Elsevier. (b) Schematic illustration of the IR780 iodide on folic acid-functionalized graphene quantum dots for targeted PTT. Reprinted with permission from ref 119. Copyright 2017 American Chemical Society. (c) Overview of mitochondrial specific PTT by rare-earth NP-mediated near-infrared graphene quantum dots. Reprinted with permission from ref 120. Copyright 2018 Elsevier.

between 10 and 100 nm in order to avoid triggering of immune response and clearance by glomerular filtration in the kidneys.[104] The spherical shape of the nanomaterials would encourage longer circulation time in blood and faster uptake by colorectal cancer cells.[105]

In short, the potential side effects arising from the off-target distribution of the molecular or drug-loaded lipid NPs require more studies for validation on the effectiveness of the delivery system. The pharmacokinetics, stability, and circulation time of the nanomedicine in the bloodstream should also be further investigated.

Graphene. Graphene and its derivatives have become the spotlight of nanotheranostics since the past decade, owing to their electrically tunable surface chemistry and mechanical robustness.[102,106−108] The sp^2-hybridized carbon atoms in a honeycomb network provide graphene with a large surface area, enabling the compounds to adsorb/functionalize on both sides of its planar surface. Moreover, the large molecular weight of graphene oxide (GO) enhances the imaging contrast,[109] while its electrical properties allow long-range fluorescence resonance energy transfer (FRET).[110] GO presented low uptake in the RES and a long blood circulation time at 1 mg/kg body weight within days.[111]

Melanoma is a form of skin cancer caused by excessive exposure to the sun's ultraviolet radiation.[112,113] A work using only GO (without the copresence of any photosensitizers) to sensitize the formation of singlet oxygen for dual nanomaterial-mediated PDT and PTT of solid melanoma tumors was reported in 2016.[114] The group proved that the nanosized graphene is suitable for *in vivo* fluorescence imaging operated using inexpensive laser setups. GO is able to absorb NIR light that subsequently induces the generation of singlet oxygen and offers deeper tissue penetration depths.[114]

However, the relatively hydrophobic nature of graphene makes it difficult to be taken up by cells, which in turn minimizes its therapeutic efficacy. Hwang *et al.* (2016)[110] has therefore suggested to graft a biopolymer of HA and a CD44 receptor-specific polysaccharide onto the GO surface (see Figure 4a).[110] The as-synthesized 170 nm HA-GO conjugate improved stability and solubility of GO in ionic solutions, without any aggregation. With such an idea, the group has also successfully developed an interesting fluorescence-switchable theranostic platform that is able to sense oncogenic miR-21 using antisense miR-21 peptide nucleic acid probes and show therapeutic effect on breast cancer simultaneously.[110] On the other hand, GO/gold nanorods (GO/GNR) theranostic nanohybrids have been synthesized *in situ* at room temperature for precise tumor computed tomography (CT) imaging and PTT of pancreatic cancer.[115] GO is chosen as the template for the synthesis of GNR due to the presence of many oxygen-containing functional groups which can improve solubility and biocompatibility of the system.[115] Meanwhile, the synthesis method is straightforward, environmental friendly, highly adaptable for different types of synthesis of GO/NPs and

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most importantly does not form any aggregates. The GO/GNRs showed a photothermal effect *in vitro*, with good optical morphological stability up to six cycles of 808 nm laser irradiation.[115]

Graphene quantum dot (GQD) is a zero-dimensional carbon material with excellent chemical stability, optical, and electronic properties, is biocompatible, and allows easy surface modifications.[116,117] GQD can also produce ROS with significantly high quantum yield (>1.0) for PDT, due to their excellent electron-donating and -accepting capability.[118] GQD has the property of extremely high intrinsic mobility of charge carriers.[119] The work of loading IR780 iodide (IR780) onto FA-functionalized GQD *via* $\pi-\pi$ stacking interactions has been reported recently.[119] The GQDs-FA contains a large and intact sp^2 domain with carboxyl groups around the edge, which exhibits excellent water solubility and is suitable for further conjugation (see Figure 4b).[119] IR780 is an effective theranostic agent for simultaneous NIR fluorescence imaging and PTT. Yet, its application is often hampered by its insolubility in different solvents due to the presence of the rigid chlorocyclohexenyl ring in the structure. Interestingly, the water solubility of IR780 (33.19%) is increased by over 2400-fold when loaded onto the GQDs-FA system, with a high photothermal conversion efficiency (87.9%). The photostability and tumor-targeting ability were greatly improved too. Most importantly, IR780/GQDs-FA, with a particle size of about 9 nm, is capable of producing sufficient hyperthermia to effectively kill cervical cancer cells and completely eradicate tumors upon 808 nm laser irradiation.[119] For future studies, it would be advantageous if pH-responsive features could be incorporated into this system, so that the therapeutic mechanism will be initiated once exposed to an acidic tumor microenvironment.

Generally, the clinical translation of PDT is often challenged due to the low yield of ROS, poor tissue penetration depth of the photosensitizer, and short lifetime of ROS.[57,120] A mitochondrial-specific PDT, named UCNP-GQD/TRITC, has been presented with the use of rare-earth-doped UCNP-mediated NIR-GQD.[120] UCNPs are a kind of inorganic nanomaterials capable of emitting efficient and sharp visible or UV light when excited at NIR. These features of UCNPs permit high penetration depth in biological tissues with high detection sensitivity.[121] Generation of singlet oxygen by the GQD becomes more prominent after UV light emission from UCNPs (see Figure 4c).[120] The high concentration of singlet oxygen observed in mitochondria is due to intrinsic advantages of GQD as well as the highly efficient energy transfer from UCNPs to GQD. Furthermore, surface modification of UCNP-GQD with mitochondrial-targeting fluorescent probe, tetramethylrhodamine-5-isothiocyanate (TRITC), allows the system to target mitochondria precisely and triggers breast cancer cells apoptosis irreversibly (with an inhibition ratio of more than 75%).[120] However, toxicity from long-term exposure and high quantum yield of singlet oxygen, surface-dependent therapeutic responses, and biological corrosion resistance (a phenomenon in which metallic ions and particles are released in a complex aqueous environment through electrochemical processes)[122] of the GQD are some of the concerns raised regarding this strategy. Also, since GQD (with a 6 nm diameter) is attached on the surface of UCNPs *via* amide linkages, it is possible that the resultant UCNP-GQD/TRITC composites would cleave off easily when the system is dispersed in a solvent. Glycyrrhetinic acid (GA), a natural product from *Glycyrrhiza glabra*, is another mitochondrion targeting ligand.[123] A biocompatible GA-functionalized GO has been fabricated and used as a carrier for targeted delivery of DOX into mitochondria. Both *in vitro* and *in vivo* studies revealed the activation of the mitochondria-mediated apoptosis pathway, suggesting GA-GO@DOX's potential for liver cancer treatment.[123]

Zhao *et al.* (2018)[111] has presented a chitosan/dimethymaleic-modified chitosan (CS/CS-DMMA)-functionalized GO NPs, also known as GON/CS/CS-DMMA. Chitosan (CS), a natural polysaccharide that commonly exists in the hard shells of marine crustaceans, has been actively explored to construct various CS-based nanomaterials because of its biocompatibility, biodegradability, and structural variability.[124] This hybrid nanocarrier is pH-sensitive and has surface charge-reversible ability, which is due to self-assembly of deprotonated carboxyl of GO NPs and the protonated amine of CS *via* electrostatic interactions. A chemotherapeutic drug, DOX, was adsorbed onto the GO *via* $\pi-\pi$ stacking interaction between the large π conjugated structures of GO and the aromatic structure of DOX. The outer CS-DMMA polyelectrolyte shell of the nanocarrier is negatively charged which prevented premature release of the coloaded DOX, when circulating in the blood system. Upon reaching the slightly acidic microenvironment (pH 6.5) of liver cancer, the nanocarrier switches to positive charge, due to detachment of CS coating, which re-exposes the amino groups of the positively charged CS. Consequently, GON/CS/CS-DMMA was capable of delivering DOX effectively at a controlled release rate.[111] In another study, reduction and functionalization of GO using dopamine formed reduced graphene oxide/polydopamine (RGO-PDA).[109] The formed PDA stabilizes the RGO against agglomeration and fouling effects. It also attenuates the *in vivo* toxicity of RGO and allows covalent surface modification with desired molecules. Conjugation of BSA (as a drug carrier, capturing agent for 4T1 breast cancer cells) onto the RGO-PDA system further permits a higher loading of MRI contrast agent diethylenetriaminepentaacetic acid (DTPA)-Mn(II) complex and anticancer drug (MTX). This multifunctional and biocompatible theranostic hybrid system is electrochemically proved to allow higher sensitivity (by a factor of 4) toward breast tumor.[109]

Liquid Tumor. Although the nanotheranostic strategies are focused more on the diagnosis and therapy of solid tumors, a considerable increase in their application to liquid tumors has been noted in recent years. However, while it is true that liquid tumors are classified as leukemia, lymphoma, and myeloma, only the former two have generated interest in the scientific community.[37] The strategy to carry out nanotheranostics in tumors is selected according to several variables, the most important being the disposition and accessibility of the tumor by the nanomaterials. Liquid tumors are more accessible than solid tumors, since they are present throughout the bloodstream, whereas in solid tumors, the nanostructures must cross tissue barriers to detect and treat.[125] In this section, we will evaluate how and why the specific nanomaterials are selected to carry out nanotheranostic strategies in liquid tumors.

Metal Nanoparticles. Metal NPs are presented as an interesting strategy for the detection and therapy of lymphoma and leukemia. Their ability to generate heat from the optical energy allows them to be nanoagents for PTT. However, its application for liquid tumor theranostics has not been fully studied, and this is due to the fact that these types of

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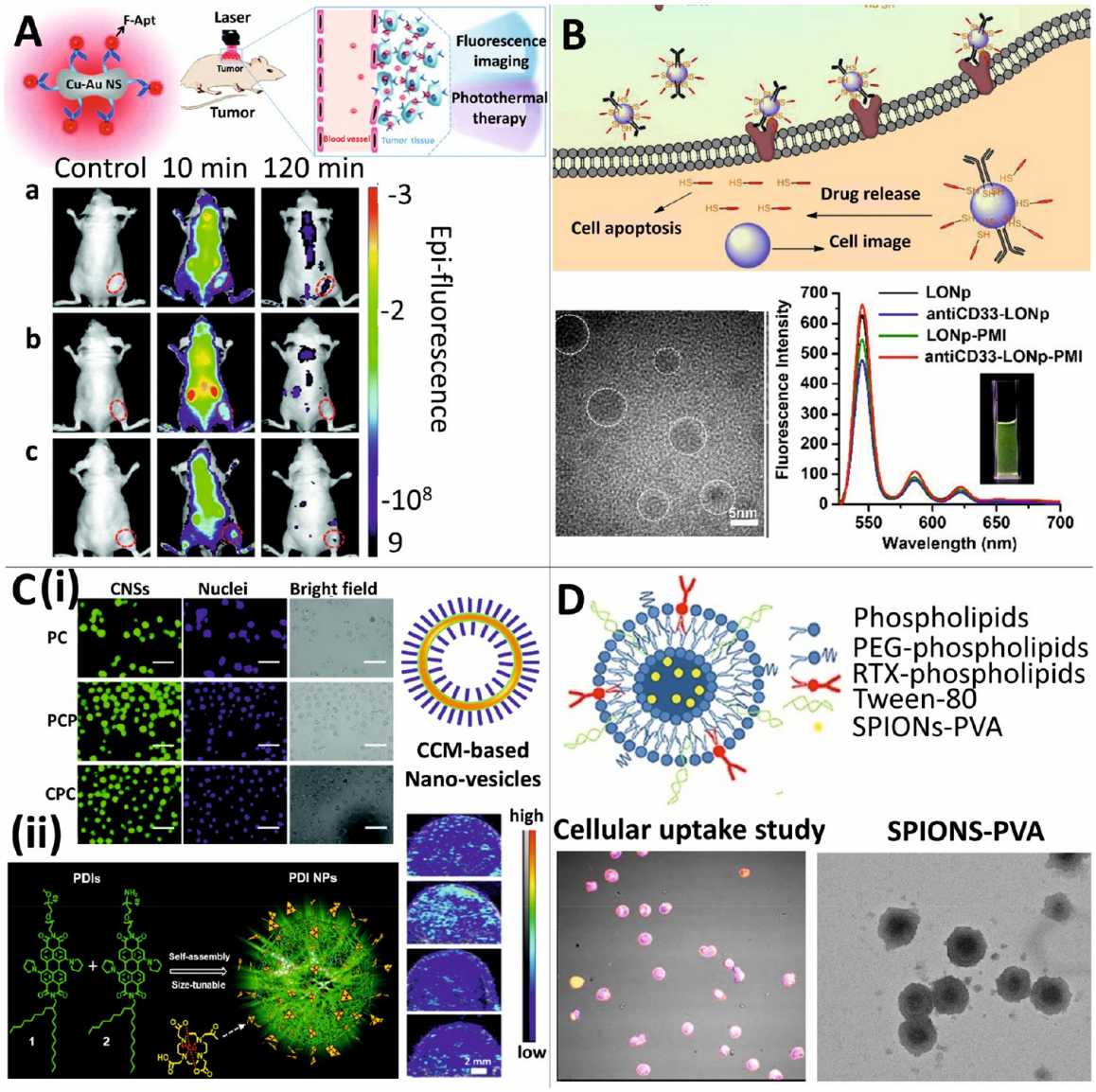

Figure 5. Nanomaterials applied as theranostic agents for liquid tumor. (a) Metal NPs. Cu-Au alloy nanostructures coated with aptamers for NIR imaging and PTT in *in vivo* leukemia cancer theranostics. Adapted with permission from ref 129. Copyright 2016 Royal Society of Chemistry. (b) Lanthanide-doped NPs. Lanthanide-doped NPs conjugated with an anti-CD33 antibody and a p53-activating peptide for acute myeloid leukemia therapy. Adapted with permission from ref 131. Copyright 2018 Elsevier. (c) Polymeric NPs: (i) Curcumisome loading on nanovesicles for fluorescence imaging and drug delivery strategy in leukemia theranostics. Adapted with permission from ref 132. Copyright 2015 Royal Society of Chemistry. (ii) Application of perylene diimide NP on lymph node mapping and cancer photoacoustic imaging and PTT. Adapted with permission from ref 135. Copyright 2017 American Chemical Society. (d) Lipid NPs: Application of liposome-containing SPIONs conjugated with anti-CD20 antibody as a theranostic agent for central nervous system lymphoma. Adapted with permission from ref 136. Copyright 2018 Elsevier.

circulating tumors are not located at a certain point and therefore may cause ablation of adjacent tissue.[126] In this context, 100 nm-sized iron oxide NPs (IONPs) functionalized with FA have been evaluated as a promising platform for imaging, followed by therapy of tumors related to the lymphatic system. Coating with FA does not require the use of linkers and therefore prevents the NPs from being oversized and enhances its accessibility to the lymph vessels. Moreover, FA provides stability to the NPs as it provides a negative surface charge, and this increases its retention in vessels. Finally, FA on the IONPs could specifically recognize the folate receptor that is overexpressed on the surface of cancer cells.[127] However, IONPs tend to aggregate when placed in biological suspensions, and therefore its heating ability is reduced. In order to exceed this limitation, IONPs have been functionalized with a protective mesoporous silica shell, which gives high heating and relaxivity properties when applied *in vivo*, while keeping its size below 100 nm.[128] Moreover, it should be noted that unlike other metal NPs, these modified IONPs allow positive MRI contrast by displaying a bright region and therefore allow effective visualization of the tumor. However, although this NP has interesting properties, its effectiveness for magnetic hyperthermia therapy of circulating cancer has yet to be demonstrated. The nanomaterial that has proved to be an excellent nanotheranostic agent for *in vivo* leukemia treatment is Cu-Au alloy nanostructures, where the

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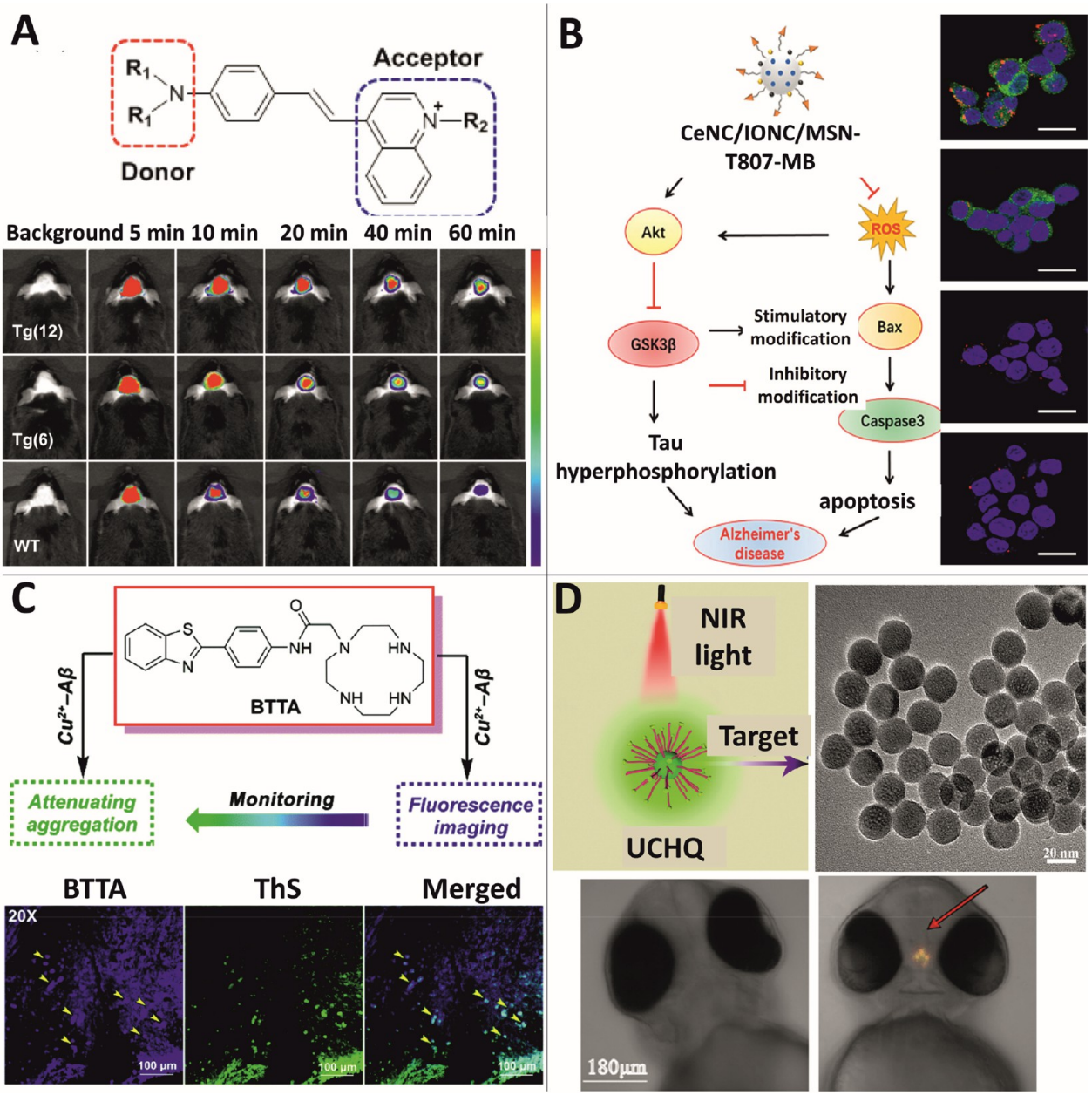

Figure 6. Nanomaterials applied as theranostic agents for neurodegenerative diseases. (a) NIR dyes for *in vivo* imaging of Aβ species and Aβ aggregation inhibition. Adapted with permission from ref 141. Copyright 2016 Elsevier. (b) Ceria and iron oxide nanocrystal functionalized nanocomposite as a nanotheranostic agent for MRI and tau aggregation inhibitor. Adapted with permission from ref 142. Copyright 2018 American Chemical Society. (c) BTTA for fluorescence imaging and Cu^{2+} chelators applied in Alzheimer's disease. Adapted with permission from ref 144. Copyright 2016 Royal Society of Chemistry. (d) Upconversion NPs for NIR Alzheimer's disease detection and therapy based on Cu^{2+} chelation. Adapted with permission from ref 145. Copyright 2016 Elsevier.

higher thermal conductivity of the copper allows excellent heating under laser irradiation once the tumor is visualized by NIR imaging. This nanoplatform was proven to target and destroy cancer cells in mice within 5 min (see Figure 5a).[129] Despite this, issues concerning renal clearance and lymphatic fenestration hinder the current nanotheranostic strategies for liquid tumor treatment. In this context, it is essential to select nanomaterials with a size range from 20 to 50 nm, as they have proven to enhance *in vivo* tumor penetration and inhibition.[130]

Lanthanide-Doped Nanoparticles. The lanthanide oxyfluoride NPs appear as an alternative to lipid and polymeric-based delivery systems, which have low retention and nonspecific cellular uptake, respectively.[131] The excellent photoluminescence property of the lanthanide and the conjugation of the NP with anti CD33 antibody enable it to be an interesting nanotheranostic agent for myeloid leukemia. These NPs are conjugated with anti CD33 that allows retention and internalization in $CD33^+$ AML cells, which otherwise could not accumulate in the blood vessels, therefore making it effective for diagnosis and therapy (see Figure 5b).[131] They have shown to be successful antitumor agents both *in vivo* and *ex vivo* by acting as a specific delivery vehicle of PMI peptide, which antagonizes the inhibitors of the tumor suppressor protein p53.

Polymeric Nanoparticles. Polymeric NPs have been applied mostly for image-guided anticancer drug delivery. In

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this context, several types of polymeric NPs have been used depending on the diagnostic strategy to be followed. For the treatment of non-Hodgkin lymphoma, amphiphilic polymers composed of hydrophobic fluorescent curcumin and hydrophilic PEG were designed as self-assembled anticancer drug nanovesicles [see Figure 5c(i)].[132] Limitations associated with the drug, such as low solubility and low bioavailability, were curtailed with PEG. The most attractive aspect of this nanomaterial is the ability of curcumin to act as both a strong fluorescent probe and an anticancer drug, avoiding the need of a fluorophore.[133] Furthermore, a multifunctional imaging theranostic approach based on core−shell CS-HA NPs has been applied in murine model of B-cell lymphoma.[134] Since they are initially conjugated with fluorophores and then loaded with paramagnetic tracers, the most suitable imaging agent can be chosen depending on the tumor type; fluorescent reflectance imaging for scanning of superficial structures such as sentinel lymph node and MRI for deep tissue visualization. Another advantage is that the HA has numerous active groups that are useful for specific targeting. In this context, these polymeric NPs were decorated with a specific mimotope (pA20-36) that exclusively recognize A20 lymphoma cells and induce cell apoptosis. Moreover, amphiphilic perylene diimide (PDI) derivatives were developed and further self-assembled into a series of PDI NPs with different sizes of 30, 60, 100, and 200 nm. They have been proven to perform activable PAI and effective PTT [see Figure 5c(ii)].[135]

Lipid Nanoparticles. Lipid NPs have also been applied as carriers for lymphoma theranostics, but as an alternative to improve cell internalization and simultaneous drug delivery. Liposomes that contain SPIONs and functionalized with rituximab antibody have been developed as theranostic agents for central nervous system lymphoma (see Figure 5d).[136] Blood−brain barrier regulates the movement of molecules, ions, and cells between the continuous nonfenestrated microvasculature and the central nervous system.[137] The restrictive nature of the blood−brain barrier poses challenges for targeted drug delivery to the central nervous system, and it is usually associated with neurological diseases including neurodegenerative diseases.[138] In this case, free rituximab is not able to cross the blood−brain barrier, hence it requires a drug delivery system to perform effective therapy. The liposome is used as a rituximab vehicle, with sizes of <200 nm. Surface modification of liposome with a nonionic surfactant allows penetration into the blood−brain barrier and therefore can develop its antitumor function. The liposome which also contains SPIONs allows *in vivo* MRI with both T_1 and T_2 modes. Nevertheless, the antilymphoma activities of the liposome have only been tested *in vitro*, and therefore this strategy only remains as a promising tool for clinical translation.[136]

NEURODEGENERATIVE DISEASES

Neurodegenerative diseases are a set of heterogeneous disorders that result in a progressive loss of certain neuronal systems and finally loss of cognitive abilities. Alzheimer's disease (AD), Parkinson's disease, amyotrophic lateral sclerosis, and Huntington's disease are the prototypes of degenerative diseases.[139] Among them, AD is the most common neurodegenerative disorder, and this is the reason that most of the nanotheranostic strategies applied on brain diseases are focused on this specific disorder. While it is true that the causative mechanism of the disease is unknown, there are several hypotheses that consider the deregulation of metal levels in the brain is associated with multiple pathological factors of the disease, such as amyloid aggregation and oxidative stress. In this context, the nanotheranostic platforms are classified according to the therapeutic strategy to be performed, which is usually the amyloid-β aggregation inhibition and metal chelation.[140]

Nanomaterials for Amyloid-β Aggregation Inhibition. The application of nanotheranostics to AD is a clear example of how a nanoplatform is designed according to the type of therapy to be performed. Unlike nanotheranostics for cancer disease, in which the therapy is usually tumor thermal ablation or specific drug delivery, for AD, the therapy is usually based on the inhibition of the Aβ aggregation, since these have a direct relationship with the disease's poor prognosis. In this context, three NIR dyes (DMA-SLOH, DBA-SLOH, and DPA-SLM) for *in vivo* imaging of Aβ species and inhibition of Aβ aggregation have been developed (see Figure 6a).[141] The advantage of using fluorescence imaging is that the use of high cost and low sensitivity MRI and positron emission tomography (PET) imaging (in which radioactive compounds and use of sophisticated instruments) are completely avoided. Moreover, the use of NIR fluorescence reduces the interference caused by native fluorescence biological compounds, which have a wavelength emission peak below 550 nm. Furthermore, the NIR dyes are proven to have excellent blood−brain barrier permeability, good biostability, and renal clearance ability.[141] However, since the strategies of nanotheranostics reported for inhibiting the aggregation of β-amyloids have shown to fail in clinical trials, a multifunctional nanocomposite has been developed for the specific targeting of tau and its aggregation inhibition. Tau aggregation is an independent amyloid-β AD pathology that leads to mitochondrial dysfunction and consequently oxidative stress generation and cognitive deficit. The nanocomposite consists of a mesoporous silica NP that acts as a carrier of ceria and iron oxide nanocrystals, for antioxidant function and MRI probe, respectively (see Figure 6b).[142] The tau aggregation inhibition is due to the loading of the carrier with methylene blue. This nanomaterial proved to be an effective *in vivo* theranostic agent due to its retention capability in the axon and its synergic therapeutic effect on AD. Despite this, in order to promote clinical translation of this nanoplatform, the nanocomposite must fulfill the Lipinski's rules, which determine its capability to cross the blood−brain barrier.[143]

Nanomaterials for Cu^{2+} Chelation. The process of Aβ aggregation is promoted by the increase in the concentration of trace metal ions, such as Cu^{2+}; therefore, determining its concentration in the brain is an essential tool for diagnosis of AD. In this context, fluorescence chelators, BTTA composed of a cyclen group and a benzothiazole aniline group (BTA) have been developed, in which BTA allows specific fluorescence imaging of Aβ species and the cyclen group acts as an attenuator of the metal induced Aβ aggregation (see Figure 6c).[144] This nanotheranostic agent satisfies the restrictive terms of Lipinski's rules and has demonstrated its functionality *in vitro* and its ability to penetrate the blood−brain barrier *in vivo*. However, it should be noted that it requires structural modifications for longer fluorescence emissions or even NIR emission with acceptable penetration depth.[144] For this reason, UCNPs modified with complex 8-hydroxyquinoline-2-carboxylic acid (HQC) have been developed. The fluorescence emission of the UCNPs is quenched

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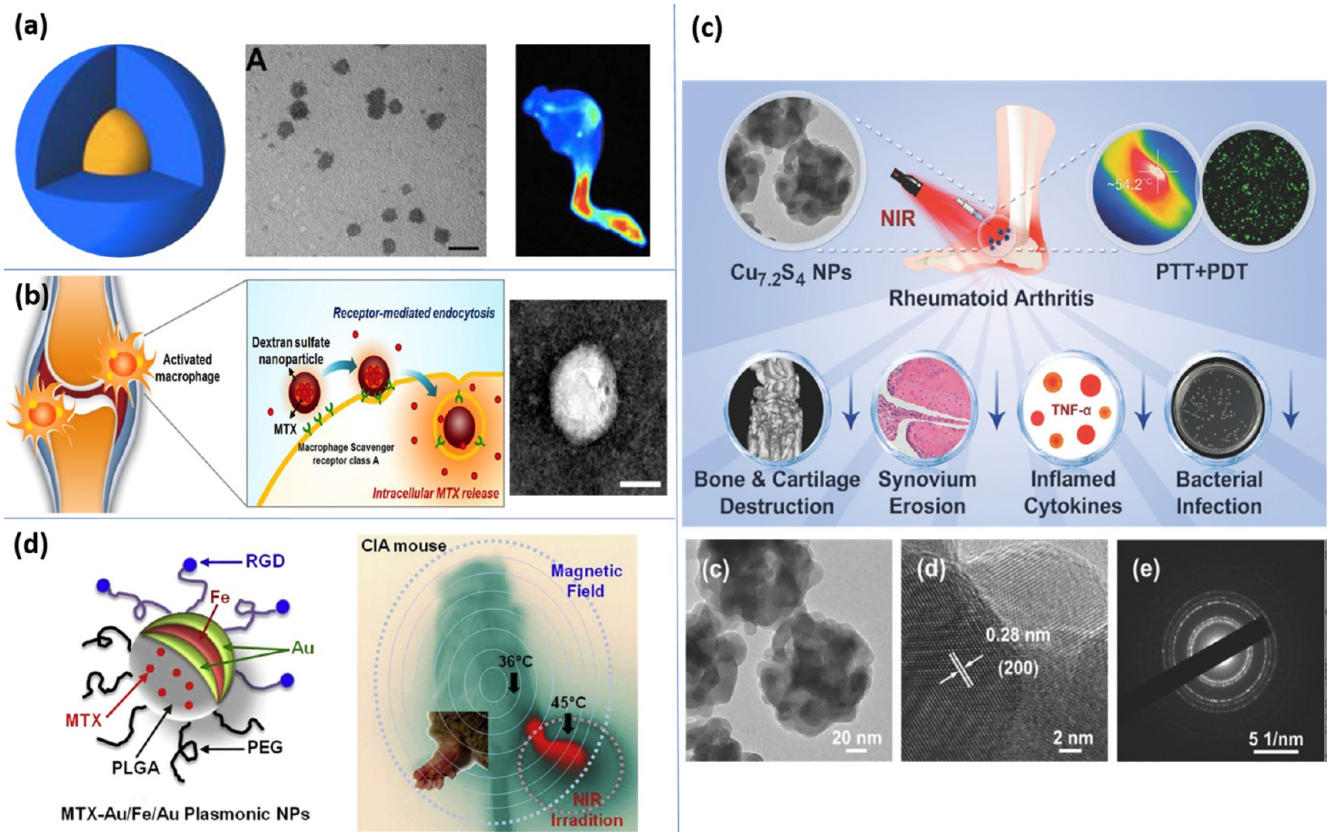

Figure 7. Brief overview of the structure of the nanomaterials used for RA theranostics. (a) MTX prodrug, TEM microimages of DS-*g*-MTX and its *ex vivo* FITC image of affected joints. Adapted with permission from ref 149. Copyright 2017 Ivyspring International Publisher. (b) DS-NP as a nanocarrier for targeted RA theranostic. Adapted with permission from ref 150. Copyright 2017 Elsevier. (c) Application of $Cu_{7.2}S_4$ NPs in RA theranostic when combined with PTT and PDT. The respective TEM image, SAED, and interplanar crystal spacing of $Cu_{7.2}S_4$ NPs. Adapted with permission from ref 156. Copyright 2018 John Wiley and Sons. (d) MTX-Au/Fe/Au plasmonic NPs for magnetic targeted chemo-photothermal treatment of RA. Adapted with permission from ref 153. Copyright 2015 Elsevier.

when Cu^{2+} is detected, due to luminescence resonance energy transfer. As the Cu^{2+} is captured by HQC, it inhibits the aggregation of Aβ and subsequently eliminates the toxic Aβ intermediates (see Figure 6d).[145] Although this nanomaterial was reported as a promising nanotheranostic agent in human brain, it is noteworthy that the *in vivo* experiment was performed on zebrafish, which has a transparent brain compared to a complex human brain. In order to determine the efficacy of this nanotheranostic agent for AD patients, further *in vivo* assays should be conducted.

AUTOIMMUNE DISEASES

The immune system in our body protects us from disease and infection. However, if a person has an autoimmune disease, the body's defense mechanism will launch an attack against specific cells, body tissues, and organs of the host. Autoimmune diseases can affect many parts of the body and significantly affect the patient's well-being. Environmental, infectious, and genetic factors are some possible factors initiating or exacerbating autoimmune diseases. There are more than 80 types of autoimmune diseases; with the classic symptom of inflammation. Current clinical treatment modalities are generally nonspecific and focus on reduction of inflammation. Moreover, the use of anti-inflammatory drugs lack of desired specificity has severe toxic effects and limited therapeutic benefits.[146]

NPs can be used as a drug delivery system to specifically target cells and tissues. Co-delivery of targeting and therapeutic agents using NPs can greatly improve pharmacokinetics and enhance bioavailability of therapeutics. NPs used for the treatment of autoimmune diseases can be classified as colloidal NPs (consist of a metal core stabilized by an organic/polymeric coating) and organic-based NPs (either polymeric or lipid-based).[147] The biodegradability, biocompatibility, biodistribution, and clearance of NPs are very important issues to take into consideration when constructing an efficient NPs-based nanomedicine for autoimmune disease theranostics.

Rheumatoid Arthritis. Rheumatoid arthritis (RA) is a chronic systemic inflammatory disease, characterized by severe cartilage and bone destruction and massive synovial joint inflammation. Currently, there is no cure for RA.[148] The integration of targeting and therapeutic agents in RA into a single nanomaterial-based theranostic platform is increasingly advancing in rheumatology. This section will present a few nanomaterials that have been discovered lately, with the potential for synergistic RA theranostics.

Activated macrophages are the main "culprit" of inflammation in RA. The macrophages actively release cytokines which trigger onset and persistence of RA. Dextran sulfate (DS) is a hydrophilic polysaccharide that can specifically target the scavenger receptor (SR, one of the receptors overexpressed on the macrophages). MTX is a chemotherapy drug that is commonly used for the treatment of RA. However, the utility

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of MTX is limited by its severe drug resistance and random distribution in the body which may cause serious side effects. Combining both the benefits of nanoscale prodrugs and modified conjugates, a biocompatible polymer-drug conjugate, namely dextran sulfate-*graft*-methotrexate conjugate (DS-*g*-MTX), has been designed for treatment of RA (see Figure 7a).[149] The conjugate (about 100 nm in diameter) exhibited excellent SR targeting properties, with improved anti-inflammatory efficiency in the affected joints of collagen-induced arthritis (CIA) mice.[149] Similar work has also been presented by Heo *et al.* (2017)[150] using MTX-loaded DS NPs (220 nm in diameter), with the loading efficiency of 73% (see Figure 7b).[150] NPs permit prolonged circulation in the bloodstream and passive accumulation of drugs into inflamed synovial tissues (12-fold higher than control), with controlled drug release at desired action sites. The results further confirmed that polymeric NPs are potentially useful theranostic nanomedicine for RA.[150]

Solid lipid NPs (SLNs) are formed by a mixture of solid lipids dispersed in inner cores. SLNs are widely used as a matrix for drug encapsulation, mainly because SLNs possess attractive features such as good physical stability, enhanced biocompatibility and biodegradability, protection against labile drug degeneration, controlled release, and facile synthesis.[98,151] HA is another commonly used drug carrier and targeting ligand in RA treatment.[148] HA targets the overexpressed hyaluronic receptor CD44 on the surface of activated macrophages. Encapsulation of glucocorticoid prednisolone (PD) can be carried out within the SLNs conjugated with HA, and the resultant product is known as HA-SLNs/PD, approximately 147.8 nm in diameter. Encapsulation of PD in HA-SLNs improved colloidal stability, slowed down PD release (37.6% compared to 56.22% from free drug solution during the first 30 h), and enhanced biodistribution and therapeutic efficacy in CIA model (with a histopathology score of 2.0).[152]

Metallic NPs have been successfully translated to RA treatment due to their size and magnetic properties which can serve as a multifunctional drug delivery and theranostic platform.[148] In a study, researchers designed drug-loaded gold/iron/gold plasmonic NPs for simultaneous magnetic targeted chemo-photothermal treatment and dual (NIR absorbance and magnetic resonance) imaging of RA.[153] The NPs combine the properties of both iron (magnetic) and gold (surface plasmon resonance), and the gold exterior shell provides an anchorage site for further functionalization. Arginine-glycine-aspartic acid (RGD) peptide was conjugated onto the Au surface to target $\alpha_v\beta_3$ integrins expressed at the inflammation sites. Meanwhile, MTX was loaded inside the poly(lactic-*co*-glycolic acid, PLGA) NPs. PLGA is selected due to its excellent biodegradability, biocompatibility, and stability.[154] This RGD-conjugated MTX-loaded PLGA Au/Fe/Au half-shell NP has an average diameter of 135 nm. Upon NIR irradiation, NIR resonance of the Au half-shells generates heat at the inflammation sites to accelerate the release of MTX from PLGA NPs. The Fe half-shell layer embedded between the Au half-shell layers also allows *in vivo* T_2- MRI and NIR absorbance imaging (see Figure 7d).[153] The externally generated magnetic field not only speeds up the delivery of the NPs to the inflammation sites but also enhances the retention of the NPs. The combination of NIR absorbance imaging and MRI allows higher spatial resolution of inflammation regions with outstanding contrast features and higher sensitivity and specificity. Interestingly, the MTX dosage required in this case is only 0.05%, as compared to free MTX therapy for the treatment of RA.[153] The *in vivo* behavior (such as biodistribution and vascular penetration) of the as-synthesized NPs requires in-depth studies before wide clinical application.

A combined strategy PSDT (PDT followed by sonodynamic therapy), using PLGA phase-transition NPs co-loaded with oxygen and indocyanine green (ICG), termed OI-NPs, has been proposed for theranostic of RA by Tang *et al.* (2017).[154] PSDT may reduce the sensitizer dosage and ultrasound/light energy that can alleviate side effects, while improving the curative effect dramatically. ICG can strongly absorb NIR once activated by light and ultrasound, suitable for therapy or imaging. The stability of the ICG is improved when co-loaded with oxygen onto PLGA phase-transition NPs. The synergistic oxygen and ICG are found to act as a sensitizer and oxygen carrier for PSDT. The prepared NPs have advantages in terms of biosafety and stability, at the same time showing cytotoxic effects on synoviocytes (a specialized cell type located inside the joints, responsible in producing cytokines and proteases, which cause cartilage destruction).[154] Nonetheless, the authors did not report on the performance of the as-synthesized NPs in n *in vivo* model and its therapeutic effect in a hypoxic environment.

Titanium dioxide (TiO_2) has shown potential in PDT for some diseases, mainly because of its excellent biocompatibility, easy availability, and ROS generation properties upon excitation. Tetra sulfonatophenyl porphyrin (TSPP) is a porphyrin derivative that can generate ROS for PDT, but its application is often hampered by neurotoxicity, phototoxicity, and nonspecific accumulation in body tissues. Interestingly, the photoactivated TSPP-TiO_2 nanocomposites were found to be able to ameliorate RA by PDT in CIA models, when coupled with allogenic bone marrow stem cells.[155] Meanwhile, Cu is an essential element in the human body, useful in promoting osteogenesis and chondrogenesis. Cu-based nanomaterials were reported as excellent PTT agents and photosensitizers for PDT. An approach using Cu-based nanomaterials in RA treatment has been proposed with good biocompatibility and facile synthesis (see Figure 7c).[156] Upon NIR irradiation at 808 nm, the as-synthesized L-cysteine (Cys) assisted CuS NPs (named $Cu_{7.2}S_4$ NPs) not only showed better bone preservation but also displayed outstanding antibacterial ability during intra-articular injection. Hence, the $Cu_{7.2}S_4$ NPs could serve as a synergistic PDT and PTT modality for RA.[156]

Drug delivery systems can be manipulated in a way that the nanomaterials only release the drug from the conjugate in response to certain conditions. This is important in avoiding systemic distribution of drugs in the body that necessitates the use of sustained high-dose therapy and may give rise to adverse effects. As such, Li *et al.* (2017) presented pH-sensitive polymeric micelles for targeted drug delivery to inflamed joints.[157] The polymeric micelles (with particle size of 45.76 nm) are stable in the bloodstream, until they reach the inflammation sites. An imbalance between increased metabolism and insufficient oxygen supply contributes to low pH in the inflamed synovial fluid (as low as pH 6.0, in some cases even lower than 5.0).[158] Recognition of acidosis of synovial fluid triggers hydrolysis of hydrazone bonds, subsequently releasing the drug, PD, in affected joint areas. The same process has also been reported for targeted drug delivery to the acidic microenvironment of solid tumors. The results demonstrated improved therapeutics efficacy, with the therapeutic benefits from each injection lasting for 48−72 h

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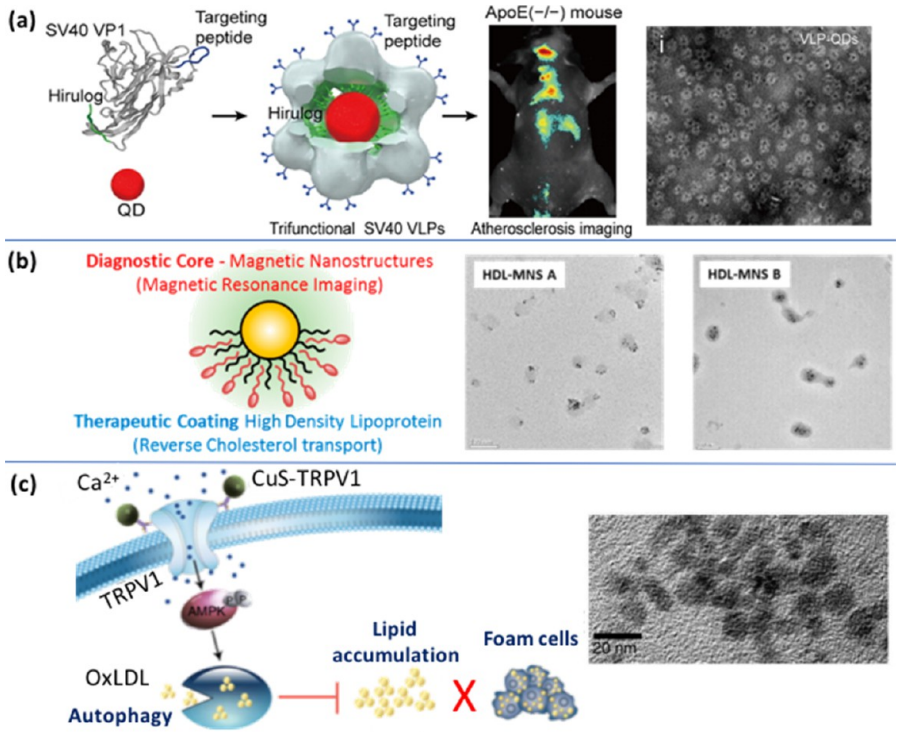

Figure 8. Brief overview of the structure of the nanomaterials used for atherosclerosis theranostics. (a) Multifunctional virus-like particles of Simian virus 40 NPs (SV40 VLPs) with the TEM image. Adapted with permission from ref 166. Copyright 2016 American Chemical Society. (b) HDL-MNs with their TEM images when synthesized using different approaches. Adapted with permission from ref 172. Copyright 2017 American Chemical Society. (c) Copper sulfide (CuS) NPs as a photothermal switch for TRPV1 signaling to attenuate atherosclerosis, with the TEM image. Adapted with permission from ref 164. Copyright 2018 Springer Nature.

in preclinical models,[159] fulfilling the needs of sustained prodrug activation kinetics for RA treatment. The as-prepared polymeric micelles inevitably display minimal toxicity, which could be due to micelle uptake by phagocytic cells in liver and spleen that initiates inflammatory responses.[157] Key mechanistic details that induce potential toxicity and inflammatory effects and long-term nanomaterial fates in clearance organs as well as macrophage−nanomaterial interactions are generally unexplored.[160] Future research can be anticipated on fabrication of micelles with bone regeneration capabilities in eroded joints.

Generally, the RA severity often fluctuates over time. Usually, the treatment offered, doses of drug applied and its release rates are irrespective of the disease stage, resulting in non-optimal therapeutic efficacy with potential side effects. Herein, a drug-loaded hydrogel that responds to RA flare-ups in real time has been innovatively introduced.[159] A hydrogel is a three-dimensional (3D) polymer network of hydrophilic monomers that can absorb and retain a large amount of water, without affecting its shape. Since it can mimic a native tissue's architecture and functions, hydrogel often has been used as drug-delivery carriers.[161] In this case, a hydrogel is formed from the self-assembly of triglycerol monostearate (TG-18), encapsulated with drug triamcinolone acetonide (TA).[159] Synovial fluid from RA joints has a higher expression of matrix metalloproteinases (MMPs) and other tissue-degrading enzymes than synovial fluid from healthy joints.[159] Therefore, upon exposure to synovial fluids from patients with RA, MMPs cleave the ester bond in TG-18, disassemble the hydrogel, and release the encapsulated TA on-demand, which exclusively corresponds to the concentration of MMPs expressed in the synovial fluids. The severity of the RA is reflected by the co-loaded fluorescent dye 1,1-dioctadecyl-3,3,3,3-tetramethylindotricarbocyanine iodide (DiR).[159] The metalloproteinase-3 (MMP-3) gene is one of the biomarkers of RA and often correlated with systemic inflammation. Although the precise role of MMP-3 in RA progression requires further elucidation, TA is believed to be able to alter genes expression of MMP-3.[162] However, the system still requires extensive *in vivo* biocompatibility evaluation, sustained TA drug release, and encapsulation studies especially in large animal models. It is challenging to maintain a consistent release profile in the setting of constant physiochemical changes.

CARDIOVASCULAR DISEASES

Cardiovascular diseases (CVDs) are the leading cause of noncommunicable illness worldwide. Current surgical intervention and therapy for CVDs are not completely effective and face many medical challenges. For instance, current recommended therapeutic regimes barely lead to full recovery and often involve poor efficacy and drug instability and resistance as well as adverse effects and high costs.[163] Advances in nanomedicine offer theranostic approaches for CVDs.[161] It is observed that most of the scientific research is focused on the study of non-invasive biological imaging applications (particularly MRI and near-infrared fluorescence (NIRF)) for early detection of atherosclerotic plaque. Additional therapeutic strategies for CVDs are highly imperative in actualizing CVDs theranostic applications.

Atherosclerosis. Atherosclerosis, a systemic disease affecting arteries, is the major pathological cause of CVDs. Atherosclerosis is characterized by the formation of atherosclerotic plaques, which are developed through the accumu-

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lation of cholesterol and formation of foam cells in the arterial wall.[164] Atherosclerotic plaques tend to induce hardening of the artery and thus obstruct blood circulation.[165]

Report for non-invasive fluorescence imaging of atherosclerosis in live atherosclerotic mice has been published in 2016, with the use of Simian virus 40 virus-like particles (SV40 VLPs) as a platform to load imaging probes, targeting elements and therapeutic compounds (see Figure 8a).[166] Controllable *in vitro* self-assembly and the capacity as the cargo for foreign peptides or proteins make SV40 VLPs stand out as a nanomaterial in various nanotheranostic applications.[167] Encapsulation of NIR QDs (QD 800) inside SV40 VLPs improved QDs photostability, brightness, and detection sensitivity during fluorescence imaging of atherosclerotic plaques in mice.[166] In fact, different atherosclerosis biomarkers or targeting peptides are present at various developmental stages of atherosclerosis.[168] Vascular cell adhesion molecule-1 (VCAM-1), macrophages, and fibrin have been identified and used to target atherosclerosis at early, development, and late stages, respectively. The multifunctional QD, with a diameter of 26 nm, permits its accumulation inside the atherosclerotic plaque tissues mediated by an EPR effect, in response to the inflammatory process in the vascular. Enhanced targeted delivery of anticoagulant drug Hirulog (about 6.5-fold increase) and higher antithrombin activity (1.8 μg/mg of tissue) at atherosclerotic plaques have been reported when QDs are functionalized with VCAM-1 targeting peptide.[166] However, the group did not provide strong justification on the atherosclerosis efficacy of these NPs, such as reduced areas of plaques, counts of infiltrated immune cells, or the expression of inflammatory markers.[169] Future studies should be focused on more detailed biocompatibility evaluation of the SV40 VLPs, including blood-half-life, immunogenicity, and comparisons with other protein cages to justify its potential as theranostic tools for atherosclerosis.

H_2O_2 is a highly promising theranostic biomarker in various pathological disorders, however, its fluorescence imaging modalities are hindered by its short tissue penetration depth. ICG is a widely used photoacoustic contrast agent with a high signal-to-noise ratio and maximum emission at around 800 nm. Yet, its application is often challenged by instability, rapid blood clearance, and nontargeting ability.[170] Jung *et al.* (2018) loaded ICG onto boronated maltodextrin (BM) NPs to form spherical ICG-BM NPs with a diameter of 500 nm.[170] Maltodextrin, one of the polysaccharides obtained from partial hydrolysis of starch, is water-soluble, biocompatible, biodegradable, versatile, and easy to modify. Hence, maltodextrin is suitable to be used as a diluent, coating material, and carrier of diagnostic or therapeutic agents in drug delivery systems. Substitution of hydroxyl groups of maltodextrin with boronic ester forms BM, rendering maltodextrin with H_2O_2-responsive properties. ICG-BM NPs react with H_2O_2 to generate echogenic carbon dioxide (CO_2) bubbles which significantly enhanced fluorescence (almost 2-fold higher), ultrasound (signal detectable even with low-frequency ultrasound transducer), and photoacoustic signals in a H_2O_2-triggered manner. Moreover, ICG-BM NPs could exert therapeutic effects by scavenging the overexpressed H_2O_2 and simultaneously release therapeutic 4-hydroxybenzyl alcohol (HBA). HBA displays anti-inflammatory, antioxidant, and antiplatelet functions by suppressing the expression of pro-inflammatory tumor necrosis factor-alpha (TNF-α) and soluble CD 40 ligand in activated platelets,[171] thus relieving inflammation and accelerating angiogenesis.[170] Future work can be anticipated on reducing the size of ICG-BM, since NPs with sizes over 100 nm are easily recognized by macrophages and accumulate in lymph nodes, liver, and spleen as well as lungs.[59]

High density lipoproteins (HDL) are responsible for reverse cholesterol transport (RCT), a process to efflux excess cholesterol in the periphery back to the liver. RCT is important in protecting against CVDs. A magnetic nanostructure (MN) functionalized with phospholipids and apolipoprotein A1 (apoA1), named HDL-MN, has been developed to mimic the natural HDL particles present in the body (see Figure 8b).[172] The MNs are biocompatible and composed of Fe_3O_4 NPs, suitable to be used as contrast agents for MRI. The use of HDL-MNs for CVDs is a non-invasive imaging and therapeutic approach. Apart from being capable of precise targeting of macrophages, HDL-MNs are able to perform RCT by inducing cholesterol efflux (about 4.8%, in natural HDL is about 4.7%) from cholesterol-rich macrophages. The HDL-MNs have also shown a 5 times higher MR contrast enhancement than commercial FDA approved T_2 MRI contrast agent (Ferumoxytol). The HDL-MNs do not induce cytotoxicity in *in vitro* settings, in macrophages of up to 350 μM HDL-MNs.[172] The hydrodynamic diameter of the nanostructure, however, is approximately 80−100 nm, which is too big for EPR-based extravasation and may impact its circulation time in blood and accumulation at atherosclerotic plaques. It is of interest to further investigate the targeting ability of this nanostructure in *in vivo* settings. In addition, the use of iron-based NPs could potentially generate harmful radicals (Fenton reaction). This may limit their use in humans for diagnosis and treatment, especially under oxidative stress-related conditions.

Recently, researchers have turned their attention to the activation of transient receptor potential vanilloid subfamily 1 (TRPV1) signaling pathway as one of the alternatives for attenuating atherosclerosis (see Figure 8c).[164] Activation of TRPV1 cation channels may reduce lipid storage and formation of atherosclerotic lesions. Yet, clinical use for the normally used TRPV1 cation channels activator, capsaicin, is limited by its chronic toxicity and infusibility. Unlike the optical absorption in gold nanostructures, which is due to the surface plasmon resonance, NIR absorption of CuS NPs derives from the d−d transition of Cu^{2+} ions. In other words, CuS NPs absorption would less likely be influenced by the solvent or the surrounding factors, which is perfect for *in vivo* settings. CuS NPs also possess almost analogous high heat conversion efficiencies (as high as 80%) compared to gold nanostructures, making them remain stable under prolonged optical excitation.[173] Coupling of CuS NPs to antibodies targeting TRPV1 acts as a photothermal switch for TRPV1 signaling in vascular smooth muscles. Upon irradiation of CuS NPs by continuous wave laser at 980 nm, 5 W/cm^2 for 350 s, the NPs (with particle size of 13 nm) generate local heat and a strong photoacoustic signal, which subsequently opens TRPV1 channels and causes calcium ion (Ca^{2+}) influx. The increase in intracellular Ca^{2+} induces autophagy and reduces lipid accumulation and foam cell formation. The cholesterol efflux was enhanced with no obvious long-term toxicity *in vivo*. With photoacoustic imaging, high-resolution visualization with high temporal and spatial precision of blood vessels in the deeper cardiac regions (such as aortic arch, carotid artery and femoral artery) were achieved.[164]

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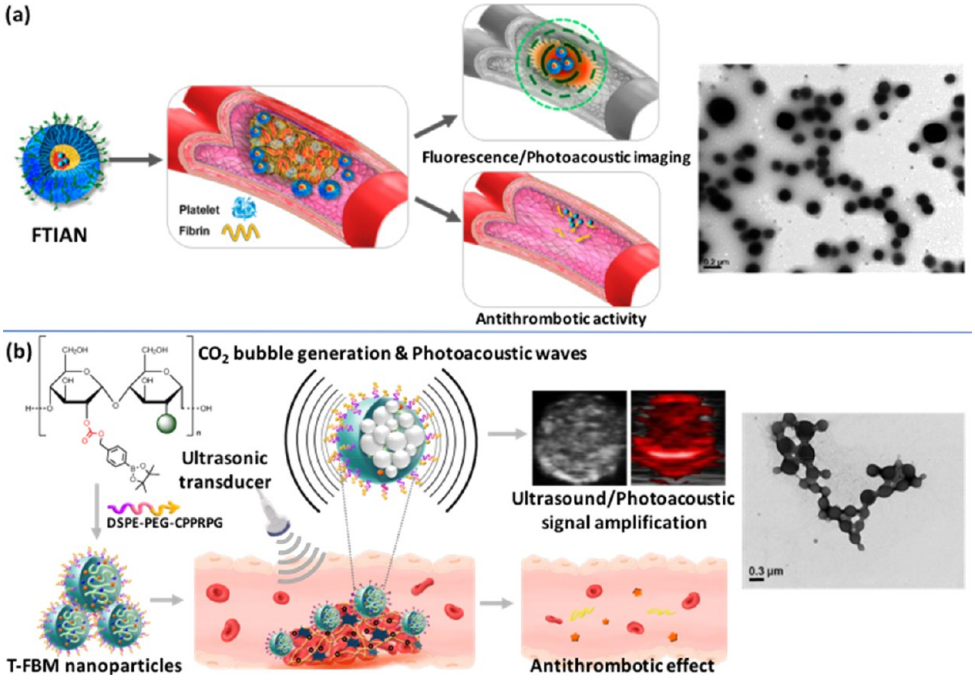

Figure 9. Brief overview of the nanomaterials used for thrombosis theranostics, with their TEM images. (a) Fibrin-targeted and H_2O_2-responsive NPs as a theranostics for thrombosed vessels. Adapted with permission from ref 165. Copyright 2017 American Chemical Society. (b) T-FBM NPs as a H_2O_2-activatable photoacoustic signal amplifier and a thrombus-specific nanotheranostic agent. Adapted with permission from ref 171. Copyright 2018 American Chemical Society.

Thrombosis. The vulnerable plaques located in the arterial wall are prone to rupture due to a soft and weak fibrous cap. The rupture exposes collagen and various components to the blood, leading to the formation of blood clots (thrombi (plural); thrombus (singular)) in the lumen. This condition is known as arterial thrombosis.[164] Thrombosis rarely show any symptoms until late stage and sudden death.[174] Generally, a thrombus is made up of blood factors, mainly activated platelets and water-insoluble fibrin. P-selectin is an adhesion molecule mainly involved in the pathophysiology of thrombosis and other CVDs.[174] Li *et al.* (2018) innovatively functionalized fucoidan, a marine polysaccharide that specifically targets P-selectin in thrombus, on polysaccharide-coated microbubbles (MBs).[174] Ultrasound imaging is one of the commonly used medical diagnostic imaging modalities owing to their portability, non-invasiveness with excellent safety profile, high spatial resolution, lack of ionizing radiation, reasonable cost, and real-time imaging properties.[59] The as-synthesized fucoidan functionalized microbubbles (fucoidan-MBs) exhibit high echogenicity and stability in suspension at 4 °C (up to 2 months),[174] hence suitable to be used as a sensitive molecular ultrasound contrast agent by creating strong acoustic reflections that may identify a thrombus. However, possible treatments for thrombosis after imaging are not discussed by the authors of this study. Future studies could, therefore, focus on theranostic capabilities, safety, and efficacy of fucoidan-MBs as well as the possibility of incorporation of anti-thrombotic drugs into the system.

A thrombus is also usually associated with an elevated level of H_2O_2. H_2O_2 is an important signaling messenger regulating the activity of signaling proteins, enzymes, and ion channels. Upregulation of H_2O_2 may bring harmful oxidative damage, leading to apoptosis and tissue damage.[161] Inspired by these phenomena, fibrin-targeted imaging and antithrombotic nanomedicine (FTIAN) have been constructed for thrombosis theranostics (see Figure 9a).[165] With a diameter of 160 nm, FTIAN has been prepared from self-assembly of IR820 NIR fluorescent dye-conjugated boronate antioxidant polymers (fBAP) and lipopeptides (lipid-PEG-CREKA) composed of 1,2-distearoyl-*sn*-glycero-3-phosphoethanolamine (DSPE), PEG, and a pentapeptide, CREKA (Cys-Arg-Glu-Lys-Ala). High levels of H_2O_2 in a thrombus oxidizes boronate in FTIAN and stimulates subsequent release of HBA from fBAP,[165] initiating antioxidant and anti-inflammation activities.[171] On the other hand, the high affinity of CREKA in the lipopeptide toward fibrin facilitates the specific targeting of fibrin on the obstructive thrombus using FTIAN. With the use of IR820 as an NIR fluorophore and photoabsorber, the fluorescence/photoacoustic imaging of thrombi has also significantly enhanced by 5-fold. Most importantly, the intrinsic antithrombotic activity of FTIAN has suppressed thrombus formation (required a dose of 24 μg/kg of tirofiban only as compared to a clinically used dose of 80 μg/kg).[165]

Another thrombus-specific theranostic (T-FBM) NP has been developed with a mean diameter of 260 nm (see Figure 9b).[171] T-FBM NPs are composed of a lipopeptide, GPRPPC-PEG-DSPE (distearoylphosphatidylethanolamine). The pentapeptide, GPRPPC, is used to target the thrombus since it has a high affinity to fibrin as well. PEG (3.4 k) serves as a surface corona which may prevent nonspecific interaction of T-FBM NPs with plasma proteins. The ultrasound/photoacoustic contrast of T-FBM NPs has been significantly enhanced (by 5-fold) when triggered with H_2O_2. This is because H_2O_2 generates CO_2 bubbles to amplify the photoacoustic signal. These NPs are also suitable to be used as an anti-thrombotic nanomedicine, since the NPs can release antioxidant and anti-inflammatory HBA under oxidative stress-related conditions. Based on the findings, there is an obvious suppression of the

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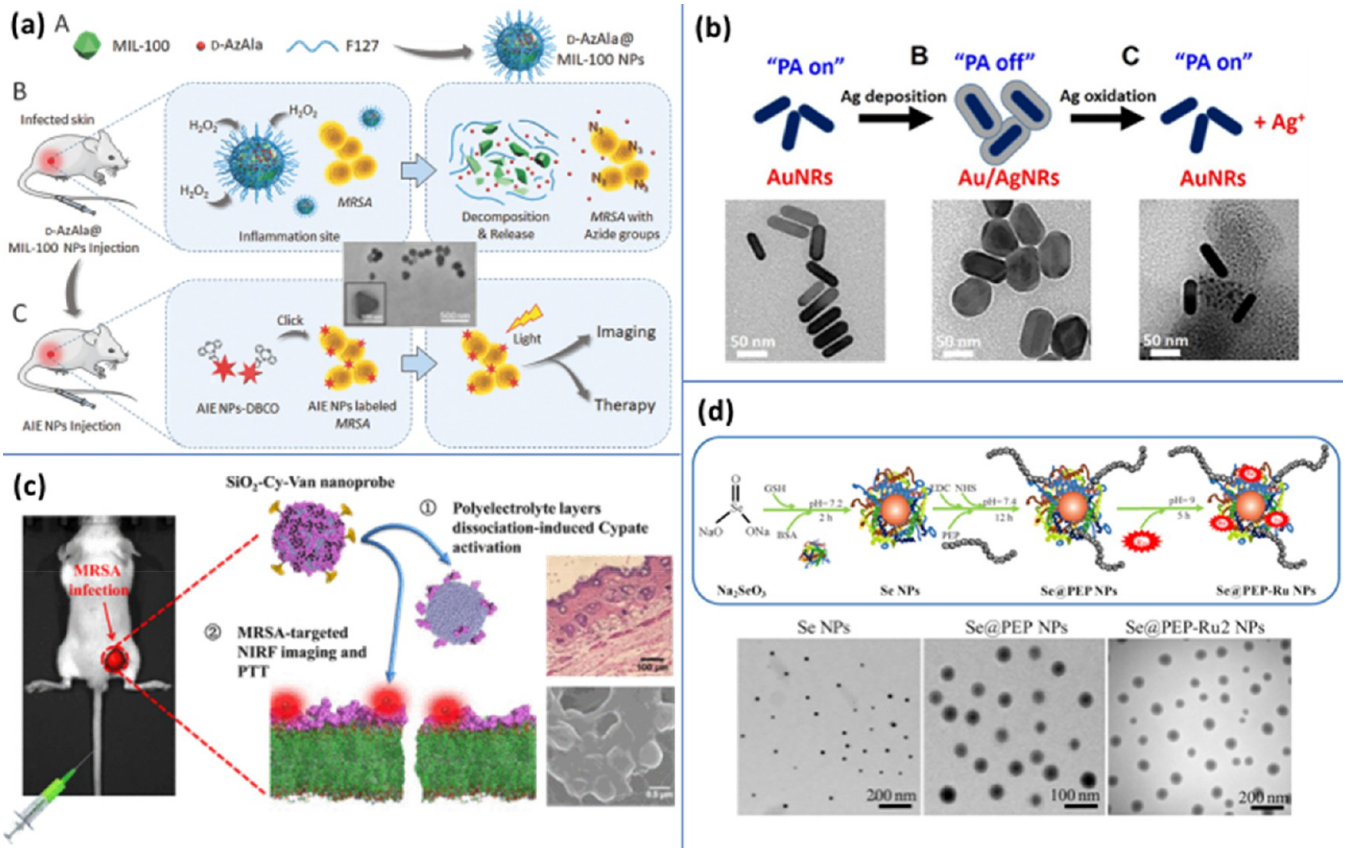

Figure 10. Brief overview of the nanomaterials used for bacterial infections theranostics with their TEM images. (a) H_2O_2-responsive MOFs assisted *in vivo* metabolic labeling of bacteria and precise antibacterial therapy. Adapted with permission from ref 181. Copyright 2018 John Wiley and Sons. (b) Formation of Au/AgNRs hybrid NPs by Ag coating on AuNRs. The addition of ferricyanide solution results in oxidative etching of the Ag shell. Adapted with permission from ref 187. Copyright 2018 American Chemical Society. (c) SiO_2-Cy-Van as a theranostic nanoprobe against MRSA infections. Adapted with permission from ref 183. Copyright 2017 American Chemical Society. (d) Fabrication of Se@PEP-Ru NPs for identification of bacterial infection with simultaneous targeted antibacterial activity. Adapted with permission from ref 178. Copyright 2017 Elsevier.

thrombus formation in the studied mouse models. However, for most of the works described in this section, the researchers did not report the dose, pharmacokinetics, side effects, and toxicology of the NPs used. In fact, the biocompatibility and biodegradability of the NPs are equally important in future clinical applications. Also, unlike a nonmotile solid tumor, thrombi ultrasound imaging analysis is often challenged by poor contrast resulting from the interference of motion artifact caused by respiratory and cardiac activities.[174]

BACTERIAL INFECTION

Bacterial infection is one of the world's leading causes of premature deaths and mortalities. Current methodologies for diagnosis and therapy of bacterial infection are often hindered by a difficult bacteria isolation and early detection, low numbers of bacteria in the clinical specimen, false negatives, and contamination of the specimen.[1] Poor sensitivity and late diagnosis often delay the therapy and thus increase the cost and discomfort to the patients. The development of drug resistance in the bacterial pathogen and the overuse of antibiotics are also concerns in bacterial infection management. This section will discuss different nanomaterials with their potential in bacteria nanotheranostics and provides a critical review on their advantages and limitations.

The work on both *in vitro* and *in vivo* multimodal mapping and targeted PTT against bacterial infection of gastrointestinal tract was introduced in 2015, with the use of tungsten-based theranostic agents.[175] Since then, different nanoprobes capable of selectively imaging bacteria with high antimicrobial properties have been proposed. Selenium (Se) is a semimetallic element with low electronegativity and large atomic radius compared with sulfur, endowing Se-containing compounds with high reactivity and sensitivity.[176] Moreover, the stimulus-responsive property of Se gives the materials a big potential in construction of smart and sensitive theranostic systems responding to biomolecules.[176] Ruthenium (Ru) is a rare metal in the earth's crust with diverse biomedical and antimicrobial applications, especially in its complex form.[177] For instance, Ru complexes have been found to display synergistic antimicrobial activity with antibacterial peptide UBI29-41 (PEP)-modified Se particles (see Figure 10d).[178] This multifunctional theranostic nanoplatform, or known as Se@PEP-Ru NPs, displayed good biocompatibility, excellent selectivity, and potent antimicrobial activity. The NPs strongly interact with both Gram-positive and Gram-negative bacteria cell membranes, followed by severely damaging the structures of the bacterial cell and cytoplasmic membranes. The wound sizes of the mice treated with Se@PEP-Ru NPs were found to decrease by about 40% on the fourth day after surgery, showing a significant therapeutic effect. Since Se@PEP-Ru NPs are sensitive to sites of bacterial infection, they were found to be able to identify and distinguish bacterial infection from

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inflammation and tumor-induced tissue infection with high specificity.[178] Evident fluorescence can be observed (after 4−48 h of injection) at the site of the bacterial infection, but the fluorescence was almost negligible (2−3 times weaker) at the site of inflammation. Future studies can be focused on engineering the as-synthesized Se@PEP-Ru NPs (with a size of about 78 nm) into a smaller size, as the size and surface area of NPs could affect the antibacterial activity.[179] Smaller NPs (<10 nm) are generally more effective since they allow favorable surface area of NPs for interaction with the bacterial cell membrane and disruption of bacterial permeability and respiration.[180]

Metabolic biomolecular labeling is an emerging technology to modify the surface of cells and pathogens with chemical functional groups, which in turn allows conjugation of fluorescent dyes (for imaging purpose) or drugs (for therapeutic effect) onto cell membranes.[181] Metal−organic frameworks (MOFs) can be engineered as drug nanocarriers, thanks to their versatile chemical properties, good biocompatibility, sensitivity to low pH tumor environment, and fast body clearance after drug delivery. A bacteria theranostic strategy through coupling of MOFs with metabolic labeling technique has been reported recently (see Figure 10a).[181] Mao *et al.* (2018)[181] innovatively used MIL-100 (Fe) NPs (with an average diameter of 120 nm) as the nanocarriers for metabolic labeling molecule and 3-azido-D-alanine (D-AzAla), to target bacterial cells. The NPs are stabilized by polymer pluronic F-127. The high H_2O_2 inflammatory environment stimulates degradation and rapid release of D-AzAla from MIL-100 (Fe) at the inflammation sites. Upon internalization of D-AzAla by the bacteria, unnatural azide groups will be expressed on the bacterial cell walls. Ultrasmall photosensitizer NPs with around 10 nm, named dibenzocyclooctyne (DBCO)-modified 2-(1-(5-(4-(1,2,2-tris(4-methoxyphenyl)vinyl)phenyl)thiophen-2-yl)-ethylidene)malononitrile NPs (US-TPETM NPs), with aggregation-induced emission characteristics are subsequently administered. DBCO groups on the surface of NPs will bind and react with the bacteria through *in vivo* click chemistry. The bacterial cell walls will be lightened up to produce fluorescence signals for imaging, facilitating subsequent image-guided antibacterial therapy and PDT.[181] This breakthrough in *in vivo* incorporation of unnatural functional group into bacteria for metabolic labeling and antibacterial therapy could soon enable the discovery of more effective bacterial theranostic approaches.

Luminescent porous silicon (LuPSi) has tunable porosity and surface chemistry and good biocompatibility and degradability, making it suitable as an optical biosensor for bioimaging and drug delivery. LuPSi can be loaded with the antibiotic ciprofloxacin (CIP) to form CIP-LuPSi for theranostic application.[182] For wound care application, a smart bandage composed of polyurethane (PU) membrane and CS film has been presented by Chen *et al.* (2017) for monitoring and inhibition of wound infection.[182] A high level of ROS and elevated pH (above 7.4, normal skin pH = 5.5−6) are two main biomarkers in chronic or infected wounds.[182] The luminescent property of LuPSi is correlated with its surface chemistry. The blue luminescence of CIP was quenched by red LuPSi due to the fluorescence resonance energy transfer (FRET) effect. When the smart bandage is applied onto the infected wound that was usually associated with an elevated level of ROS and alkaline ions (such as PO_4^{3-} or OH^-), the surface of LuPSi was oxidized into an insulating oxide layer that blocked the energy transfer between LuPSi and CIP. As a result, the fluorescence of CIP recovered (from red to blue) and can be observed by naked eyes and a cell phone camera. Therefore, by detecting the ratiometric fluorescence intensity, the kinetic process of surface oxidation of CIP-LuPSi can be precisely measured. The oxidation of LuPSi also simultaneously triggers the release of CIP to inhibit bacterial activity. In the same year, Zhao *et al.* (2017) developed silica NPs coated with vancomycin-modified polyelectrolyte-cypate complexes (SiO_2-Cy-Van), with a size of about 72.7 nm, as a bacteria-activable theranostic nanoprobe (see Figure 10c).[183] The polyelectrolyte acts as an adsorbate or dissociation energy barrier on silica NPs, conferring the NPs with bacteria-responsive feature, as well as enhanced biocompatibility and relatively prolonged blood circulation. The cell wall of methicillin-resistant *Staphylococcus aureus* (MRSA) bacteria is capable of forming hydrogen bonding with vancomycin (Van) on the nanoprobes. The interaction between Van and MRSA detaches the layer-by-layer assembled polyelectrolytes from silica NPs, changing the state of cypate (Cy), a dye with NIR fluorescence emission at around 825 nm, from OFF (aggregation) to ON (disaggregation). This leads to rapid MRSA-activated NIR imaging (4 h post-injection, high sensitivity up to 10^5 colony-forming units) and effective PTT upon 808 nm laser irradiation.[183] However, the possibility of autofluorescence and influences of bacterial environment on the sensitivity and selectivity of the nanoprobes are not clearly demonstrated. On the other hand, the idea of bacteria-responsive intelligent wound dressing proposed by Zhou *et al.* (2018)[184] has also offered a different perspective in the fabrication of nanomaterials to combat bacterial infection. The group constructed a biocompatible UV-photo-cross-linkable methacrylated gelatin (GelMA) encapsulating both antimicrobials and self-quenching dye carboxyfluorescein vesicles. The working principle is that upon bacterial infection, toxins, or enzymatic factors secreted from bacteria could break down the lipid vesicles and release the payloads. This eventually leads to bacterial inhibition in addition to a visual color change (due to the fluorescence recovery of carboxyfluorescein). Supported by both *in vitro* and *in vivo* studies, the release of antimicrobials occurs only when pathogenic bacteria (specifically MRSA and *Pseudomonas aeruginosa*) exist.[184]

Gold nanomaterials are antibiotic agents owing to their tunable size, facile functionalization, and minimal toxicity. It is interesting that recently, gold nanoclusters (AuNCs) have been demonstrated to exhibit antibacterial activity,[185] especially by manipulating their surface ligand chemistry.[186] Quaternary ammonium (QA) capped AuNCs (QA-AuNCs), with a size of about 2 nm, can selectively target MRSA and Van-resistant *Enterococci* (VRE), *in vivo*.[185] Since QA-AuNCs can disrupt the bacterial cell membrane (in terms of integrity, permeability and inner potential), catalyze the generation of ROS, and disturb the intracellular metabolic pathway of the bacteria, QA-AuNCs displayed excellent therapeutic effects. The intensely fluorescent QA-AuNCs interact with live/dead bacteria differently, suggesting their potential for image-guided bacteria discrimination and counting. QA-AuNCs are also stable for long-term storage, even at room temperature.[185] On the other hand, it should be noted that it is difficult to compare the antibacterial performances of different nanomaterials, since the composite design and concentration of each multifunctional nanomaterial used can be very different, unless more

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Table 2. A Summary of Functional Theranostic Nanomaterials Translated into Clinical Studies

Cancer/Disease/ Illness	Type of nanomaterial/ Composition	Physiochemical properties	Therapeutic/ Imaging modality	Clinical trial phase/Status	Ref.
Solid tumors	Ruthenium NPs (NKP-1339)	Targeting of GRP78 (key regulator of misfolded protein processing); mean half-life: 113 hours; mean total clearance (CLtotal): 164 mL/hour	Targeting & therapy	Phase I completed (2012)	209
	Gold nanospheres, bounded to PEG-THIOL & recombinant human tumor necrosis factor alpha (rhTNF)	Size: 27 nm; liquid, intravenous injection; net negative surface charge	Targeting & immunostimulant therapy	Phase I completed (2012)	210,211
	Polymeric NPs, containing cyclodextrin-based polymer, small interfering RNA (siRNA), human transferrin protein (hTf) targeting ligand & hydrophilic PEG (CALAA-01)	Size: 70 nm; liquid, intravenous injection; siRNA is not chemically modified; 1:1 charge ratio of positive charged polymer to negatively charge nucleic acid; endosomal disruption & siRNA release into the cytoplasm of target cells due to imidazole residues	Targeting & therapy (RNAi)	Phase I terminated (2012), progressive disease was observed	207,212
Advanced solid tumors	Colloidal gold NPs, bounded with recombinant human tumor necrosis factor alpha (rhTNF) & thiolyated PEG (CYT-6091)	Size: 7-20 nm; intra-tumour injection; well-tolerated doses at 50-600 μg/m^2; 85 % complete remission rates	Targeting, immunotherapy & imaging	Phase I completed (2009)	210,213
Breast cancer	Liposome NPs encapsulating DOX & trastuzumab (for targeting of HER2 receptor protein) (MM-302)	Size: 100 nm; enhanced antitumor activity, activation of p53 protein levels phosphorylation/activation; decreased intracellular signaling (p-Akt); increased DNA damage signaling	Targeting & therapy	Phase II/III terminated (2017) (does not show benefit over control & confirmed *via* futility analysis)	214
	CdS/ZnS core-shell quantum dots, carboxylic acid-functionalized, coated with veldoreotide (VELD)	Size: 1-10 nm; conjugation with VELD at pH 7; somatostatin receptors (SSTR) agonist with anti-cancer activity; in the form of topical cream	Imaging & therapy	Phase I recruiting (estimated completion year 2022)	215
Squamous cell cancer of the head & neck	Manganese oxide (GC4419)	Intravenous injection; about 2 hours half-life with minimal accumulation upon repeated dosing	Targeting & therapy	Phase I completed (2015)	216
Head and neck melanoma, breast cancer, colorectal cancer	Silica NPs (cRGDY-PEG-Cy5.5-C dots)	Size: 6-7 nm; superior brightness; enhanced tumor tissue retention with low background signal; portable & real-time optical detection of nodal metastases	Tracking & imaging	Phase II ongoing (estimated completion year 2020)	79
Head and neck cancer	Ultrasuperparamagnetic nanoparticle iron oxide (Ferumoxytol)	Size: 17-31 nm; 3D quantitative tumor characterization	Targeting & imaging (MRI)	Phase I completed (2019)	217

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Table 2. continued

Cancer/Disease/ Illness	Type of nanomaterial/ Composition	Physiochemical properties	Therapeutic/ Imaging modality	Clinical trial phase/Status	Ref.
Atherosclerosis	Gold NPs coated on silica/iron oxide shells	Size: 90–150 nm; stenting & micro-infusion of stem cells bearing NPs into the lesion	Targeting & therapy (plasmonic photothermal & stem cell therapy)	Phase I completed (2016)	[218]
Myocardial infarction	Ultrasuperparamagnetic nanoparticle iron oxide (Ferumoxytol)	Size: 17-31 nm; 4-6 times enhanced phagocytosis; higher uptake by cells due to cardiac inflammation; possible visualization of heart muscle damage area	Targeting & imaging	N/A Completed (2012)	[219]
Type 1 diabetes	Gold NPs coupled with proinsulin peptide (C19-A3 GNP)	Size: 5 nm; intradermal delivery by microneedles; negatively charged (-40 to -60 mV)	Targeting & therapy	Phase I ongoing (2016)	[220]
	Ultra superparamagnetic nanoparticle iron oxide (Ferumoxtran-10), dextran-coated	Size: 30 nm; monocrystalline; with long-circulating properties; real time visualization of inflammatory lesions *in vivo*	Targeting & imaging	N/A completed (2009)	[221]
Brain metastases	Gd NPs (AGuIX)	Size: 4.5 nm; can be used in combination with fractionated stereotactic radiation in oligo brain metastases	Targeting & imaging (MRI)	Phase I recruiting (estimated completion year 2020)	[222]
Gliosarcoma	Spherical gold NPs carrying nucleic acids & drugs (NU-0129)	Size: 13 nm; can cross the blood-brain barrier; targeting of Bcl2L12 gene to stop cancer cells from growing	Targeting & therapy	Phase I ongoing (2017)	[223]
Transthyretin-mediated (hATTR) amyloidosis	Lipid NPs Patisiran (ALN-TTR02)	Size: 60-100 nm; liquid, intravenous injection; prevented the deterioration of left ventricular global longitudinal strain over 18 months	Targeting & therapy (gene silencing)	Phase III completed (2017)	[224]
Thyroid cancer	Lymphotrophic superparamagnetic NPs loaded with drug (Ferumoxytol)	Size: 30 nm; intravenous injection (lyophilized iron oxide injected dose: 2.6 mg per kg of body weight); imaging with high sensitivity & specificity in detecting small lymph nodes (even 2 nm)	Imaging (MRI) & therapy	N/A completed (2015)	[225,226]

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Table 2. continued

Cancer/Disease/ Illness	Type of nanomaterial/ Composition	Physiochemical properties	Therapeutic/ Imaging modality	Clinical trial phase/Status	Ref.
Prostate cancer	Hafnium oxide NPs (NBTXR3)	Size: 50 nm; liquid, intra-tumoral injection; non-pyrogen, sterile; white aqueous dispersion; negative surface charge; stable in aqueous solution at pH 6-8; able to deposit high energy within tumors; chemically inert in cellular & subcellular systems; therapy activated by intensity modulated radiotherapy	Targeting & therapy (radiotherapy)	Phase I & II ongoing (estimated completion year 2020)	[227]
	Silica NPs (^{64}Cu-NOTA-PSMAi-PEG-Cy5.5-C' dots)	Size: sub-8 nm; intravenous injection; targeting of prostate-specific membrane antigen (PSMA); specific uptake at prostate specific (PC-3) cells	Targeting & imaging (PET/MRI)	Phase I ongoing (estimated completion year 2021)	[228]
	Magnetic iron oxide NPs, conjugated with dual peptides targeting luteinizing hormone-releasing hormone receptor (LHRH-R) & urokinase-type plasminogen activator receptor (uPAR)	Size: 15.74 nm; surface charge: −58.06 ± 1.72 mV; preferential binding & accumulation in PC-3 cells; 2 times enhanced cytotoxicity; 10 times lesser dose required; possess double-receptor targeting and imaging capability	Targeting & imaging (MRI)	Phase I completed (2015)	[104]
Cervical cancer	Ultrasuperparamagnetic nanoparticle iron oxide (Ferumoxtran-10)	Size: 30 nm; intravenous injection; increased MRI sensitivity to detect lymph nodes metastasis	Targeting & imaging	N/A completed (2019)	[229]
	Gd NPs (AGuIX), grafted with additional DOTA chelates, complexation of bismuth	Size: 4.5 nm; improved longitudinal relaxivity (4.87 s^{-1} mM^{-1} & r_2/r_1 of 1.46); a contrast of 4.26 Hounsfield unit mM^{-1} (close to those of clinically used CT contrast agents)	Theranostic agent (imaging, targeting & therapy)	Phase I ongoing (2019)	[88]
Multiple sclerosis	Ultra superparamagnetic nanoparticle iron oxide (Ferumoxytol)	Size: 17-31 nm; intravenous injection; contrast agent for brain MRI; ultrahigh-field MRI & phase contrast; highly sensitive	Targeting & imaging (MRI)	Phase I completed (2019)	[230]
Pancreatic cancer	Ultrasuperparamagnetic nanoparticle iron oxide (Ferumoxytol)	Size: 17-31 nm; targeting of bombesin receptors; relaxivity: 70 $mM^{-1}s^{-1}$; identification of small/undetectable lymph nodes metastasis	Targeting & imaging (MRI)	Phase IV completed (2012)	[231]

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Table 2. continued

Cancer/Disease/ Illness	Type of nanomaterial/ Composition	Physiochemical properties	Therapeutic/ Imaging modality	Clinical trial phase/Status	Ref.
Non-small cell lung cancer	Polymeric NPs, with a hydrophobic polylactic acid polymeric core, encapsulating DOX & hydrophilic PEG corona decorated with small molecule prostate-specific membrane antigen (PSMA) targeting ligands (BIND-014)	Size: 100 nm; biocompatible; demonstrated dose linear pharmacokinetic profile; prolonged persistence	Targeting & therapy	Phase II completed (2016)	232
Relapsed or refractory B cell malignancies	Polyethylenimine NPs, comprised of small interfering RNA–mediated suppression of hypusinated eukaryotic translation initiation factor 5A (eIF5A) & plasmid-based overexpression of a non-hypusinable eIF5A mutant (SNS01-T)	Size: 72 nm; rod-shaped; polydispersity index: 0.197; positive surface charge; inhibits tumor progression in a number of B-cell malignancies	Targeting & therapy (RNAi)	Phase I/II recruitment status (2014)	233
Relapsed or refractory leukemia	Lipid NP, composed of cationic DOTIM/cholesterol liposomes & plasmid DNA (JVRS-100)	Size: >100 nm; liquid, intramuscular injection; cationic; with immunostimulatory properties; enhanced humoral & cell-mediated immune responses	Targeting & immunotherapy	Phase I completed (2017)	234
Parkinson's disease	Gold nanocrystals, modified with montmorillonite	Single crystallized in the face centred cubic lattice; with a preferential growth direction along the (111) plane; specific surface: 327–579 m^2/g; large specific pore volumes ~0.7 cm^3/g; pore diameters: 0–10 nm; synthesized propargylamines with 82–94 % yield & 100 % selectivity	Therapy & diagnosis	Phase II ongoing (estimated completion year 2020)	235
Central venous catheter related infections	Impregnated with silver NPs (AgTive)	Size: 50 nm; 10^{-9} mol/l required for bactericidal activity; concentration of 0.8 % in an active surface of 450 cm^2/g polyurethane	Targeting & therapy	Phase IV completed (2008)	236,237

comparable studies are conducted under standard experiment conditions.

Gold nanorods (AuNRs) are an excellent contrast agent for PA imaging and have a characteristic strong NIR absorption. Kim *et al.* (2018) have developed a gold/silver hybrid NPs, named as Au/AgNRs, as theranostic antibacterial/photoacoustic agents (see Figure 10b).[187] Au/AgNRs (with a diameter of 104.9 nm) are formed by coating AuNRs with silver (Ag) to decrease the photoacoustic signal.[187] Oxidative etching of the Ag shell induced by the addition of ferricyanide solution (1 mM) could recover the photoacoustic contrast as the Ag is released. The release of Ag also effectively triggers and monitors the release of Ag^+ ions (a well-known antibacterial agent) from its reservoir AgNPs. Ag^+ ions exhibit strong bactericidal efficacy toward both MRSA (32 μM Ag^+) and *Escherichia coli* (8 μM Ag^+). The photoacoustic signal increased by 730% pre- and post-etching, and the bacterial counts in infected tissues were reduced by 1000-fold (log CFU/g = 4.15 *vs* 7.75) in the treated group.[187] This is the only report that quantitates Ag release *in vivo* and correlates the released dose to antibacterial outcomes.

Hydrogels are the 3D water-swollen polymer networks composed of hydrophilic polymers. They can be used as a scaffold for local bacterial drug delivery since it can achieve a long retention at the focal area with low unwanted diffusion.[188] A NIR light-triggerable and thermosensitive hydrogel that can combat bacterial infection and promote wound healing has been introduced recently.[188] This injectable hydrogel is

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composed of ciprofloxacin (Cip)-loaded polydopamine NPs (PDA NPs) and glycol chitosan (GC). The aromatic rings on the surface of PDA NPs enable the adsorption of drugs *via* $\pi-\pi$ stacking and hydrogen bonding, while the quinone groups on the surface of PDA NPs allow facile conjugation with the chemicals containing thiol or amine groups. GC is rich in amine and, therefore, has been used to cross-link with PDA NPs. With a uniform size of about 30 nm, PDA NPs also possess an excellent photothermal effect (the ability to convert NIR light into heat) and are biocompatible and biodegradable. The positive charge of GC and the adsorbability of PDA NPs are able to trap bacteria on the surface of the hydrogel with minimal leakage under physiological conditions. Once irradiated with NIR light, Cip antibiotic will be released. Meanwhile, PDA NPs in the hydrogel will be activated and subsequently generate local heat to kill the bacteria, with a bactericidal efficacy up to 98.9%.[188]

Despite its efficacy, inorganic NPs as antibacterial agents are constrained by their nonspecific biological toxicity or potential long-term *in vivo* retention. Applications of metal-free antibacterial agents such as polymers are still facing limitations, including poor biocompatibility, complicated synthetic steps, limited structural tunability, and/or the need for suitable carriers to ensure the spatial stabilization at the injection site. Generally, it is difficult to compare different nanomaterials from the aspects of their photothermal conversion efficiency or bactericidal performances.

CLINICAL TRANSLATION OF THERANOSTIC NANOMATERIALS

While we focus here on nanotheranostics of different diseases (see Table 2), theranostic nanomaterials in human clinical trials are still in their infancy when compared to NP predecessors, which focuses only on either imaging, diagnostics, or therapy. There are numerous review articles on NPs for single functions that are in clinical trials.[190−194] An all-in treatment (comprising of imaging, diagnosis, and therapy) is lucrative, however, years of clinical trials are required in order to gain patients' confidence.

Based on our extensive search, only one NP qualifies as a theranostic agent: gadolinium nanoparticles (GdNPs), under the name of (AGuIX) where imaging, targeting, and therapy were incorporated into a single system.[88] GdNPs in the AGuIX function as a radiosensitizer. GdNPs improve tumor-targeting and diagnosis of HCC using external beam radiotherapy.[195] Conjugation of cisplatin and polysiloxane on the GdNPs allows therapy and passive tumor-targeting, respectively. Functionalization of AGuIX NPs with a chelator of radiometal (^{64}Cu or ^{68}Ga), NIR heptamethine cyanine dye, and a bioconjugatable handle also form a trifunctional (PET, MRI and optical) imaging probe with fast tumor accumulation and renal clearance.[196] AGuIX demonstrated an enhanced MRI contrast than other FDA-approved Gd chelates and is currently under Phase Ib clinical trials and estimated to be completed in April 2021.[197]

Another close relative is NBTXR3, a hafnium oxide radioenhancer, which has been used in various types of cancer patients and is currently in Phase II−III clinical trials. There are also various NPs in clinical trials that have successfully incorporated dual functions: either as imaging and targeting or imaging and therapeutic agent. Magnetic NPs have been used for anemic patients as therapy and recently developed as an MRI-contrast agent. Some commercially known brands (such as Ferumoxtran and Ferumoxytol) are ultrasmall SPION NPs coated with either a dextran or synthetic carbohydrate shell. SPION NPs were initially tested clinically on various types of cancer (such as head, neck, prostate, and cervical cancer) by differentiating cancerous and noncancerous lymph nodes with the aid of an MRI.[104,198] Recently, SPION NPs have been used in the diagnosis of multiple sclerosis and myocardial infarction diseases (see Table 2). Some Phase I clinical trials have been completed, and a few studies have even advanced to Phase IV.[199,200]

Similarly, AuNPs have been translated into clinical trials since year 2008 and have been used for thermal ablation of tumors.[191,192] However, to the best of our knowledge, AuNPs have advanced to only Phase I clinical trials due to the limitation in penetration depth of laser light during PTT and their application *in vivo*.[17,201,202] The use of a fiber optic NIR laser for deeper laser penetration into tumors or a synergistic PTT and other therapies (or surgery) are some of the possible alternatives to the use of nanomaterials for PTT.[17]

Another addition to clinical trials is the Cornell or C dots which are inorganic protein-coated-fluorescent-silica NPs with potential in theranostics of melanoma.[203] C dots allow real-time preoperative and intraoperative sentinel lymph node (SLN) tissue localization and retention using a hand-held fluorescent camera.[79] Although complete lymph node dissection for patients who had SLN biopsy was deemed inappropriate as a form of treatment after 2017,[113] the C dots are still believed to possess therapeutic effects by reduction in the size of tumor and are currently under further investigation.[203] Phase III trials of both concurrent triplet combination therapy (vemurafenib, cobimetinib, and atezolizumab) and sequential combination therapy (vemurafenib and cobimetinib alone) in advanced melanoma patients are ongoing.[204] The results of the trials would allow a better understanding of the safety and efficacy of targeted therapy and immunotherapy combinations.

Most of the targeted theranostic probes for ovarian cancer are still in various phases of clinical trials and have yet to be approved by the FDA.[205] For the triple-negative breast cancer, only paclitaxel and irinotecan loaded liposomes, also known as EndoTAG-1 and MM-398, have proceeded through clinical studies.[206] A Phase III trial of EndoTAG-1 in combination with gemcitabine is currently ongoing in patients with pancreatic cancer. Recently, a Phase I study to understand the biodistribution of MM-398 and the feasibility of using ferumoxytol as a solid tumor and brain cancer imaging agent has been completed.

Nanomaterials such as carbon nanotubes and graphene are not yet approved for clinical trials as wearable sensors and implantable devices, which aid in clinical interventions and treatments of various diseases.[108] Primary challenges including human health risks (biocompatibility, biological toxicity), environmental impact, selectivity for biomarkers detection, long-term stability should be addressed before clinically approved graphene and its derivatives move forward.

There are various clinical trials that have been terminated due to numerous reasons such as inadequate enrollment, variations in the clinical findings, and no improvements compared to controls/placebos. For example, CALAA-01, a targeted nanocomplex that contains antiribonucleotide reductase small interfering RNA (siRNA) has been terminated after Phase I. Despite showing a potential in solid tumors, the nature

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and complexity of CALAA-01 raised several concerns (possible immunostimulation, coagulopathic effects, kidney toxicity, off-target deposition, hepatotoxicity), therefore hindering its clinical translation.[207]

One of the flaws in clinical trials is the disconnection between mice and human models.[202] Nanomaterials showing positive theranostic results in *in vitro* and *in vivo* settings do not grant their applicability in clinical trials, mainly due to a combination of multiple complex bionano interactions in the body.[68,208] Research on nanotheranostic nanomaterials is rapidly advancing to incorporate biocompatibility, specific targeting, advanced imaging and diagnosis as well as localized drug delivery in the human body.[12,17,23,56,138] An increase in knowledge of physiochemical properties of nanomaterials coupled with the design of multifunctional theranostic platform and microenvironment-priming approaches is likely to radically expedite clinical approval of more nanotheranostic nanomaterials and bring them to clinical applications.

CONCLUSION AND FUTURE PERSPECTIVE

Nanotheranostics refers to the use of nanomaterials capable of providing concurrent diagnostics and therapeutics at the disease sites. In this review, we have discussed the key properties of different nanomaterials, and how these nanomaterials are designed and tuned to meet the selectivity and specificity of the target disease. The specific properties of the nanomaterials in terms of feasibility and drawbacks and their potential applications in nanotheranostics were presented.

Both solid and liquid cancerous tumors are different in regard to their tumor vascularity and heterogeneity, which require different diagnostic treatment and targeting strategies. Au nanostructures are biocompatible and permit facile surface functionalization for wide biological applications. In addition, Au nanostructures serve as a good photothermal transducer. Conjugation of a photosensitizer on the Au-based nanoplatform could generate high singlet oxygen and activate PDT. Most of the nanomaterials presented here are stimuli-responsive and able to kick-start the sequential theranostic effects and release the chemotherapeutic drugs only when reaching tumor sites. If the potential side effects of each drug are well-understood, future studies can be expected on the co-delivery of drug combinations in a single platform for broader pharmacological applications.

Inorganic nanomaterials are relatively stable over large ranges of pH and temperature, yet, concerns are raised over their low biodegradation and biosafety issues. Modification of different molecules (targeting and imaging contrast agents and drugs) on the surface of the inorganic nanomaterials permits diverse applications of the nanomaterials. However, the characterization and fairly weak fundamental understanding of the structure−function correlations often restrict the predictive functions in nanotheranostics. Polymeric and lipid NPs are usually used as nanovehicles for delivering therapeutics and diagnostics agents to the tumor sites, thanks to their biocompatibility and biostability features. Generally, the poor spatial resolution, shallow tissue penetration, and relatively low quantum yield are some of the challenges of NIR-emissive polymeric NPs in theranostics. Since each drug varies in surface area and solubility, their loading mechanism into lipid NPs sometimes remains challenging. Knowledge of the drug loading mechanism allows optimal formulation of the nanocarrier system with theranostic properties and minimal limitations or potential side effects.

As one of the most interesting and versatile materials, graphene and its derivatives offer a relatively simple but highly integrated and multifunctional nanotheranostic platform for biomedical applications. Nevertheless, more systemic investigations are required to better understand its behavior, biodegradability, and toxicological profiles in complex biological environment.

Concerning nanotheranostic applications in liquid tumors, research is still in its infancy compared to solid tumors. Most of the approaches done thus far are directed to the diagnosis and treatment of blood cancers, such as lymphoma and leukemia. It is surprising to note that although the physicochemical scenario of blood cancers is different than solid tumors, the same types of nanomaterials are being used. This can be clearly observed in the use of metal NPs for thermal ablation in both solid and liquid tumors. In solid tumors, the nanomaterial is anchored to the surface of the tumor, leading to an effective and non-invasive ablation, whereas in liquid tumors, the target element is in constant circulation and can lead to ablation of adjacent tissue. The same phenomenon is observed with the use of polymeric and lipid NPs as drug delivery systems in both solid and liquid tumors, where the different requirements are not clear in terms of blood−brain barrier penetration, stability, and renal clearance. This question needs to be solved and more work should be carried out in order to push nanotheranostics for *in vivo* applications in circulating tumors.

For neurodegenerative diseases, all the nanotheranostic strategies have been applied for the diagnosis and treatment of AD, and interestingly the selection of the nanomaterial is based on the therapeutic strategy (inhibition of Aβ aggregation and Cu^{2+} ions chelation). In both cases, fluorescence imaging modality is selected as a cost-effective and simple alternative to MRI and PET. Moreover, both therapy strategies have proven to be effective in *in vivo* therapy of AD, although it would be important to develop them also for the other neurodegenerative diseases.

The NPs used for the theranostics of autoimmune diseases can be colloidal-based or organic-based. The nanomaterials are mostly designed for targeting of the scavenger receptor present on the activated macrophages. The NPs permit prolonged circulation in the bloodstream and subsequently controlled release of the therapeutic drugs at the inflammation sites. Safety concerns (biodistribution in nontargeted tissues, potential inflammation, biodegradability, biocompatibility, and clearance) are the biggest obstacle that hampers the clinical application of most of the nanomedicine of RA.

For cardiovascular diseases, the research is mainly focused on the non-invasive imaging modalities such as MRI and NIR fluorescence for detection of atherosclerotic plaque. The pursuit of therapeutic agents for atherosclerosis and its potential impact remains an open field for research. Currently, there is less information about the dose, pharmacokinetics, long-term side effects, and toxicology of the NPs employed in most of the studies. Future research should also be emphasized on more detailed biocompatibility (such as blood-half-life) and immunogenicity evaluation of the NPs as well as development toward precision drug delivery and early detection of atherosclerotic plaque.

Inorganic NPs as antibacterial agents still face drawbacks such as nonspecific biological toxicity or potential long-term *in vivo* retention. Applications of metal-free antibacterial agents are limited by poor stability and biocompatibility, complicated synthetic steps, and limited material structural tunability.

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Besides, the long-term biosafety of antibacterial nanomaterials is another big concern, as it is usually associated with possible risks including excessive or insufficient heating, undesired diffusion, and potential impact on the immune system.

Continuous and multiple pharmacological and physical approaches have been developed to overcome biological and physiological barriers of the nanomaterials in complex biological systems. The ideal size of the NPs is highly dependent on the cancer type, tumor site, and the stage of the diseases. Overall, NPs with a tunable size between 10 and 100 nm are the most favorable in the development of cancer theranostics, mainly due to enhanced cellular uptake, biodistribution, blood circulation half-life, cellular uptake, tumor penetration, and targeting at this size range.

The pH value, antioxidant levels, and enzymatic activity belong to endogenous stimuli, while light, ultrasound, and magnetic are some of the examples of external stimuli. Theranostic applicability of external stimuli-responsive nanomaterials is less dependent on tumor type or pathological properties. Such nanomaterials can be applied at the disease site in a controlled manner, but the efficacy is severally compromised in metastasized lesions. In contrast, theranostic efficacy of endogenous stimuli-sensitive nanomaterials is highly heterogeneous between different types of tumors/diseases. Moreover, staging (a process to determine if cancer has spread within the organ or to other parts of the body) is important to determine the stage of the cancer/disease. The design of nanomaterials (dose requirements, efficacy, side effects, *etc.*) must be tuned according to the pathological properties of tumors/diseases.

Safety, efficiency, and controllability are the major criteria in biomedical applications. Eco-toxicological, biosafety, and biocompatibility evaluation must be conducted for theranostic nanomaterials, taking into account factors including route of administration/exposure, biodistribution, biodegradability, long-term exposure, *etc.* The morphology, size distribution, nature of interfaces (charges and surface chemistry), and colloidal stability of the nanomaterials in different media might influence the nanotoxicity of nanomaterials. The interaction of NPs with cell organelles also requires further studies, as it plays a critical role in impacting the biogenesis and biological activities.

No theranostic nanomaterials have been approved by the FDA for commercialization to date, mainly due to significant heterogeneity in the design, synthesis, safety, and efficacy of the nanomaterials in clinical trials. The behavior of the nanomaterials in the dynamic physiological and pathological alterations *in vivo* is also not well-defined. Most of the current nanomaterials are in various phases of clinical trials, though the future perspective is brilliant. Future research should be focused on improving the clinical relevance and translational feasibility of nanomaterials for theranostic applications. The strength and limitations of each nanomaterial, particularly the potential side effects/toxicities, should be comprehensively understood upon developing them with robust efficacy and clinical benefit. Understanding of pharmacokinetic profile of nanomaterials in humans should be emphasized, along with clinical translation in appropriate animal models. After all the concerted efforts from multidisciplinary teams of chemists, pharmacists, physicists, and engineers, it is believed that nanomaterials promise revolutionary potential as theranostic agents for a variety of clinical applications and improving the quality of life of the population.

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Notes

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VOCABULARY

Nanotheranostics, development of nanomedicine approaches for advanced theranostics (combined therapeutic and imaging/diagnostic features); **nanomaterials**, materials with one or more external dimensions in the nanoscale (sizes range from about 1−100 nm); **photothermal therapy**, thermal ablation of cancer cells with the use of photoabsorbing agents that could efficiently transfer the absorbed light energy into heat, subsequently leading to cell death; **photodynamic therapy**, an externally activatable treatment with the use of photosensitizer molecules to generate cytotoxic singlet or reactive oxygen species to kill cancer cells *via* oxidative stress; **passive targeting**, delivery of nanoparticles *via* enhanced permeability and retention effect in tumor or any leaky vasculature and anatomic barrier; **active targeting**, delivery of nanoparticles to the tissue of interest based on molecular, ligand/receptor, or antibody−antigen recognition. More focused delivery with

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reduced potential side effects, toxicity and cost of drug/delivery; **graphene**, single-layered carbon atoms packed into a two-dimensional honeycomb lattice.

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