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1 **Assembly-Enhanced Indocyanine Green Nanoparticles for Fluorescence Imaging-** 2 **Guided Photothermal Therapy**

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16 **Key words:** Indocyanine green; nanoparticles; self-assembly; fluorescence imaging;
17 photothermal therapy

18

19 **Abstract:**

20 The development of theranostic agents that offer complete biocompatibility, coupled
21 with enhanced diagnostic and therapeutic performance, is crucial for fluorescence
22 imaging-guided photothermal therapy in anti-tumor applications. However, the
23 fabrication of nanotheranostics meeting the aforementioned requirements is challenged
24 by concerns regarding biosafety and limited control over construction. Herein, we
25 reported a kind of fluorescence imaging-guided photothermal theranostic nanomaterials
26 that are composed of amino acid derivatives and clinically used small photoactive
27 indocyanine green molecules. Through manipulation of noncovalent interactions, these
28 binary building blocks can co-assemble into nanoparticles in a tunable manner.
29 Significantly, such construction not only maintained the fluorescent properties of
30 photoactive molecules, but also enhanced their stability to overcome barriers from
31 photo-degradation and complex physiological conditions. These collective features



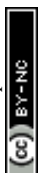
1 integrate their precise anti-tumor applications, including fluorescence imaging
2 diagnosis and photothermal ablation therapy. This study reported a kind of
3 nanotheranostics characterized by biocompatibility, adjustable construction, and robust
4 stability, which are beneficial for the clinical translation of fluorescence imaging-
5 guided photothermal therapy against tumors.



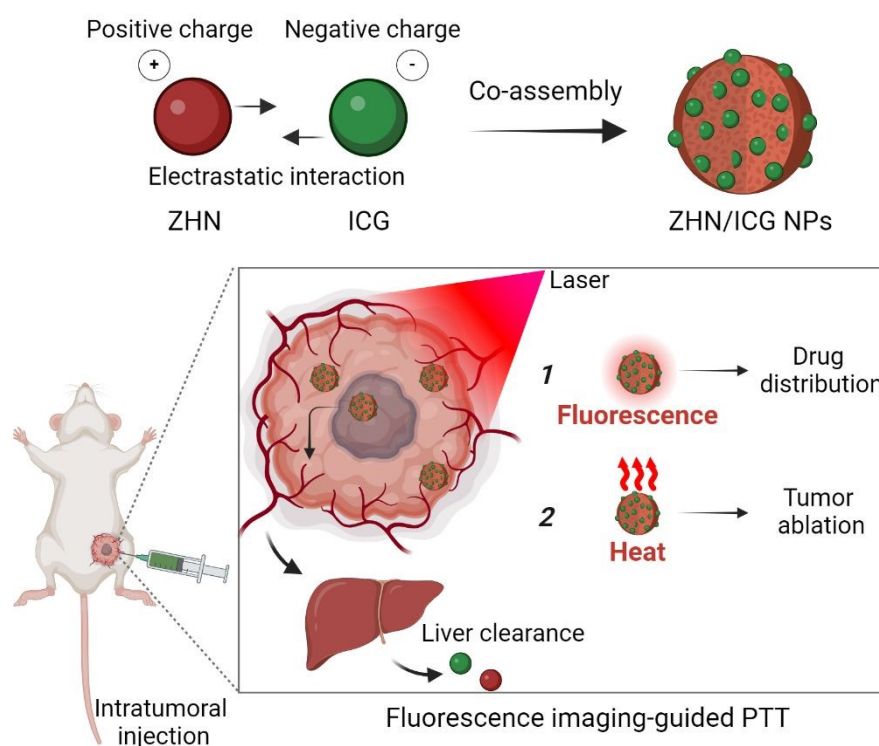
1 Introduction

2 Photothermal therapy (PTT) is a noninvasive and localized therapeutic modality for
3 cancer treatment, which can convert light energy absorbed by photothermal agents into
4 heat, rising the local temperature as to rapidly kill the tumor entity¹⁻⁵. Further, imaging-
5 guided PTT, which is assisted by diagnostic techniques to indicate the bio-distribution
6 of photothermal agents in a real-time manner, enables a more precise anti-cancer
7 outcome⁶⁻⁹. With the continuous development of nanotechnology, the theranostic
8 materials for imaging-guided PTT have been wildly fabricated¹⁰⁻¹³. These
9 nanomaterials aim to tailor therapeutic performance but still face challenges when
10 considering their potential clinical theranostic applications. Specifically, many
11 theranostic agents with dual imaging and therapeutic functions are composed of
12 nonbiodegradable components, such as nanocarbons¹⁴ and noble metal quantum dots¹⁵,
13 whose biological applications are inhibited by their long-term toxicity¹⁶. By contrast,
14 biocompatible organic nanomaterials, which predominantly involve the entrapment of
15 photothermal agents and fluorescent probes in one platform such as liposomes¹⁷,
16 micelles¹⁸ and polymeric nanostructures¹⁹, have addressed the shortcomings associated
17 with inorganic non-degradability²⁰. Unfortunately, the integration of multiple
18 components is hindered by challenges such as controllability, low entrapment
19 efficiency, and insufficient stability²¹. Therefore, there is still a need to develop
20 completely biocompatible nanotheranostic materials, particularly in utilizing biosafe
21 biomolecules and simultaneously improving theranostic performance.

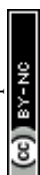
22 Indocyanine green (ICG) is a near-infrared cyanine dye and has been approved by
23 the U.S. Food and Drug Administration (FDA) as a fluorescent contrast agent for
24 medical diagnosis²². Moreover, numerous studies have demonstrated its photothermal
25 utility due to its strong absorption and deep penetration²³⁻²⁶. However, despite the
26 combined fluorescent and photothermal properties, the anti-tumor applications of ICG
27 are extremely hindered by its photodegradative instability²⁷. The utilization of peptide
28 or amino acid co-assembly, employing a spontaneous strategy based on noncovalent
29 interactions to efficiently disperse molecules within nanostructures, could provide
30 protection for ICG and therefore overcome the aforementioned issues²⁸⁻³¹. In this regard,



we present the peptide-ICG co-assemblies for fluorescence imaging-guided PTT (Scheme 1). Short peptides, even amino acid derivatives, are promising candidates for engineering nanomaterials owing to their natural occurrence and tunable noncovalent interactions³²⁻³⁴. Therefore, a histidine derivative (Z-His-NH₂, ZHN) was selected as a modulating molecule to control co-assembly with the ICG molecule. By manipulating electrostatic interactions and other noncovalent interactions between ICG and ZHN, we achieved the fluorescent and photothermal nanoparticles (NPs) with a high entrapment efficiency of ICG (up to 95% calculated). Importantly, these nanoparticles not only maintained the intrinsic fluorescence emission of ICG, but also significantly improved the stability of photothermal conversion and resistance to complex physiological conditions. Taken together, these properties of ZHN/ICG NPs made them suitable for localized tumor injection with a reliable drug dosage, thereby realizing spontaneous fluorescence imaging and photothermal ablation. This work reported a kind of fluorescence imaging-guided photothermal nanotheranostics characterized by biocompatibility, controllable construction, and considerable stability, highlighting their potential clinical translation in anti-tumor applications.



Scheme 1 Schematic illustration of fabrication of nanoparticles and their fluorescence imaging-guided photothermal therapy.



1 Results and discussion

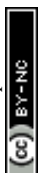
2 Characterization of ZHN/ICG NPs

3 The histidine derivative Z-His-NH₂ (ZHN) (Fig. S1, Electronic supplementary
4 information, ESI), because of its positively charged nature, has been selected as
5 building blocks for co-assembling with negatively charged indocyanine green (ICG)
6 (Fig. S2, ESI). Driven by the electrostatic interaction, combining with other interactions,
7 such as the hydrogen bonds linked by the sulfonate groups of ICG and amide groups of
8 ZHN³⁵ and hydrophobic association occurred within aromatic groups of these binary
9 building blocks³⁶, they co-assembled into ZHN/ICG nanostructures. As shown in Fig.
10 S3 (ESI) and Tab. S1 (ESI), the size of these nanostructures showed a decrease as a
11 function of ICG concentration, which can be explained that more negatively charged
12 ICG molecules interacted with more positively charged ZHN molecules (isoelectric
13 point 7.59) at the pH value of 6.5, resulting in more compact structures. It is of
14 significance to verify the electrostatic interaction, hence we further changed the pH
15 value of co-assembly systems. Fig. S4a (ESI) and Tab. S2 (ESI) showed that the
16 nanostructures formed at pH 3.3 were comparatively smaller than those at pH 6.5. This
17 can be attributed to the protonation of imidazole groups below the isoelectric point³⁷,
18 which imparts more positive charge to ZHN molecules, enhancing co-assembly with
19 ICG. Additionally, the zeta potential of the nanostructures at pH 3.3 was more negative
20 compared to that at pH 6.5 (Fig. S4b, ESI), indicating that more negatively charged
21 ICG molecules are attracted by ZHN molecules. These findings confirm the role of
22 electrostatic attraction in the formation of the nanostructures. Moreover, another
23 histidine derivative Z-His-NH₂ (ZHNN) (Fig. S5, ESI), possessing a similar
24 structure to ZHN, could also co-assemble with ICG. Not surprisingly, the
25 nanostructures can also be tuned (Fig. S6 and Tab. S3, ESI), indicating the universality
26 of this facile strategy.

27 Since the entrapment efficiency is critical for nanotheranostics design³⁸, we
28 systematically measured it by varying the ZHN: ICG mass ratio. In Fig. S7 (ESI), the
29 entrapment efficiencies of ICG and ZHN in nanostructures fabricated with a ZHN: ICG
30 mass ratio of 5:1 were found to be 63.5% and 94.5%, respectively. This performance is



1 superior to that observed with other mass ratios such as 20:1, 10:1, and 3.3:1. The
2 optimal ratio of 5:1 provided an adequate balance between ZHN and ICG, leading to
3 enhanced encapsulation efficiency of ICG molecules. Deviations from this optimal
4 ratio resulted in less efficient encapsulation. For instance, at a ZHN: ICG mass ratio of
5 20:1, the excess ZHN molecules do not effectively stabilize a high amount of ICG,
6 leading to lower encapsulation efficiency. Conversely, at a ratio of 3.3:1, the
7 insufficient amount of ZHN may result in excessive ICG molecules that are not
8 adequately encapsulated, also reducing overall efficiency. Therefore, the ZHN: ICG
9 mass ratio of 5:1 was selected for subsequent experiments due to its optimal
10 performance in entrapment efficiency. At this mass ratio, the obtained ZHN/ICG
11 nanoparticles (NPs) possessed a uniform hydraulic diameter of 153.0 ± 52.3 nm and ζ
12 potential of -37.3 mV, as characterized by dynamic light scattering (DLS) results (Fig.
13 1a and S8, ESI). The relatively high surface charge of the ZHN/ICG NPs, due to
14 electrostatic repulsion, contributed to their stable dispersion in solution, preventing
15 aggregation. Morphology characterization including scanning electron microscopy
16 (SEM) (Fig. 1b) and transmission electron microscopy (TEM) images (Fig. S9, ESI)
17 demonstrated that ZHN/ICG NPs were in a regular spherical shape, of which size was
18 in line with the DLS result. Furthermore, the absorption band of ICG molecules in
19 ZHN/ICG NPs showed a decrease while broadened to the wavelength up to 900 nm
20 (Fig. 1c), possibly because the electron delocalization of ICG molecules promoted by
21 their noncovalent interactions with ZHN²⁹, suggesting a co-assembly process. Of note,
22 the obtained ZHN/ICG NPs were still fluorescent (Fig. 1d), differing to the quenching
23 effect of chromophores caused by the aggregation¹, which is possibly because the
24 shortened intermolecular distances restrict the alkene motion of ICG molecules and
25 thereby endow them with superb dispersibility in ZHN/ICG NPs^{35, 39}, rather than their
26 self-aggregation. These results demonstrate the fluorescence imaging potential of
27 ZHN/ICG NPs.



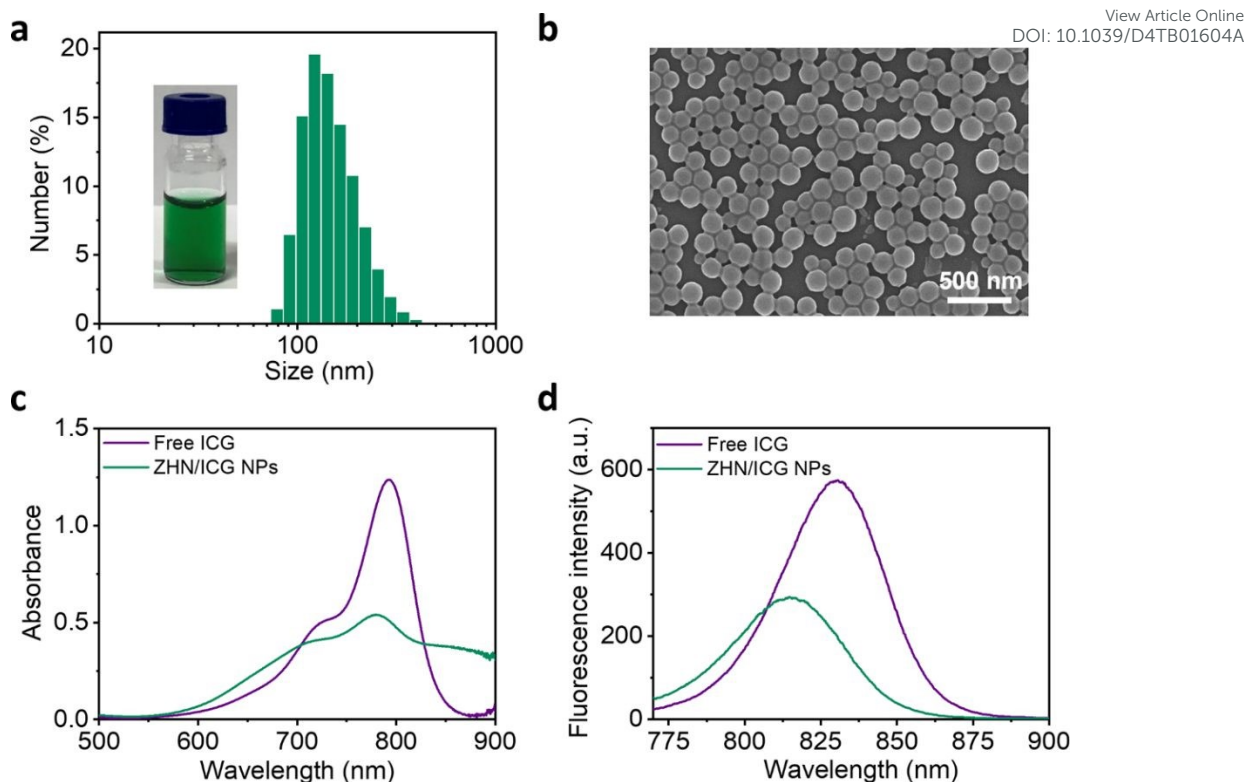
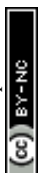


Fig. 1 Characterization of ZHN/ICG NPs. (a) DLS measurement of ZHN/ICG NPs. The inset showed their optical picture. (b) SEM image of ZHN/ICG NPs. Comparison of (c) absorbance spectra and (d) fluorescence spectra of free ICG and ZHN/ICG NPs.

Photothermal performance of ZHN/ICG NPs

As far, we have demonstrated the fluorescence property of ZHN/ICG NPs, and then we investigated their photothermal performance. ICG molecules are easily degraded upon photoirradiation due to the saturation of the double bonds in their conjugated chains⁴⁰, rendering the poor stability of photothermal conversion. When ICG molecules co-assembled with ZHN, they exhibited distinct behaviors. As depicted in Fig. 2a and 2b, free ICG and ZHN/ICG NPs with the same high concentration of $0.2 \text{ mg}\cdot\text{mL}^{-1}$, both showed considerable photostability at a laser power density of 2 W cm^{-2} , owing to that the sufficient molecules can realize efficient photothermal conversion within 10 min. The maximum temperature within 10 min of free ICG and ZHN/ICG NPs reached $66.4 \text{ }^\circ\text{C}$ and $63.5 \text{ }^\circ\text{C}$, respectively. However, when reducing ICG concentration to 0.025 mg mL^{-1} , differences between free ICG and ZHN/ICG NPs appeared. The temperature of ZHN/ICG NPs could continuously rise, while the free ICG started to degrade at 324 s. Intriguingly, at the concentration of 0.025 mg mL^{-1} , although both of them showed



1 degradation, the onset degradation time of free ICG was 205 s, while the corresponding
2 counterpart of ZHN/ICG NPs was 303 s. Whereas the control group of pure water
3 exhibited negligible temperature increase. These results demonstrated the improved
4 photothermal conversion stability of ZHN/ICG NPs. Interestingly, Interestingly, the
5 photothermal conversion efficiency (η) was calculated using a reported method⁴¹,
6 yielding 39.83% for ZHN/ICG NPs and 29.0% for free ICG. Also, the photothermal
7 conversion stability of ZHN/ICG NPs was conducted by 808 nm laser heating for 10
8 min and followed by natural cooling at room temperature for another 10 min. As shown
9 in Fig. 2c, during 3 cycles of photoirradiation, free ICG only tolerated one cycle of laser
10 irradiation. By contrast, ZHN/ICG NPs maintained a high photothermal effect (Fig. 2d),
11 confirming their enhanced capability of photothermal conversion. By these
12 comparisons, the improved photostability of ICG molecules could be ascribed to the
13 well-defined nanostructures. That is, ICG molecules were trapped and dispersed within
14 ZHN/ICG NPs after co-assembly with ZHN, which not only limited their self-
15 aggregation to impair fluorescence, but also significantly isolated their conjugated
16 chains from oxidation, and thus avoided further degradation. Given the fluorescence
17 property revealed above and the robust photothermal effect, the ZHN/ICG NPs are
18 expected to become promising nanotheranostics for imaging-guided photothermal
19 therapy.



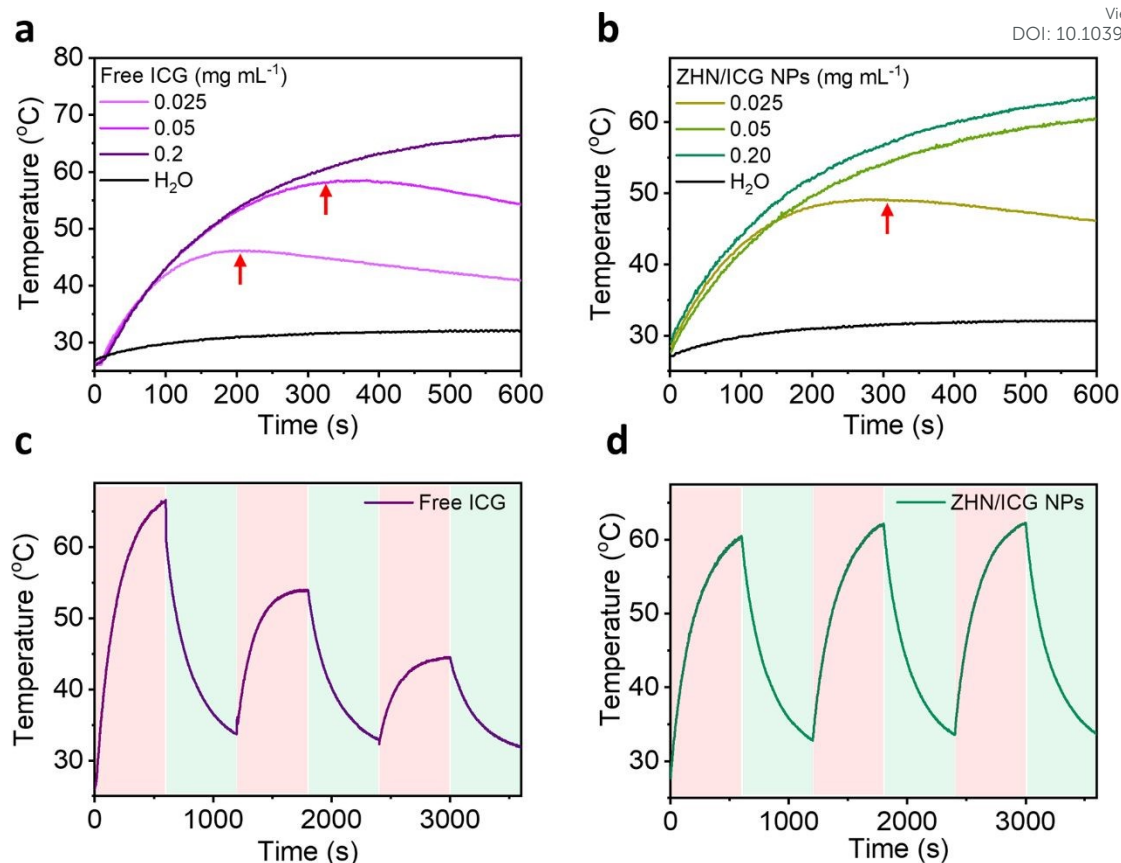


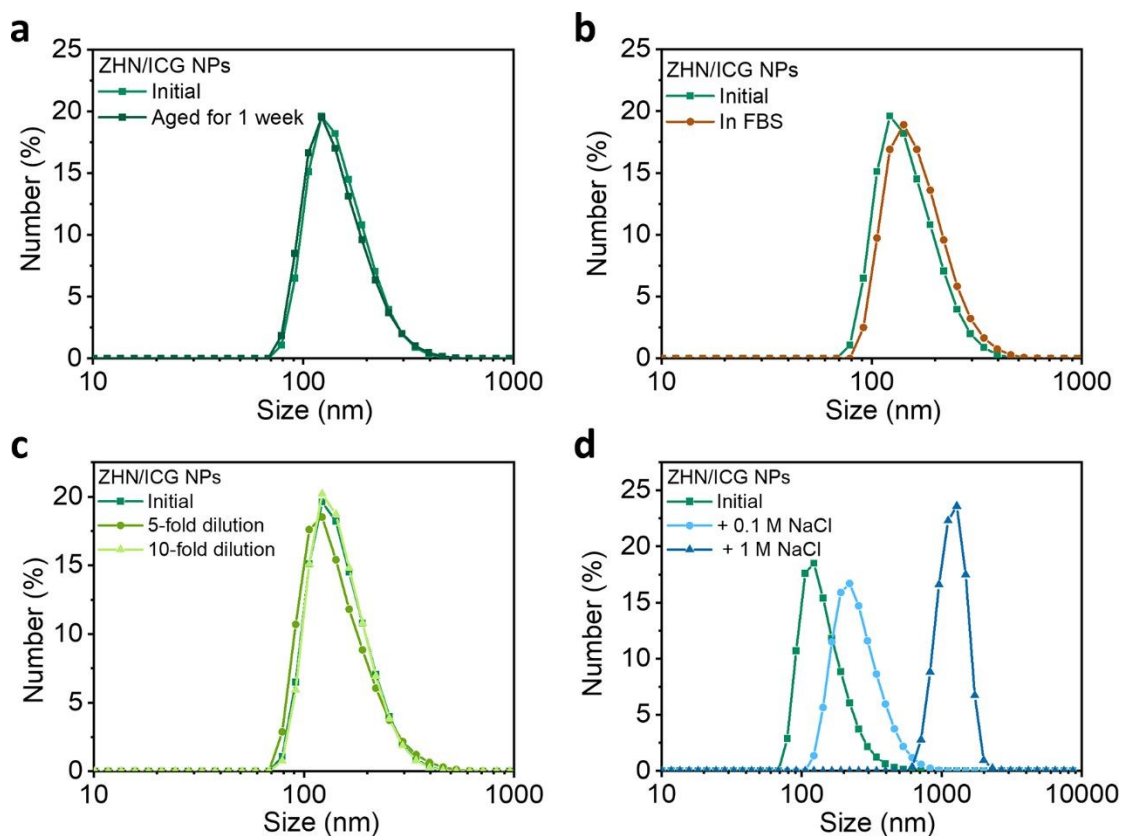
Fig. 2 Photothermal performance of ZHN/ICG NPs. The concentration-dependent temperature elevation of (a) free ICG and (b) ZHN/ICG NPs under 808 nm laser irradiation (2 W cm^{-2} , 10 min). The red arrows indicate the onset degradation time. Three heating-cooling cycles of (c) free ICG and (d) ZHN/ICG NPs at the ICG concentration of 0.2 mg mL^{-1} under 808 nm laser irradiation.

Stability test of ZHN/ICG NPs

The stability of nanomaterials is the prerequisite for biomedical applications^{42, 43}. To this end, a series of stability tests were conducted (Fig. 3 and Tab. S4, ESI). The ZHN/ICG NPs showed negligible change in terms of size over time (Fig. 3a and Tab S4, ESI), which means that ZHN/ICG NPs had suitable stability for long term storage. The stability of ZHN/ICG NPs in fetal bovine serum (FBS) medium that mimicked cell culture environment was further monitored⁴⁴. When incubating ICG NPs in 10 % FBS solution (v/v) at 37 °C for 24 h, the size and distribution of ZHN/ICG NPs remained stable as showed in Fig. 3b, and the little increase in size was owing to the slight hydrophobic interactions between FBS and ZHN/ICG NPs. In addition, the size distribution was also kept well by various folds of dilution (Fig. 3c). Furthermore, NaCl was added to the initial ZHN/ICG NPs solution (Fig. 3d). The higher concentration of



1 NaCl, the larger size of ZHN/ICG NPs. The phenomenon can be interpreted as the
 2 charge shielding effect of NaCl that induced the aggregation of ZHN/ICG NPs, which
 3 led us to conclude that electrostatic repulsion contributed to the dispersion of ZHN/ICG
 4 NPs, enabling the stability in aqueous solution. These results demonstrate the superior
 5 stability of ZHN/ICG NPs, thus paving the way for their *in vitro* and *in vivo* applications.



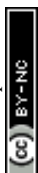
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 7 **Fig. 3** Stability test of ZHN/ICG NPs. DLS profiles of (a) freshly prepared and aged ZHN/ICG NPs,
 8 (b) ZHN/ICG NPs dispersed in FBS, (c) ZHN/ICG NPs with various dilutions, and (d) ZHN/ICG
 9 NPs dispersed in different NaCl conditions.

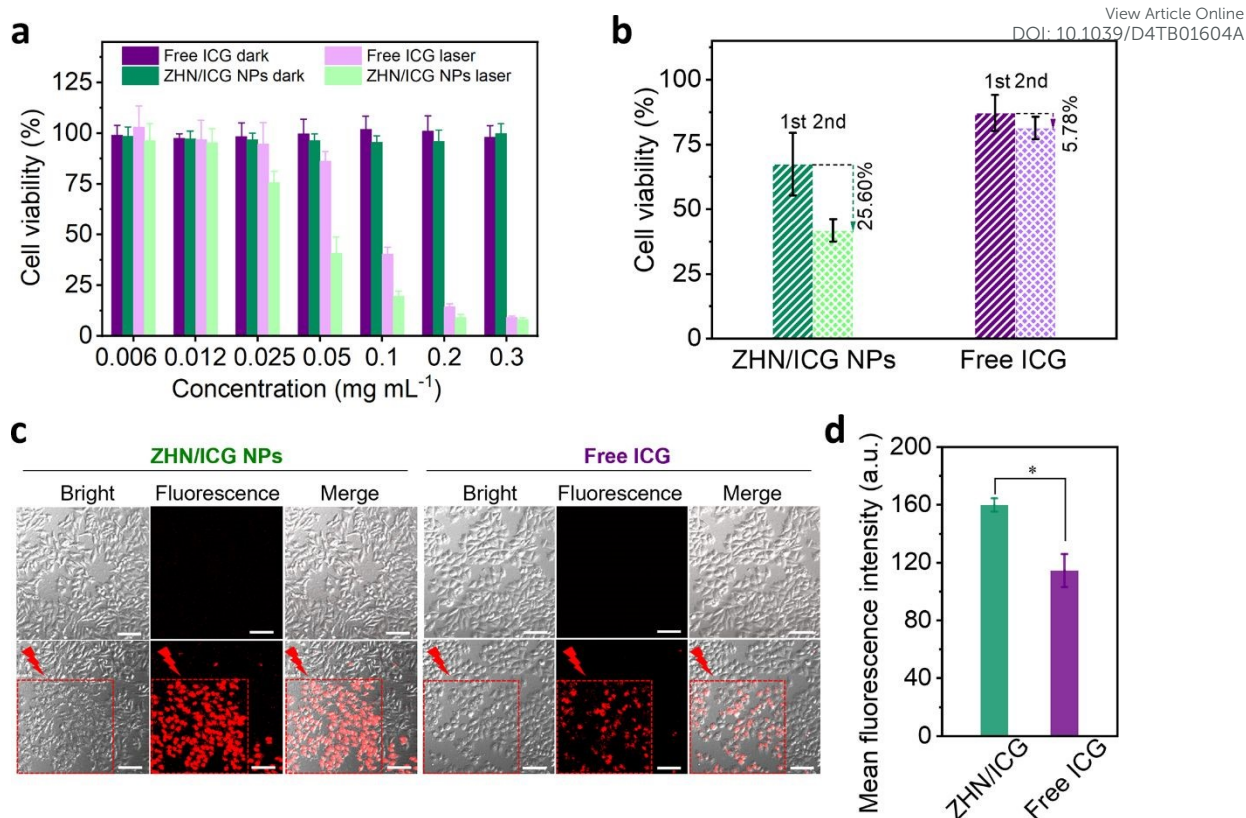
11 *In vitro* evaluation of ZHN/ICG NPs

12 Next, the photothermal conversion of ZHN/ICG NPs was investigated *in vitro*.
 13 Drug formulations including free ICG and ZHN/ICG NPs with a series of
 14 concentrations were respectively incubated with human breast adenocarcinoma cancer
 15 (MCF-7) cells (Fig. 4a). After incubation for 24 h, no discernible cytotoxicity was
 16 observed in the dark condition, even at a high concentration of 0.3 mg mL^{-1} , confirming
 17 the high biocompatibility of ICG molecules and ZHN/ICG NPs. By contrast, through
 18 808 nm laser irradiation (1.5 W cm^{-2} , 1 min), the viability of cells showed



1 concentration-dependent decrease. The IC₅₀ value of ZHN/ICG NPs was 43.16 $\mu\text{g mL}^{-1}$
2 ¹, which is almost twice lower than 82.65 $\mu\text{g mL}^{-1}$ of free ICG. The result may be due
3 to the improved stability of ZHN/ICG NPs that enabled them to be well dispersed in
4 cell culture media and achieved robust photothermal conversion within cells⁴⁵. Further,
5 the cells that respectively incubated with ZHN/ICG NPs (ICG concentration: 0.025 mg
6 mL⁻¹) and free ICG (ICG concentration: 0.025 mg mL⁻¹) were irradiated twice with the
7 808 nm laser (Fig. 4b). In free ICG group, the cell viability after these two irradiations
8 showed slightly decrease, i.e., from 87.15% to 81.37%, while the corresponding value
9 in ZHN/ICG NPs group decreased by 25.60%, i.e., from 67.45% to 41.85%. These
10 comparative results confirmed that the enhanced therapeutic effect of ZHN/ICG is
11 indeed caused by their significantly improved stability. As an intuitive method to
12 indicate the *in vitro* photothermal effect, the CLSM imaging technique was adopted.
13 After drug formulation incubation and laser irradiation, the cells were stained by
14 propidium iodide (PI) dye to distinguish dead cells⁴⁶. Apparently, in the area covered
15 by laser irradiation, abundant red fluorescence signals were observed (Fig. 4c).
16 Moreover, the mean fluorescence intensity of PI in the ZHN/ICG NPs group was much
17 higher than that in the free ICG group (Fig. 4d). A detailed image (Fig. S10, ESI) of
18 ZHN/ICG NPs group showed the typical nucleus shrinkage after laser irradiation,
19 indicating the cell apoptosis. Taken together, these results suggest that the compatible
20 ZHN/ICG NPs have significant cell-killing ability after laser excitation, highlighting
21 the possibility for *in vivo* applications.





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Fig. 4 *In vitro* evaluation of ZHN/ICG NPs. (a) MTT assay of MCF-7 cells after exposure to different concentrations of ZHN/ICG NPs and free ICG (ICG concentration: 0.006-0.3 mg·mL⁻¹) with or without 808 nm laser irradiation (1.5 W cm⁻², 1 min). Error bars represent standard deviation (n = 6). (b) Cell viability of MCF-7 cells after incubated with the ZHN/ICG NPs and free ICG (ICG concentration 25 μg·mL⁻¹) and irradiated by 808 nm laser (1.5 W cm⁻², 1 min) twice. Error bars represent standard deviation (n = 6). (c) CLSM images of MCF-7 cells stained with PI dye. Before staining, MCF-7 cells were respectively incubated with ZHN/ICG NPs and free ICG (ICG concentration 150 μg·mL⁻¹) for 24 h, followed by the 808 nm laser irradiation (1.5 W cm⁻², 1 min). (d) Quantitative analysis of mean fluorescence intensity of MCF-7 cells after the treatment from Fig. (c). Error bars represent standard deviation (n = 3), and *P* values are calculated by one-way ANOVA **P* < 0.05.

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14 *In vivo* fluorescence imaging-guided PTT

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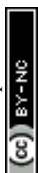
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Since the ZHN/ICG NPs retained the intrinsic fluorescence of ICG molecules, which can be used as imaging contrast to indicate the drug distribution, we first conducted the *in vivo* fluorescence imaging of ZHN/ICG NPs. The intratumoral injection mode, an emerging dosing delivery owing to its preferable drug accumulation and distribution in tumor tissue⁴⁷, was employed. After the injection of ZHN/ICG NPs (1.5 mg mL⁻¹, 50 μL), the mice were monitored (Fig. 5a), and the average fluorescence intensity in the tumor and liver was analyzed (Fig. S11, ESI). The fluorescence in the tumor gradually



1 increased within 4 h after injection, demonstrating the fully dispersion of ZHN/ICG
2 NPs. In the subsequent time intervals from 4 h to 48 h, the fluorescence in the tumor
3 gradually weakened, while the fluorescence in the liver showed a gradual increase,
4 especially from 2 h to 8 h, followed by a decrease after 8 h, probably owing to the quick
5 clearance of ZHN/ICG NPs from the body through liver metabolism⁴⁸. Taking the
6 optimal drug distribution into consideration, 4 h post-injection was selected as the
7 therapeutic window. Under the aforementioned time window, the mice tumors were
8 respectively injected with PBS (control), free ICG, and ZHN/ICG NPs and further
9 irradiated by 808 nm laser (0.8 W cm^{-2} , 10 min). An IR thermal mapping camera was
10 used to monitor the real-time photothermal conversion in situ (Fig. 5b and 5c). By
11 comparison, the average temperature of mice tumors in the ZHN/ICG NPs group was
12 elevated to $55.2 \text{ }^\circ\text{C}$ at the end of irradiation, which was much higher than $46.3 \text{ }^\circ\text{C}$ in
13 the free ICG group. Additionally, the average temperature of mice tumor injected with
14 PBS showed little increase. These data suggested the highly photothermal efficacy of
15 ZHN/ICG NPs, of which temperature ($\geq 50^\circ\text{C}$) is sufficient enough to cause irreversible
16 damage to tumors via coagulative cell necrosis⁴⁹. Such successful photo-ablation of
17 ZHN/ICG NPs eradicated tumor tissues, leaving dark burned scar at their original sites.
18 Then the scars healed within 21 days (Fig. 5d and 5e). In contrast, the tumors treated
19 with free ICG firstly shrunk but recurred at the 18-day post-injection, while the tumors
20 in the control group showed an increase after laser irradiation as well. These results
21 assured their high potency of ZHN/ICG NPs as photothermal agents. Moreover, the
22 body weights of mice in different groups were not affected significantly (Fig. 5f),
23 demonstrating the biosafety of treatment. Collectively, the ZHN/ICG NPs have
24 successfully demonstrated their photothermal efficiency and biocompatibility in the
25 fluorescence-imaging guided PTT application.



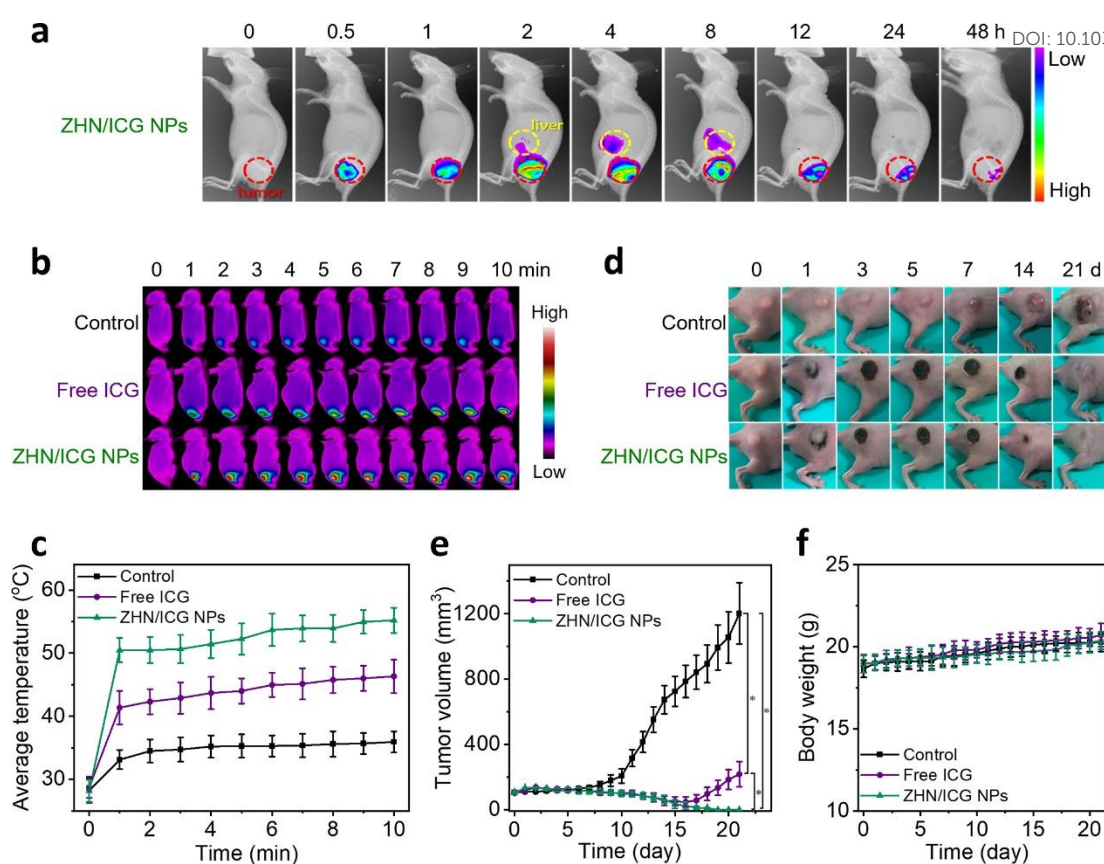


Fig. 5 *In vivo* evaluation of ZHN/ICG NPs. (a) Fluorescence images of mice bearing MCF-7 tumors after intratumorally injected with ZHN/ICG NPs (1.5 mg mL^{-1} , $50 \mu\text{L}$) at different time intervals. The red circles indicate the tumor and the yellow circles indicate the liver. (b) Representative IR thermal images and (c) average temperature of mice bearing MCF-7 tumors upon 808 nm laser irradiation (0.8 W cm^{-2} , 10 min) at 4 h post-injection of ZHN/ICG NPs and free ICG (ICG concentration of 1.5 mg mL^{-1} , $50 \mu\text{L}$), respectively. Error bars represent standard deviation ($n = 6$). (d) Representative images, (e) tumor volumes, and (f) body weights of mice bearing MCF-7 tumors at different time intervals after treatment. Error bars represent standard deviation ($n = 6$), and P values are calculated by one-way ANOVA $*P < 0.05$.

Conclusions

In summary, we have reported a kind of fluorescence imaging-guided photothermal nanotheranostics, which are co-assembled by the histidine derivatives (Z-His-NH₂, ZHN) and clinically used small photoactive indocyanine green (ICG) molecules. Through the combination of multiple noncovalent interactions, the ZHN/ICG nanoparticles (NPs) with high entrapment efficiency were successfully fabricated, which not only maintained the fluorescent properties of ICG molecules, but also enhanced stability against photo-degradation and physiological challenges. Under the diagnostic capabilities provided by fluorescence imaging, these ZHN/ICG NPs



1 effectively ablate tumor tissues without recurrence. Compared to existing
2 nanotheranostics, these nanoparticles offer significant advantages toward anti-tumor
3 clinical translation. On the one hand, the building blocks of both amino acid derivatives
4 and ICG are unparalleled biocompatible and biosafe. On the other hand, the
5 performance of as-prepared nanodrugs, including entrapment efficiency and stability,
6 can be flexibly regulated by the co-assembly strategy. Therefore, the nanodrugs
7 represented in this study hold promise for advancing anti-tumor treatment applications.

8 9 **Author contributions**

10 Shukun Li, Yudong Li and Mengqian Shi performed the experiments and data
11 analysis; Shukun Li, Ruirui Xing, and Xuehai Yan finished the original manuscript
12 writing and revision; Jan C. M. van Hest critically read the manuscript. All authors
13 discussed the results and implications.

14 15 **Data availability**

16 The data supporting this article have been included as part of the ESI.

17 18 **Conflicts of interest**

19 The authors declare no conflicts of interest.

20 21 **Acknowledgments**

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26 BioRender.com.

27 28 **References**

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Data availability

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The data supporting this article have been included as part of the Supplementary Information.

