

Expert Opinion

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Targeting gold nanocages to cancer cells for photothermal destruction and drug delivery

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Importance of the field: Plasmonic nanoparticles provide a new route to treat cancer owing to their ability to convert light into heat effectively for photothermal destruction. Combined with the targeting mechanisms possible with nanoscale materials, this technique has the potential to enable highly targeted therapies to minimize undesirable side effects.

Areas covered in this review: This review discusses the use of gold nanocages, a new class of plasmonic nanoparticles, for photothermal applications. Gold nanocages are hollow, porous structures with compact sizes and precisely controlled plasmonic properties and surface chemistry. Also, a recent study of gold nanocages as drug-release carriers by externally controlling the opening and closing of the pores with a smart polymer whose conformation changes at a specific temperature is discussed. Release of the contents can be initiated remotely through near-infrared irradiation. Together, these topics cover the years from 2002 to 2009.

What the reader will gain: The reader will be exposed to different aspects of gold nanocages, including synthesis, surface modification, *in vitro* studies, initial *in vivo* data and perspectives on future studies.

Take home message: Gold nanocages are a promising platform for cancer therapy in terms of both photothermal destruction and drug delivery.

Keywords: drug delivery, nanomedicine, nanotechnology, photothermal therapy

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1. Introduction

The fight against cancer has proved to be a much more challenging battle than first predicted. Surgery, radiation and chemotherapy remain the most successful methods so far for cancer treatment. Despite many new insights surrounding conventional methods, there is still a great need for new treatments that can eradicate cancerous cells without causing damage to the healthy tissue. Nanomedicine is a rapidly evolving area of research that shows great promise in the fight against a complex disease such as cancer [1-4]. Although small compared with a cell, nanostructures are large enough to attach multiple functional moieties to the surface, enabling significant tuning of their properties and distributions in the body [5-7]. In general, the pharmacokinetic profile and biodistribution of nanostructures vary with particle size, shape, surface coating and the attachment of a targeting moiety, giving researchers many potential routes to optimize nanostructures for a specific biomedical application and help avoid undesired side effects [8-11].

The first generation of nanostructure-based therapies approved by the FDA consists of drug-loaded liposomes and micelles [3]. These structures encapsulate drugs inside the hollow shells and allow for extra surface coatings, both increasing

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Article highlights.

- Plasmonic nanostructures can be engineered to absorb near-infrared light for photothermal applications in cancer therapy.
- Gold nanocages represent a unique class of plasmonic nanostructures with compact sizes, hollow interiors, porous walls and easily tailored surface chemistries.
- Gold nanocages can target tumor cells *in vitro* by conjugating with antibodies through the gold-thiolate linkage.
- When gold nanocages are exposed to laser irradiation, the generated heat can significantly damage tumor cells in both *in vitro* and *in vivo* experiments.
- When coated with a smart, thermosensitive polymer, gold nanocages can also serve as drug delivery vehicles, releasing their contents in response to near-infrared irradiation.

This box summarizes key points contained in the article.

the solubility of hydrophobic drugs and extending the circulation time through minimizing the binding of serum proteins that enhance liver uptake [6]. Although a step forward in some ways, these currently approved therapies simply enable greater concentrations of drug to circulate in the bloodstream and do not allow for temporal control over release [2].

A variety of systems are being investigated to take nanostructure-based therapies to the next level [12-15]. One particularly promising area of research focuses on the unique optical properties of metal nanostructures known as localized surface plasmon resonance (LSPR). When a metal nanostructure is illuminated with light, the photons are strongly absorbed or scattered at specific resonant wavelengths [16]. The absorbed light can be transformed into heat, a process known as the photothermal effect, allowing for an increase in temperature to be triggered and managed from a distance [17]. When tissues are heated above the hyperthermia temperature (42°C), irreversible cellular damage occurs. The heat generated from the photothermal effect can be used to destroy cancer cells directly or trigger drug release. To maximize the amount of heat generated, it is important both to match the resonant wavelength of the nanostructure with the light source and to ensure that the maximum amount of radiation reaches the treatment site. Although blood and tissue absorb and scatter most incoming light over much of the optical spectrum, a transparent window exists in the near-infrared (NIR) region from 650 to 900 nm [18]. The LSPR peaks of nanostructures can be easily tuned using three different approaches: i) by elongating spherical nanoparticles into nanorods to generate tunable longitudinal modes [19-22]; ii) by coating the surfaces of dielectric colloidal spheres with polycrystalline shells of Au [23,24]; and iii) by emptying out the interiors of Au nanoparticles to form hollow nanoboxes, nanocages and nanoshells with voids in the surface [25-27]. Photothermal treatment has been applied with these new nanostructures in recent years with great success both on

the cellular level [28-30] and in animal models or *in vivo* studies [31-33]. The heat generated from the photothermal effect can also be used to activate drug release in several hybrid systems, such as heat-responsive gel matrices [34,35], microcapsules [36,37] and liposomes [38,39]. In this review, recent advances in gold nanocages for both photothermal treatment and drug delivery are discussed.

2. Gold nanocages

The authors' group has developed a new class of nanostructures known as gold nanocages that have compact sizes (typically 20 – 50 nm), straightforward and precise tuning of LSPR, and large absorption cross-sections per volume that are particularly significant for photothermal conversion [17,25,26]. These highly favorable properties of gold nanocages are achieved through the use of a simple galvanic replacement reaction between a silver template and a gold salt. In a typical reaction, an aqueous solution of HAuCl_4 is slowly titrated into a boiling suspension of silver nanocubes. Owing to the different electrochemical potentials between these two metals, the silver will give up its electrons and dissolve into the solution as ions while a thin layer of gold is being deposited on the outer surface of the cube. As the reaction continues, more and more silver from the interior of the cube will be removed through a small pit in the wall, forming a hollow gold-silver alloyed nanobox whose wall thickness can be precisely tuned by adjusting the amount of HAuCl_4 added. In a later stage of the reaction when all the pure silver has been removed, the HAuCl_4^- will begin to remove silver from the gold-silver alloy walls, forming a highly porous structure known as a nanocage [40].

Tuning the LSPR of gold nanocages is simple and straightforward. Figure 1A, B shows the results of a typical titration experiment where the same batch of nanocubes was reacted with different amounts of HAuCl_4 , corresponding to the different stages described above. The resulting products showed LSPR peaks across the visible spectrum and into the NIR. This can be seen from both the bright colors and the UV-visible extinction spectra. Figure 1C, D shows typical electron microscopy images taken from the starting silver nanocubes and the final nanocages, respectively; both displayed a high degree of uniformity.

The size and scattering/absorption properties of the nanocages can also be adjusted by using silver template particles of different sizes [41]. As several techniques have been developed to produce silver nanocubes of different sizes, this is relatively straightforward [25,42,43]. The absorption and scattering cross sections of gold nanocages can be calculated with the discrete dipole approximation. In general, at a size <40 nm, absorption is responsible for almost all of the light extinction, whereas scattering becomes more dominant at sizes significantly >60 nm [44].

As an extra advantage, a gold nanocage has a hollow interior and porous walls, allowing drugs to be loaded into the interior [45]. When the silver cubes used as a sacrificial template

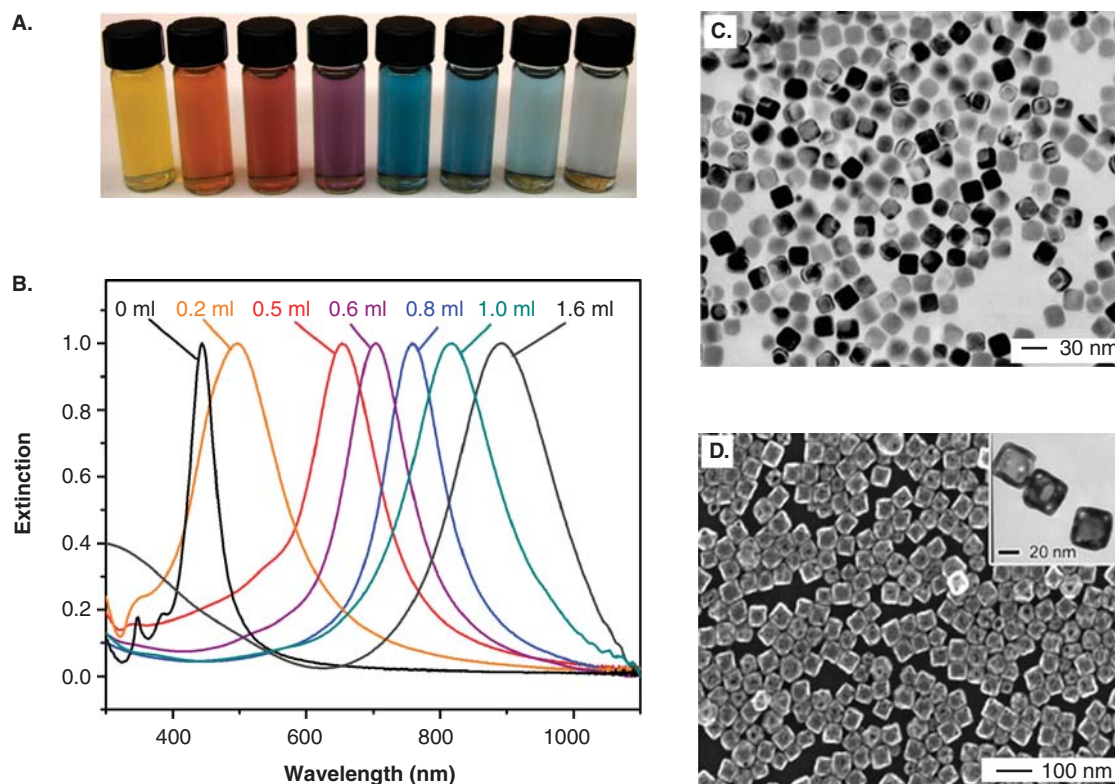


Figure 1. A. Photograph and (B) UV-visible spectra of gold nanocages tuned to a range of specific wavelengths by controlling the amount (volume listed above each trace) of chloroauric acid added into the reaction system. Modified with permission from [26]. C. Transmission electron microscopy (TEM) image of silver nanocubes, the starting template for the synthesis of gold nanocages. Modified with permission from [17]. D. Scanning electron microscopy image of the gold nanocages, with TEM inset.

Modified with permission from [44].

have rounded corners, pores will selectively form at the corners instead of randomly across the surface, creating well-defined routes for drugs to enter and exit the interior of the structure [45,46]. Typically, such well-defined nanocages can be produced with sizes in the range 35 – 60 nm while the LSPR is tuned to 800 nm. The pores can be controllably opened and closed by coating the nanocages with a thermosensitive, smart polymer that expands and covers the pores at low temperatures and collapses to expose the pores at high temperatures. This system has been demonstrated for the release of a variety of compounds including dyes, drugs and enzymes, which will be described in further detail below [46].

3. Tumor-specific delivery

One of the reasons why nanoparticles are being heavily investigated as drug delivery agents is their potential for targeting therapies to tumors while causing minimal damage to other tissues [47]. Current cancer treatments such as traditional chemotherapeutic drugs affect the body broadly, leading to harsh side effects resulting from nonspecific interactions.

Nanoparticles, however, can be directed to the tumor site through both passive and active targeting mechanisms. Passive targeting occurs *in vivo* owing to a phenomenon known as the enhanced permeability and retention (EPR) effect [48,49]. This effect is twofold. Initially, nanoparticles leak into the tumor site more easily because of the highly porous nature of blood vessels in this area caused by rapid and irregular angiogenesis. Once at the tumor site, the nanoparticles can remain there for a long period of time owing to decreased lymphatic drainage, leading to a higher concentration of nanostructures in the tumor region than in healthy tissues. This effect can be enhanced by coating nanoparticles with compounds such as polyethylene glycol (PEG) that inhibit both aggregation and the adsorption of blood serum proteins on the surface, reducing uptake by the liver and consequently extending the circulation time so that more nanoparticles have a chance to accumulate in the tumor through passive targeting [6].

Active targeting takes advantage of the fact that tumor cells overexpress certain receptors on the cell surface [47,50]. If a nanoparticle is coated with ligands that bind specifically to these receptors, the concentration of nanoparticles in the tumor

region could be enhanced. Owing to the high surface area of nanoparticles, it is possible to attach a large number of ligands, such as the arginine-glycine-aspartic acid (RGD) peptide, epidermal growth factor (EGF), folate, transferrin, and antibodies or antibody fragments, in addition to other molecules such as PEG or a therapeutic payload. This targeting capability has been demonstrated with Au nanocages *in vitro* in an effort to optimize the parameters for future *in vivo* studies [51].

One of the advantages of using gold-based nanostructures is the straightforward surface modification due to a strong interaction between gold and thiolate group, making the attachment of targeting molecules straightforward and robust [52]. Figure 2A shows a typical protocol for conjugating antibodies to the surface of gold nanocages. In the initial step, a PEG terminated in an *N*-hydroxysuccinimide (NHS) group at one end and an orthopyridyl disulfide (OPSS) group at the other is attached to the surface of the nanocages by breaking the disulfide bond of the OPSS group and forming a gold–thiolate bond with the surface of the cage [53]. In the next step, a primary amine on an antibody reacts with the NHS group at the distal end of the PEG molecule, completing the bioconjugation. A red-shift (typically <10 nm) in the LSPR is usually observed after conjugation owing to the change in refractive index near the surface of the nanoparticle, but this shift can be accounted for during nanocage synthesis if desired [54].

In addition to increasing the specificity of nanoparticle uptake, ligand binding can initiate receptor-mediated endocytosis (RME), leading to an increased concentration of nanoparticles inside the cell and even clusterization within the endosome, not just binding to the surface [55,56]. Interestingly, gold and silver nanoparticles with a targeting capability have been shown to play an active role in the endocytosis process, inducing receptor internalization and affecting downstream protein expression [57]. Antibody-conjugated gold nanocages show significantly higher uptake than nanocages that are conjugated with OPSS-PEG only. To demonstrate this *in vitro*, U87MGwtEGFR cells were incubated for 3 h with nanocages either conjugated with anti-EGFR antibodies (Figure 2B – D) or PEG only (Figure 2E – G). The nanocages were detected using two-photon microscopy (panels B and E), and the cell membranes and vesicles were stained with FM4-64 dye (panels C and F). Overlays of these images are presented in the final column of Figure 2 (panels D and G) and show strong colocalization of the cells and the nanocages for the antibody-conjugated sample and essentially no uptake for the PEGylated nanocages. In addition, it was found that several parameters could influence the cellular uptake of the antibody-conjugated nanocages, such as incubation time, the number of antibodies per nanocage and the size of the nanocages. These results confirmed that the nanocages were successfully functionalized with a targeting ligand (e.g., an antibody) and RME uptake greatly increased the accumulation of the nanocages in the cancer cells. Nonetheless, the active targeting

efficacy of gold nanocages still needs to be optimized further *in vivo* [58].

4. Photothermal treatment

To demonstrate the photothermal effect with gold nanocages, initial studies were performed *in vitro* [30]. SK-BR-3 cells were incubated with anti-HER2-modified gold nanocages, and then washed with phosphate buffered saline (PBS) and irradiated with a Ti-Sapphire laser coupled to a 5-m-long single-mode fiber ($\lambda = 810$ nm, temporal pulse width ~ 20 ps, 82 MHz repetition rate). The sample was placed ~ 140 mm away from the beam focus and the corresponding irradiation spot size at the sample was ~ 2 mm in diameter. In an initial attempt, cell death was qualitatively analyzed using fluorescence microscopy. Figure 3A, B shows the results of a live/dead cell fluorescence assay performed after the cells incubated with the antibody-targeted nanocages had been irradiated for 5 min at mean power density of 1.5 W/cm^2 . A circular region of destruction can be seen in both images, with red indicating dead cells and green indicating live cells. Control experiments with laser irradiation in the absence of gold nanocages are shown in Figure 3C, D, showing that the same laser at this power density caused no damage to the cells in the absence of gold nanocages.

Further experiments used flow cytometry and propidium iodide staining to provide more quantitative data about the photothermal effect [59]. The percentage of cell death was monitored as the laser irradiation time or laser power density was gradually increased. Although only a small region of the dish was irradiated by the laser spot (9.8%), cell killing, in some cases, extended to over half the cells as the laser power or radiation time was increased (Figure 3E, F). The threshold in laser power density for cell death was $\sim 1.6 \text{ W/cm}^2$, with a linear dependence on laser power density as it was increased above that level. Cell death was observed at the shortest period of time tested, 1 min, and linearly increased until 5 min when the percentage of cell death leveled off [59].

Ultrafast laser spectroscopic studies have shown that the electrons in gold nanostructures absorb the incoming photon energy and subsequently equilibrate with the lattice through an electron-phonon process on the order of a picosecond time-scale [60–62]. Once the temperatures of electrons and lattice reach equilibrium, the heat diffusion to the surroundings (i.e., aqueous solution) typically takes tens to hundreds of picoseconds. Consequently, cell death in photothermal therapy is generally caused by two mechanisms: local hyperthermia from efficient heat diffusion to the surroundings or cavitation effects resulting from superheating around the particle [63–65]. Further mechanistic studies need to be conducted to determine the relative contributions of these mechanisms to the photothermal effect of gold nanocages under different laser settings.

To observe the photothermal effect *in vivo*, changes to the tumor metabolism before and after treatment with

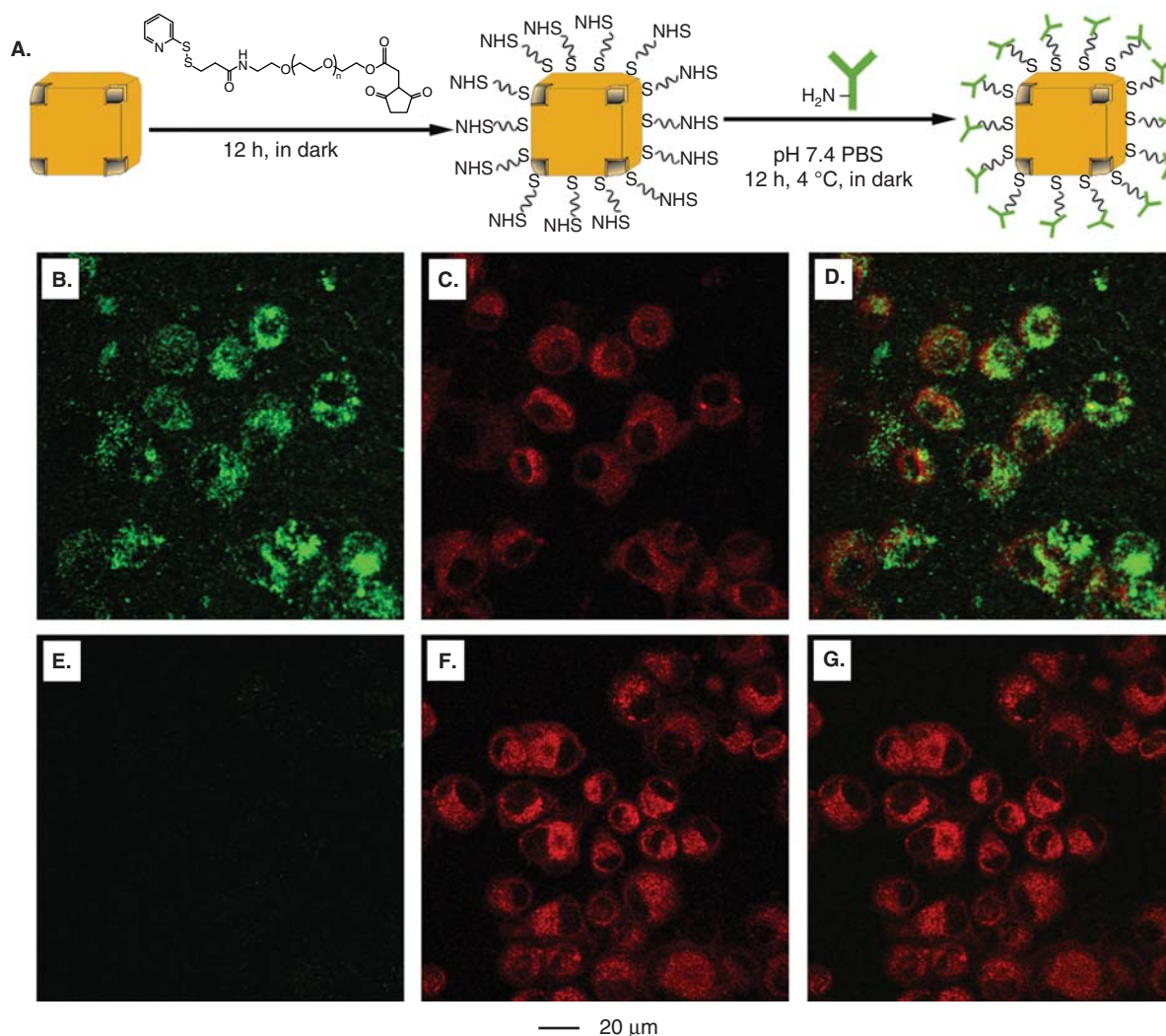


Figure 2. A. Schematic illustrating the protocol for conjugating antibodies to the surface of nanocages to create immunogold nanocages. B – D. U87MGwtEGFR cells after incubation with gold nanocages functionalized with EGFR antibodies. E – G. Cells after incubation with gold nanocages covered by PEG. B, E. Two-photon images of gold nanocages showing little uptake for the PEG-covered nanocages. C, F. Fluorescence images of SK-BR-3 cells with FM4-64 dye used to stain the membranes. D, G. Overlay of the images from gold nanocages and from FM4-64 dyes, showing clear overlap between the two for the EGFR-covered nanocages.

Modified with permission from [51].

48-nm PEGylated gold nanocages were recently studied by monitoring the level of [^{18}F]fluorodexoyglucose with positron emission tomography (^{18}F -FDG PET) [66]. This technique allows for non-invasive observations of tumor metabolic activity, which indicates whether or not the treatment was successful [67-70]. The resulting images are presented in Figure 4 for a saline-injected control and a nanocage-injected mouse (via tail vein) before and 24 h after laser irradiation. In these experiments a portable continuous wave diode laser ($\lambda = 808 \text{ nm}$, 0.7 W/cm^2) was used instead of the pulsed laser used for *in vitro* studies. Little change was seen in images for the control mouse before (Figure 4A, E) and after

treatment (Figure 4C, G, see the arrows). Conversely, the formerly clear signal from the tumor in the nanocage-treated mouse before treatment (Figure 4B, F) disappeared after irradiation (Figure 4D, H, see the arrows). Figure 4I shows the PET signal of the treated tumors after normalization against the signal from the untreated tumor on the other side of the same mouse. For the nanocage-treated mouse, the PET signal decreased from 1 to 0.3, whereas no decline was observed for the saline-treated mouse. Tissue distribution showed that the uptake of nanocages in the tumor was $\sim 5\%$ of the injected dose (ID) per gram of tissue at 96 h post injection. The decreased ^{18}F -FDG uptake in the tumor

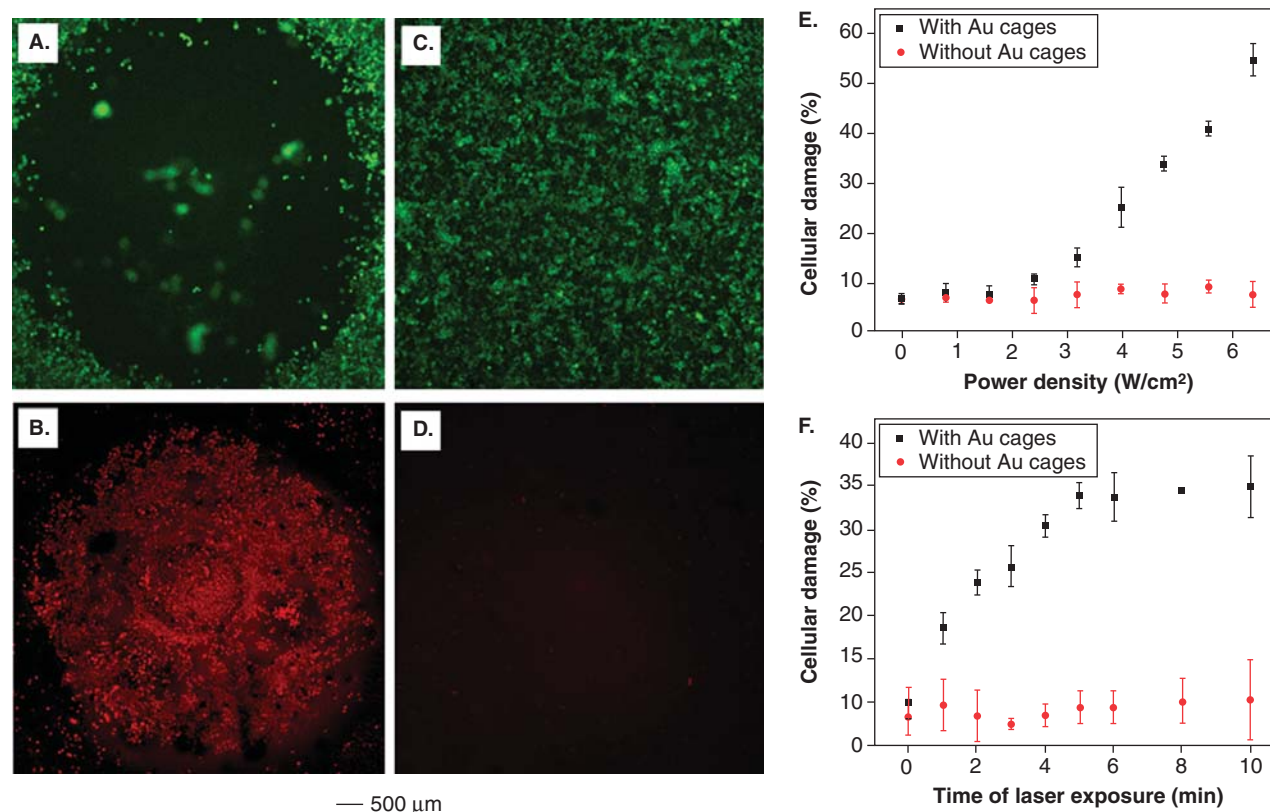


Figure 3. Qualitative and quantitative analysis of the photothermal effect of gold nanocages *in vitro*. A, B. The cells were incubated with gold nanocages and illuminated for 5 min at a power density of 1.5 W/cm² and examined with a fluorescence microscope. C, D. Control experiments with the same laser irradiation, but no nanocages present. A, C. Calcein AM assay, where green fluorescence indicates live cells. B, D. Ethidium homodimer 1 assay, where red fluorescence indicates dead cells. E. Dependence of cellular damage on laser power density (irradiation time: 5 min). Data from cells incubated with targeted gold nanocages is depicted in black whereas data from controls with no gold nanocages is depicted in red. Although only 9.8% of the cells in the plate were in the irradiated area, the heat spread to surrounding areas to increase cellular damage. F. Dependence of cellular damage on laser exposure time (power density: 4.77 W/cm²).

Figures 3A – 3D were modified with permission from [30].

Figures 3E – 3F were modified with permission from [59].

indicated a positive treatment response to photothermal therapy. Long-term observation of the tumor regression still needs to be investigated further.

5. Drug delivery

There is great interest in developing new methods to trigger and control the release of biologically active species (or effectors) at a specific time or site of interest [13,71-74]. Polymer systems have been developed that change from an extended state to a collapsed state when the temperature is increased over a critical value [75-78]. When these polymers are attached to the surface of a porous, hollow metal nanostructure, this transformation can be used to open and close the pores, releasing the contents in a controlled manner [46].

A schematic of the release process is presented in Figure 5A. Below the transition temperature (low critical solution

temperature [LCST]), the polymer is in a hydrophilic, extended state, blocking the transport of materials through the pores of the cages. When the solution is heated above the transition temperature, the polymer chains collapse and become hydrophobic, opening the pores and allowing the encapsulated content to diffuse into the environment. The heat needed for switching between these two conformations can be applied directly by heating or by irradiating the desired region with a laser by means of the photothermal effect. The authors demonstrated this release with a system based on poly(*N*-isopropylacrylamide) (pNIPAAm), with a disulfide group that facilitates attachment to the surface of the cages (Figure 5B) [46]. The phase transition temperature can be adjusted from 32 to 50°C by incorporating different amounts of acrylamide (AAm) into the polymer chain. The polymers were initially designed to change conformation at physiologically relevant temperatures (e.g., 39°C) that are

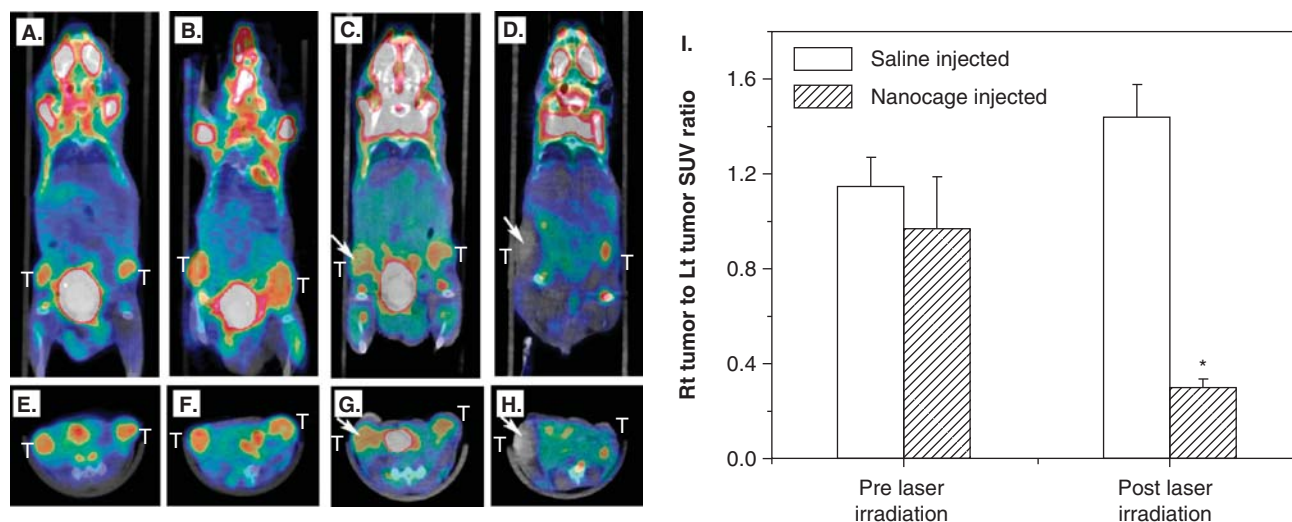


Figure 4. ^{18}F -FDG PET/CT co-registered images (coronal plane: A – D; axial plane: E – H) of mice injected with either gold nanocages or saline solution before and after laser irradiation. A, E. A saline-injected mouse before laser irradiation. B, F. A nanocage-injected mouse before laser irradiation. C, G. The saline-injected mouse after laser irradiation. D, H. The nanocage-injected mouse after laser irradiation. The white arrows indicated the tumors that were exposed to the diode laser at a power density of 0.7 W/cm^2 for 10 min. I. Plot showing the ratios of laser-treated tumor to non-treated tumor for ^{18}F -FDG standardized uptake values (SUV, *indicates statistical significance, $p < 0.001$).

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above body temperature (37°C) but below the hyperthermia temperature (42°C), above which cell killing may occur depending on the amount of heat generated.

The authors recently used this system to demonstrate release of a common chemotherapeutic drug, doxorubicin (Dox) [46]. Figure 5C shows the amount of Dox released after heating the system to 45°C for different periods of time. As the heating time was increased, increasing amounts of the drug were able to exit the cages as the pores were open for a longer period of time. Figure 5D shows the effects of the released Dox on breast cancer cells *in vitro*. In these experiments, the heat necessary for triggering the polymer conformational transformation was generated through the photothermal effect due to laser irradiation. The cells were incubated with Dox-loaded nanocages and then irradiated with a pulsed laser at 790 nm for 2 – 5 min. The per cent of viable cells remaining was determined using the MTT (3-(4,5-dimethylthiazol-2-yl)-2,5-diphenyltetrazolium bromide) assay. The laser power density was kept relatively low (20 mW/cm^2) to minimize cell death from the photothermal effect. The control experiments with no nanocages present (C-1) showed essentially no cell death and with Dox-free nanocages (C-2) showed minimal cell death, whereas the cells incubated with Dox-loaded nanocages showed ~ 40% cell death. This system was also used to release enzyme lysosome, which could retain ~ 80% of their bioactivity after the encapsulation and release processes, comparing favorably with other release methods [79,80].

6. Conclusion

Through careful manipulation of the synthetic parameters for gold nanocage preparation, a wide size range of gold nanocages can be created, with their LSPR peaks tuned to the NIR region of the optical spectrum. By controlling the surface functional groups, it is possible both to extend circulation time with a PEG coating and to target the nanocages to cancer cells with an antibody or other types of ligand. Combined with passive targeting due to the EPR effect, these features makes gold nanocages a strong candidate for highly localized cancer treatment, minimizing the harsh side effects that are the norm at present. The use of gold nanocages for two such applications has been highlighted here: photothermal therapy and externally triggered drug release. Both examples take advantage of the photothermal conversion of light into heat, one generating enough heat to kill cells directly, and the other inducing a conformational change in a smart polymer coating to open pores and release drugs or other biological agents.

7. Expert opinion

Gold nanoparticles are fascinating materials that hold great promise for multi-modal cancer imaging and treatment. The ability to manipulate the strong interaction between these materials and light through synthetic methods has allowed scientists to create particles with strong, specific resonances in the NIR region, ideal for biomedical applications. Of the

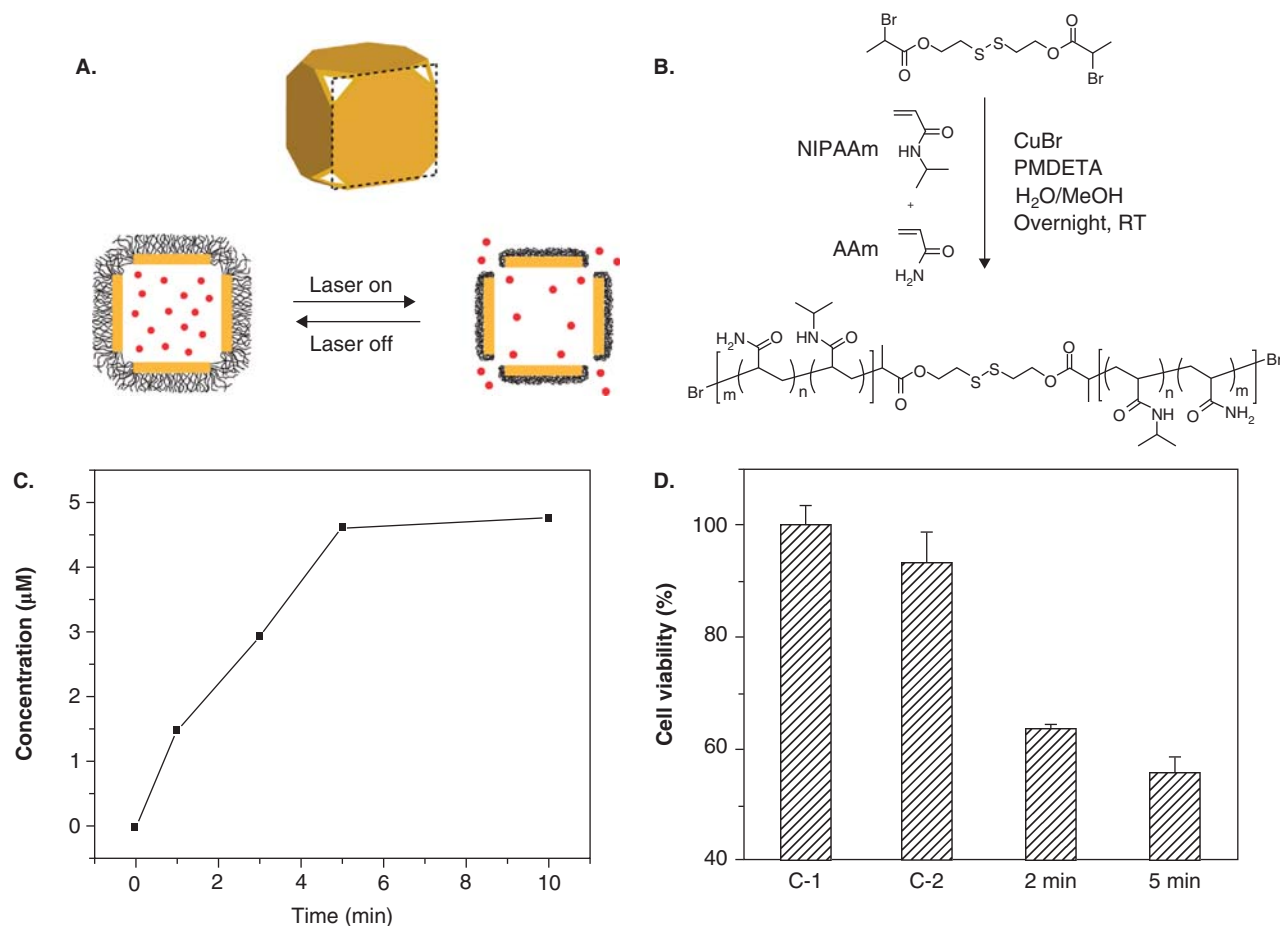


Figure 5. **A.** Schematic illustrating the release mechanism for gold nanocages coated by smart polymer chains. **B.** Atom transfer radical polymerization of NIPAAm and AAm monomers (at a molar ratio of m/n) as initiated by a disulfide initiator and in the presence of a Cu(I) catalyst. **C.** Concentration of Dox released by heating the system at 45°C for different periods of time. **D.** Cell viability after pulsed laser irradiation at 20 mW/cm² for 2 and 5 min, respectively, in the presence of Dox-loaded nanocages. Controls: no nanocages present (C-1) and in the presence of Dox-free nanocages (C-2), both irradiated for 2 min. Modified with permission from [46].

different morphologies being investigated, gold nanocages are particularly exciting because of their precise LSPR tuning, desirable size and the extra potential to trap drug molecules or enzymes in their interiors and then release them through an externally controlled mechanism.

In the future, it will be exciting to explore the dual functionality of targeted gold nanocages by combining the contrast enhancement for cancer diagnostics and the photothermal effect for cancer therapeutics. Although not discussed in detail here, gold nanocages can also enhance the contrast for a variety of optical imaging modalities, creating the potential for multifunctional particles that can make possible both early detection and effective treatment. Optical imaging techniques are non-ionizing and non-invasive alternatives for early stage cancer diagnosis and staging, but are limited by low contrast between cancerous and normal tissues [81]. The presence of highly absorbing or scattering nanoparticles in the bloodstream and/or tumor can greatly enhance the contrast possible

with these methods [82,83]. For example, gold nanocages have been shown to enhance contrast by 80% in photoacoustic imaging of a rat brain *in vivo* [82]. It should be possible to use gold nanocages first to provide contrast for tumor imaging or cancer staging with an optical imaging technique such as photoacoustic tomography (PAT), and then to release a chemotherapeutic drug and/or generate heat for effective photothermal destruction of the tumor. The combination of targeted delivery and imaging-guided cancer treatment opens up new possibilities for studying the effects of the delivered substances in real time, which may provide new insights for future research directions.

Toxicity is always a concern with any new treatment modality. Gold colloids have been used *in vivo* as a radiotracer since the 1950s so much is known about their safety for and clearance from the human body [84,85]. At present, there are two therapies based on gold nanoparticles that have been approved for clinical studies: solid gold nanoparticles for drug delivery and gold

nanoshells for photothermal therapy [86,87]. To this end, Cytimmune, Inc. recently successfully completed a Phase I clinical trial with solid gold nanoparticles coated with a combination of PEG and human tumor necrosis factor- α (TNF, therapeutic payload). Preliminary results indicated that the gold nanoparticles were well tolerated, even with total TNF doses far higher than attainable in previous human studies [86]. As gold nanoshells were one of the first nanostructure types investigated for photothermal therapy, a range of *in vivo* studies have been performed, demonstrating high survival rates after treatment in mice, and Phase I clinical trials began for head and neck cancers in 2008 [87,88]. Gold nanocages have a great potential to become one of the next platforms for cancer diagnosis, treatment and drug delivery through the integration of their compact size, tunable optical properties, and a unique structure with hollow interiors and porous walls.

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Declaration of interest

The authors declare no competing financial interests.

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