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Invited review

Nanomaterials formulations for photothermal and photodynamic therapy of cancer

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ABSTRACT

Nanomaterials with well-defined size, shape, composition, and surface functionalities offer multimodal and multifunctional platforms for various bioanalytical, bioimaging, and therapeutic applications. In this review, we focus on the different theranostic formulations of nanomaterials based on gold, silver, silica, semiconductor quantum dots, upconversion lanthanides, oxide magnets, polymers, liposomes, carbon nanotubes, graphene and carbon nanohorns, and their applications in photothermal and photodynamic therapy of cancer.

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Contents

Abbreviations: DPBF, 1,3-diphenylisobenzofuran; ADPA, 9,10-anthracenedipropionic acid; RGD, arginine–glycine–aspartic acid; CTAB, cetyltrimethyl ammonium bromide; cw, continuous wave; Cy, cyanine dyes; EGFR, epidermal growth factor receptor; GNPs, gold nanoparticles; GNRs, gold nanorods; GNS, gold nanoshells; GSNPs, gold-shelled silica nanoparticles; GO, graphene oxide; HNPs, hyaluronic acid nanoparticles; MWCNT, multi-walled carbon nanotubes; MTGNPs, multiple twinned gold nanoparticles; NPs, nanoparticles; NIR, near infra red; OCT, optical coherence tomography; PDT, photodynamic therapy; PS, photosensitizer; PTT, photothermal therapy; PAA, poly acrylic acid; PEG, poly ethylene glycol; PLA, poly lactic acid; PSGNPs, popcorn-shaped gold nanoparticles; PI, propidium iodide; QDs, quantum dots; ROI, reactive oxygen intermediates; RGO, reduced graphene oxide; AgNTs, silver nanotriangles; SWCNT, single-walled carbon nanotube; $^1O_2$, singlet oxygen; SERS, surface enhanced Raman scattering; SPR, surface plasmon resonance; SET, surface-energy transfer; $^3O_2$, triplet oxygen; UCL, upconversion luminescence.

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Norio Murase received his master degree in Chemistry from Tokyo University. Subsequently he entered into Hitachi Ltd. for the study of materials for high density optical memory, for which he obtained a PhD there in 1994. Immediately after that, he gave up the position in Hitachi, and joined in National Institute of Advanced Industrial Science and Technology (AIST). He is currently the group leader of Nanobioanalysis Research Group, Health Research Institute, AIST. Since 2010, he is also appointed as a Visiting Professor at Kwansei Gakuin University, Japan. His current research is focused on the development of silica encapsulated quantum dots.

Vasudevanpillai Biju studied chemistry at the University of Kerala and obtained his PhD in 2000. After doing postdoctoral research in AIST (2000–2002) and Nanotechnology Research Institute (2002-2003; JSPS Fellow) in Japan, he moved in Pacific Northwest National Laboratory in USA as a Postdoctoral Fellow (2003–2004). Currently, he is a Chief Scientist in Health Research Institute, AIST. In parallel, he is appointed as a PRESTO Researcher of the Japan Science and Technology Agency (JST; since October 2010), a Visiting Professor at the University of Kerala (since 2007), an Adjunct Professor at Southern University (since 2012), and a Guest Professor at the University of Tokushima (since 2012). His current research includes the development of biofunctional and photofunctional nanomaterials, single-molecule spectroscopy and microscopy, optical and magnetic properties of functional nanomaterials, and bioimaging and phototherapy. He is serving as the Associate Editor of the *J. Photochem. Photobiol. C*, Editor of *Nano Reviews*, Editorial Board Member of the *J. Bioengg. Biomed. Sci.*, and Chairman of Asian Nanoscience and Nanotechnology Association (ANNA). He has received many academic recognitions, which include the 14th Gen-nai Award by the Ozaki Foundation, Most Cited Certificate from Analytical and Bioanalytical Chemistry, Distinguished Lectureship Award by the Chemical Society of Japan (2010), Asian and Oceanian Photochemistry Award for Young Scientist (2010), Young Lectureship by the Chemical Society of Japan (2011), and the Japanese Photochemistry Association Award for Young Scientist (2011). Since 2011, he is the Fellow of the Royal Society of Chemistry (FRSC).

1. Introduction

Phototherapy is a form of medical treatment in which light is used to treat diseases such as cancers and peripheral infections to normalize the body and relieve the depression. Photothermal therapy (PTT) and photodynamic therapy (PDT) are the two kinds of phototherapy used for the treatment of diseases so far. In PTT, a photothermal (PT) agent is employed for the selective local heating for healing abnormal cells or tissues; whereas, in PDT, the treatment occurs through a series of photochemical reactions triggered by photoactivated molecules or materials called photosensitizer (PS) drugs. In recent past, nanomaterials are used in different aspects of cancer management in terms of nanomedicine. On the basis of the growing applications of nanomaterials in PDT and PPT of cancer, in this review, we mainly focus on the different formulations of nanomaterials suitable for PTT and PDT.

1.1. Photothermal therapy

Thermal treatment of cancerous cells by applying the local heating to 70 °C and general hyperthermia (heating to 41–47 °C) is known since 18th century [1]. During the local heating or hyperthermia, cells undergo irreversible damage due to the denaturation of proteins and the disruption of the cell membrane. But these thermal treatments damage the healthy tissues as well. More recently, incorporation of laser radiation treatment in thermal cancer therapy opened up a PT method for the selective treatment of cancers. As a result, laser radiation with fiber-optic waveguides finds growing applications in cancer therapy, which is called laser hyperthermia [2]. The main drawback of the laser treatment is the requirement of high-power lasers for the effective stimulation of the tumor cell death [3]. Meanwhile PTT was proposed, in which a PT agent helps the selective heating at the local environment [4]. Basic requirements of PTT are a biocompatible PT agent with large absorption coefficient in the NIR regions and an NIR light source. Thus, surface-modified nanomaterials of carbon, metals, and semiconductors with NIR absorption can be ideal PT agents. The percentage increase in the temperature during PTT strongly depends on the NIR absorption wavelength and the coefficient as well as the power of the excitation light [5]. Illumination of nanomaterials with NIR laser results in an increase in the temperature of the medium, which reaches a maximum value when the NIR absorption maximum coincides with the laser wavelength (Fig. 1).

1.2. Photodynamic therapy

The basic principle underlying PDT of cancers is a chain of photochemical reactions triggered by a photoactivated PS drug. During the irradiation of a PS drug at a suitable wavelength, it will be activated to the excited singlet (S_1) and subsequently to the triplet (T_1) state *via* intersystem crossing. The lifetime of the T_1 state is longer than that of S_1, which facilitates the extended interactions of the PS drug in the T_1 states with the surrounding molecules [6]. Two types of mechanisms, Type I and Type II, are known for

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