Bandgap Engineered Polypyrrole–Polydopamine Hybrid with Intrinsic Raman and Photoacoustic Imaging Contrasts

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Supporting Information

ABSTRACT: Intrinsically multimodal nanomaterials have revealed their great potential as a new class of contrast agents. We herein report a bandgap engineering strategy to develop an intrinsically Raman-photoacoustic (PA) active probe that is based on semiconductor conjugated polymers. This dual modal probe is prepared by doping a semiconducting conjugated polymer with polydopamine (PDA) through a one-pot reaction. When applied in the polypyrrole (PPy), this strategy can enhance Raman scattering and the PA amplitude of PPy–PDA hybrid by 3.2 and 2.4 times, respectively, so that both signals can be further applied in bioimaging. In the hybrid, such a dual-enhancement effect is achieved by infusing these two macromolecules at the nanoscale to reduce the optical bandgap energy. This work not only introduces a dual modal contrast agent but also provides a new method of manipulating semiconducting polymer’s inherent optical features for bioimaging.

KEYWORDS: Semiconducting polymers, polydopamine, intrinsically multimodal nanomaterials, intermolecular electron transfer

In cancer diagnosis, noninvasive imaging technologies have long been used to gain comprehensive information on diseased tissues. Current imaging modalities have been widely applied for clinical applications and research purposes. However, they cannot reach high temporal/spatial resolution, high sensitivity and deep tissue penetration depth at the same time.1–3 This problem can be solved by combining different imaging techniques. For example, in surgeries imaging modalities with deep penetration depths, such as photoacoustic imaging (PAI), magnetic resonance imaging (MRI) and two-photon fluorescence imaging, are applied to locate the malignant tissue, while pure optical imaging modalities can be used to delineate the tumor tissues, such as fluorescence imaging and Raman imaging.1–6 Therefore, multimodal imaging contributes to efficacious diagnosis of and therapy for cancer.

Nanomaterials feature small sizes, high loading capacity, and imaging abilities. Those properties have been utilized to construct multimodal imaging nanoplatorms.7–9 On the basis of previous studies, strategies for constructing such nanoplatorms can be divided into two categories. Loading different contrast agents onto a single nanoplatorm is typically adopted because it is flexible for a variety of imaging modalities.10–12 However, in this strategy complicated synthetic processes and harmful agents reduce the dispersity and raise the potential toxicity of nanomaterials.13 The other strategy to avoid complicated synthetic processes is to develop nanomaterials with intrinsic multimodal imaging contrasts.14–16 These nanomaterials are mainly inorganic. For in vivo applications, inorganic nanomaterials have long blood circulation time and may be toxic to other organs.17,18 Hence, we aimed to explore the strategy for developing novel polymeric nanomaterials in this research.

Among various kinds of polymeric materials, semiconducting polymer nanomaterials (SPNs) possess unique optoelectronic features that extend their applications to optical theranostics, including fluorescence imaging, PAI, and photothermal therapy. Among their imaging signals, fluorescence and photoacoustic (PA) amplitude resulted from electron transition processes. Radiative electron transition pathways lead to fluorescence or photoluminescence, and nonradiative ones lead to PA amplitude. Because of the competing relationship between radiative and nonradiative pathways, it is hard to develop SPNs with increased PA amplitude and retain their fluorescence or photoluminescence.15,20 On the other hand, Raman scattering originates from the vibration and
rotation of molecular structures which is different from fluorescence and PA amplitude. When applied to bioimaging, Raman imaging has multiple advantages, including high resolution, in situ imaging and analysis, and nonphotobleaching. Semiconducting polymers have strong Raman scattering because of their large conjugated backbone. However, reports about using SPNs alone in Raman imaging are quite rare, which may be attributed to insufficient signal intensity for imaging as well as interference brought by the fluorescence of semiconducting polymers. The objective of this study is to explore a strategy to realize the potential of SPNs in Raman imaging without interfering with their PA amplitude. For clinical applications, PAI has a deep penetration depth (approximately several centimeters) to the local solid tumor, and Raman imaging has extremely high spatial resolution (approximately several micrometers) to delineate the malignant tissues. Raman-PA active probes have been proven to be useful in imaging-guided surgeries.

A new method has been developed here by using polydopamine (PDA) as a dopant to achieve the above purposes. PDA was adopted in this research for the following reasons: (1) PDA has tunable bandgap energy for manipulating...
ing optical features for a series of semiconducting polymers.25

(2) PDA has broad spectrum absorption and a “super quenching effect”, which can be used to reduce their fluorescence background and to increase the signal-to-noise ratio in Raman imaging.26 (3) The different functional groups, adhesive property, and biocompatibility of PDA have been applied widely in constructing multifunctional nanoplat-
forms.27,28 A frequently used semiconducting polymer, polypyrrole (PPy), was chosen because of its high photothermal conversion efficiency, strong Raman scattering, and biocompatibility.29,30 To our knowledge, using PPy as a Raman imaging probe can only be realized by modifying PPy with gold nanoparticles, which can enhance the Raman scattering of PPy by surface-enhanced Raman spectroscopy (SERS).31 However, because dopamine and pyrrole monomers were polymerized with different mechanisms, it is hard to infuse these two macromolecules on the nanoscale. In previous studies, PPy−PDA composites were prepared by using a chemical or electrochemical oxidation method. These irregular or micro-sized composites exhibit increased bandgap energy compared with that of PPy.32,33

In this work, a one-pot method was developed to infuse PDA with semiconducting polymers at the nanoscale. PPy was adopted to prepare a well-defined PPy−PDA hybrid on a silica template (SiO2). Amplification of both Raman scattering and PA amplitude for bioimaging was achieved by this PPy−PDA hybrid. The morphology and cytotoxicity of this core−shell nanoparticle (SiO2−CS@PPy−PDA) was first characterized, followed by in vitro investigation into the enhancement effect of both imaging signals and the interactions between these two macromolecules. In addition, the general applicability of this strategy was conducted by using another conjugated polymer, polyaniline (PANI). Finally, the feasibility of this nanoparticle for further functionalization and imaging is demonstrated.

Generally, the nanoscale shell of PPy−PDA hybrid was coated onto a silica (SiO2) nanoparticle through a one-pot reaction (see Scheme 1). In the core−shell nanoparticle, SiO2 serves as the supportive template for growth of the PPy−PDA hybrid. Bare SiO2 has negligible Raman scattering and PA amplitude compared with those of the PPy−PDA hybrid-coated SiO2 (Figure S1). Therefore, it will not impact the Raman scattering and PA amplitude of the PPy−PDA hybrid shell on SiO2 during in vitro and in vivo imaging. Chondroitin sulfate (CS) serves as the stabilizer to confine the growth of the PPy−PDA hybrid.34 At first, the morphology and dispersity of the as-prepared SiO2−CS@PPy−PDA nanoparticle is characterized by transmission electron microscopy (TEM) and dynamic light scattering (DLS). TEM images (Figure 1A), as well as nitrogen distribution originating from pyrrole and dopamine (Figure 1B), reveal the successful coating of a well-defined and nanoscale PPy−PDA hybrid (approximately 10 nm) onto a SiO2 nanoparticle (approximately 100 nm) (Figure 1C). DLS analysis shows that this nanoparticle is approximately 196 nm in average diameter and exhibits excellent

Figure 2. (A) Raman spectra of SiO2−CS@PPy−PDA nanoparticle, PPy nanoparticle, PDA nanoparticle, and the mixture of PPy and PDA nanoparticles; all spectra were acquired using a 785 nm laser and 1 s accumulation time. (B) Raman spectra of SiO2−CS@PPy−PDA nanoparticle acquired using 532 and 785 nm lasers. (C) UV−vis spectra of SiO2−CS@PPy−PDA nanoparticle, PPy nanoparticle, PDA nanoparticle, and the mixture of PPy and PDA nanoparticles. (D) Raman imaging of HeLa cells incubated with SiO2−CS@PPy−PDA nanoparticle (top) (a representative Raman spectrum is shown in Figure S5), the PPy nanoparticle (bottom left), and PDA nanoparticle (bottom right) for 3 h. The inserted pictures were the optical images of HeLa cells. All samples were measured in a phosphate buffer saline (pH = 7.4) with the same mass concentrations between the PPy nanoparticle, the PDA nanoparticle, the mixture of PPy and PDA nanoparticles and the PPy−PDA hybrid on the SiO2 template, which was estimated for the TGA analysis. The scale bar is 5 μm.
dispersity with nearly 0.1 polydispersity (Figure 1E). Furthermore, the sulfur element (Figure 1D), as well as the negative zeta potential of the SiO$_2$−CS@PPy−PDA nanoparticle (Figure S2), confirmed the presence of CS on the nanoparticle’s surface. CS is a naturally derived mucopolysaccharide and has been reported to further stabilize nanoparticles through blood circulation. Then, the bio-compatibility of the SiO$_2$−CS@PPy−PDA nanoparticle is characterized before further imaging tests are conducted. Assayed by CCK-8, the nanoparticle produces a negligible influence on the cell viabilities after being incubated with HeLa and A549 cells (Figure 1F). Therefore, the SiO$_2$−CS@PPy−PDA nanoparticle is biocompatible for further in vitro and in vivo imaging.

Then, a series of in vitro Raman imaging and PAI-related experiments were conducted to comprehensively investigate the intrinsic contrasts of the SiO$_2$−CS@PPy−PDA nanoparticle. In the Raman spectrum of this nanoparticle (Figure 2A), the signal intensity of the Raman band at approximately 1600 cm$^{-1}$ was 3.2 times higher than that of the PPy nanoparticle when the mass concentrations between PPy and the PPy−PDA hybrid on the SiO$_2$ template were the same (estimated from thermogravimetric analysis (TGA), Figure S3). In addition, the nanoparticle had negligible fluorescence signals, with no significant impact on the Raman scattering and PA amplitude in the bioimaging (Figure S4). Here, the PPy nanoparticle prepared by poly(vinyl alcohol) was used as a control group because it had been widely applied in the construction of theranostic nanomaterials. The mixture of PPy and PDA nanoparticles also did not exhibit any enhancement effect in another control experiment (blue line in Figure 2A). For the Raman imaging, current popularly adopted enhancement techniques are mainly surface-enhanced Raman spectroscopy (SERS) and resonance Raman spectroscopy (RRS). For SERS, usually noble metal nanoparticles act as the substrate to enhance the Raman scattering of the probes. These two facts lead to undesirable variation in signal intensity. By contrast, RRS originated from the resonance effect between the incident light and the electron transition energy. Moreover, RRS does not require noble metal substrates. However, existing RRS probes are mainly small molecules in the visible region. These probes are not suitable for in vivo applications because the penetration depth of visible light is only a few micrometers. For the SiO$_2$−CS@PPy−PDA nanoparticle, the absorption band of electron transition is located in the near-infrared region with a few millimeters of penetration depth. The signal intensity of the nanoparticle acquired by the 785 nm laser was 4.7 times higher than that acquired by the 532 nm laser (Figure 2B). Furthermore, no noble metal nanoparticle was introduced in this core−shell nanoparticle. These two facts support that increased Raman scattering of the SiO$_2$−CS@PPy−PDA nanoparticle is the resonance Raman effect. In this nanoparticle, amplified Raman scattering resulted from elevated light absorption in the near-
infrared region (pink line Figure 2C). Moreover, the enhancement of the relative intensity of the Raman band at approximately 1600 cm$^{-1}$, which is associated with the C=C stretching oscillation, can be attributed to the local electric field between PDA and PPy.$^{39}$ Therefore, this PPy−PDA hybrid with unique Raman scattering can be tracked without any further labeling process.

Then, the feasibility for cellular imaging was investigated by incubating HeLa cells with SiO$_2$−CS@PPy−PDA, as well as PPy and PDA nanoparticles, for 3 h. The color-decoded image acquired from the Raman band centered at 1600 cm$^{-1}$ of SiO$_2$−CS@PPy−PDA exhibits superior signal intensities compared with that of the PPy or PDA nanoparticle (Figures 2D and S5). This nanoparticle may also be applied for in vivo imaging because the Raman scattering intensity of the PPy−PDA hybrid on the SiO$_2$ template was close to that of single-walled carbon nanotubes (SWCNT) (Figure S6). To the best of our knowledge, SWCNT is the only RRS nanoprobe that has been applied widely in both in vitro and in vivo imaging.$^{40,41}$ This nanomaterial with similar Raman scattering and superior functionality has great potential for further applications.

PPy or PDA nanomaterials have a high light−heat conversion ability for PAI and photothermal therapy. In comparison with inorganic nanomaterials like gold nanorods, PPy and PDA have better photothermal conversion efficiency and stability under irradiation.$^{29,42}$ Interestingly, this nanoscale hybrid of PPy and PDA on the SiO$_2$ template also showed significant enhancement in the PA amplitude, which were 340% of PPy and 180% of PDA with the same mass concentrations (Figure 3A). Because the signal intensity of PAI is mainly impacted by photothermal conversion efficiency and the light absorption ability of contrast agents,$^{43}$ these two impact factors were investigated separately on the PA amplitude. The light−heat conversion abilities of the SiO$_2$−CS@PPy−PDA nanoparticle, PPy, PDA, and the mixture of PPy and PDA nanoparticles were estimated by irradiating the above samples under the same experimental conditions. Only the PPy−PDA hybrid can rapidly heat the medium to 55 °C, while suspensions of other photothermal agents only exhibited a mild increase of temperature after being irradiated for approximately 15 min (Figure 3B). The photothermal conversion efficiency of the SiO$_2$−CS@PPy−PDA nanoparticle is approximately 40.7%, which is superior to that of the PPy nanoparticle (29.6%) or the PDA nanoparticle (20.1%) (detailed calculation is given in the Supporting Information). On the other hand, light absorption in the near-infrared region of the PPy−PDA hybrid on the SiO$_2$ template is also higher than that of PPy, PDA, and their mixture (Figure 2C). Therefore, increased photothermal conversion efficiency,
as well as light absorption, contributes to the enhancement of PA amplitude. For further applications, the stability of this nanoparticle under irradiation and the relationship between PA amplitude and concentration were also studied. The PA amplitude of this nanoparticle remains stable after 3.4 × 10^4 pulses of exposure (Figure S7), whereas that of the gold nanorods decreases by approximately 30% under the same acquisition conditions. Moreover, the PA amplitude at 700 nm presented a linear relationship with the mass concentrations (Figure 3C), which suggested that the accumulation of the PPy−PDA hybrid could be measured quantitatively in vivo. In vitro PA images were also acquired by using SiO_2−CS@PPy−PDA nanoparticle-embedded gel cylinders with different concentrations (Figure 3D). All of these characteristics suggest that the SiO_2−CS@PPy−PDA nanoparticle is suitable for PAI.

The synergy between PPy and PDA in the hybrid may contribute to amplification in Raman scattering and PA amplitude because the mixture of PPy and PDA nanoparticles do not exhibit any enhancement effect on these two signal intensities (blue line in Figures 2A and 3A). For semiconducting conjugated polymers, their PA amplitude and resonance Raman scattering were correlated to the optical bandgap energy. The optical bandgap energy of a macroscopic amorphous semiconducting polymer can be processed from its UV-vis spectrum and estimated by Tauc’s plot. The calculated bandgap energies of the SiO_2−CS@PPy and SiO_2−CS@PPy−PDA prepared with the same experimental conditions were approximately 3.02 and 2.32 eV, respectively (Figure 4A). As determined from the above data, the integration of PDA by this method can reduce the optical bandgap energy.

For semiconducting polymers, the variation of bandgap energy could be attributed to changes in the conjugation length and doping of the secondary component. The conjugation length can be characterized by peak positions in the Raman spectrum of semiconducting conjugated polymers. The C=C stretching band peak at approximately 1600 cm⁻¹ showed no significant difference between SiO_2−CS@PPy−PDA and SiO_2−CS@PPy nanoparticles (Figure 4B). Furthermore, the FTIR spectrum of the SiO_2−CS@PPy−PDA nanoparticle did not exhibit any new peak compared with the SiO_2−CS@PPy and PDA nanoparticles (Figure S8). Because pyrrole and dopamine are polymerized with different mechanisms, PPy and PDA form a hybrid through physical interactions. In the hybrid, PDA acts as the dopant and reduces the bandgap energy through an intermolecular energy transfer process. From the molecular structures, conductive electrons can be transferred between PPy and PDA. The intermediate in the polymerization of dopamine, 5,6-dihydroxyindole, has a similar five-member heterocyclic-containing nitrogen atom compared with that of pyrrole monomers. The similarity in the molecular structure could contribute to the π−π interactions between PDA and PPy. Moreover, the absorption peak of PPy at approximately 800 nm represents the delocalized conductive π-electrons shifted to approximately 700 nm (Figure 2C). This phenomenon indicates that the integrated PDA can disrupt the chain packing of PPy. Hence, it can be concluded that the enhancement of the PA amplitude and Raman scattering resulted from the photoinduced electron transfer process between the PPy and PDA molecules.

Optimization of the experimental conditions was performed to approach the lowest bandgap energy in the PPy−PDA hybrid. To form better π−π stacking between PPy and PDA, two variables, the initial pH values and feeding ratio of pyrrole and dopamine monomers, were adjusted in the following experiments. First, considering the polymer chain structures, the dopamine monomer was the better dopant compared with PDA to form π−π interactions with PPy chains. However, the polymerization of dopamine cannot be inhibited in the conditions of pyrrole polymerization. This is because the oxidative reagents required in the pyrrole polymerization can also trigger dopamine polymerization. In this work, reduction of dopamine polymerization was performed by using acidic conditions to prepare the PPy−PDA hybrid because the oxidation of 5,6-dihydroxyindole would generate two protons during the polymerization of dopamine. The bandgap energies decreased by reducing the initial pH values of the reaction medium (Figure 4C). This result indicates that suppression of dopamine polymerization leads to better interactions between these two components. Then, the molar feeding ratio of two monomers is varied (n_Py/n_DA ranged from 10 to 0.1), because it is hard to analyze the contents of PPy and PDA in their hybrid form. The lowest point in the curve of n_DA versus E_g occurred with the increasing amount of dopamine. The above results indicate that incorporation of PDA could initially reduce the bandgap energies. At the same time, the excess amount of dopamine tends to form π−π stacking with each other rather than with PPy, which leads to reduced electron transfer and increased bandgap energy in the PPy−PDA hybrid (Figure 4D). Therefore, PDA can act as the dopant for manipulating the optical properties of various semiconducting conjugated polymers. To investigate general applicability of our strategy, some preliminary studies were performed by using PDA to dope polyaniline with similar experimental conditions. In comparison with PANI on SiO_2, the prepared PANI−PDA hybrid on the SiO_2 nanoparticle also exhibited reduced bandgap energy as well as enhanced Raman scattering and PA amplitude (Figure S9). These results can be improved further by modifying the experimental conditions. The strategy provided here can be utilized to develop a series of semiconducting conjugated polymer nanomaterials with intrinsic multimodal contrasts.

In addition to the dual amplification of Raman scattering and PA amplitude in this hybrid, diverse reactive sites of PDA can improve the functionality problem of PPy materials. In comparison with the penetration depth of optical imaging techniques (approximately several centimeters at most), MRI is a noninvasive imaging technique and can penetrate throughout the entire human body. Therefore, the SiO_2−CS@PPy−PDA nanoparticle is facilitated by the MRI contrast. Here, the complex formed between the dopamine and ferric ion acted as a T₁−weighted contrast agent. The iron concentration of the supernatant was measured by ICP-AES. According to the reduced iron concentration after the reaction, the ferric-dopamine complex was successfully loaded through π−π interactions between the complex and PPy−PDA hybrid on the SiO_2 nanoparticle (Table S1). The reciprocal of the T₁ relaxation time increased linearly with the ferric concentration (Figure S10), which suggested that this nanoparticle has potential as an MRI active probe. Reactive sites of PDA (such as catechol groups, amide) can also be conjugated with other functional units (including therapeutics, contrast agents) to further develop a multifunctional thanerotic agent. A targeting moiety, folic acid (FA), was conjugated to the SiO_2−CS@PPy−PDA nanoparticle. After being incubated with HeLa cells for 3 h, Raman spectrum of cells labeled with SiO_2−CS@PPy−
PDA–FA exhibited much clearer characteristic peaks in the PPy–PDA hybrid compared with those of cells labeled with unconjugated nanoparticles (Figure S11). Both results reveal that this hybrid material can serve as a platform for further physical or chemical modifications in developing multifunctional theranostic agents.

The SiO₂−CS@PPy−PDA nanoparticle prepared with optimized experimental conditions was applied for further in vivo imaging and detection. BALB/c experiments indicated that the SiO₂−CS@PPy−PDA nanoparticle did not raise any disorder in the liver/kidney functions, or in other blood panel parameters, according to the blood analysis (Figure S12, Table S2). Furthermore, no obvious damage to the major tissues was observed in the injected group according to the histological examinations (Figure S13). These results ensured that SiO₂−CS@PPy−PDA is biosafe for further in vivo imaging. First, the feasibility of this nanoparticle for PAI and Raman detection was investigated through intratumoral injection of A549-tumor-bearing mice. After the nanoparticles were injected, an intense PA signal could be clearly observed in the tumoral region (Figure S14). Simultaneously, the Raman spectrum acquired at the injected site revealed the distinct features of the as-prepared core−shell nanoparticle (black line in Figure 5A). High sensitivity and spatial resolution features of Raman scattering can help to rapidly recognize tumor tissues under the surface of normal tissues. Moreover, the biodistribution of injected nanoparticles in the tumoral region could be clearly delineated by the point mapping method after harvesting the solid tumors. (Figures 5B and S15). As mentioned in the introduction, such contrast agents with the combination of PAI with deep penetration depth and Raman imaging with high spatial resolution are useful for imaging-guided resection.

The accumulation of the SiO₂−CS@PPy−PDA nanoparticles in the tumor region and in the major organs through systematic administration was also investigated in this work. Before intravenous injection of as-prepared nanoparticles, the tumor region exhibited weak PA intensity at 700 nm, which originated from endogenous oxyhemoglobin and deoxyhemoglobin (Figure 5C, top). After systematic administration of the SiO₂−CS@PPy−PDA nanoparticles for 1 h, a significant enhancement of the PA intensity was observed in the tumoral region. In addition, the accumulated nanoparticles clearly delineated major blood vascular in malignant tissues (Figure 5C, down). Then, the SiO₂−CS@PPy−PDA nanoparticles started to clear from the tumor with decreasing PA intensity (Figure S16). In addition, after 24 h the ex vivo PA intensity of major organs and tumors were measured at 700 nm. In comparison with the PBS group, the ex vivo PA intensities of the SiO₂−CS@PPy−PDA nanoparticle group exhibited a significant increase in the liver and in the spleen (Figure S17). These results suggested that injected nanoparticles were mainly captured by the reticuloendothelial system (RES). Moreover, in comparison with the PBS group, the ex vivo Raman spectra acquired from the liver of the SiO₂−CS@PPy−PDA nanoparticles group also revealed the characteristic peak of this nanoparticle at approximately 900 and 1600 cm⁻¹ (red shaded area in Figure 5D). This result, in turn, proved that our nanoparticles were captured by RES. As a pure optical imaging

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**Figure 5.** (A) Raman spectra of SiO₂−CS@PPy−PDA nanoparticles acquired at the injected site (black line) and in the PBS buffer (pH = 7.4, red line). Raman spectra were acquired with a 785 nm laser and 10 s accumulation time. (B) Raman images of a resected tumor tissue (a representative Raman spectrum is in Figure S15). (C) PA images were acquired at 700 nm of the tumor before (top) and after (down) injecting the SiO₂−CS@PPy−PDA nanoparticles. (D) Ex vivo Raman spectra of livers harvested from PBS group and SiO₂−CS@PPy−PDA nanoparticles group. Raman spectra were acquired with a 785 nm laser and 10 s accumulation time.
technique, the inherently weak Raman scattering largely constrained its applications in noninvasive imaging. Generally, abundant Raman probes should be enriched in the malignant tissues and thus can generate detectable signals for in vivo imaging. Therefore, this nanomaterial can also be applied for further in vivo imaging by being modified with targeting moieties.

In summary, we proposed a convenient doping method to develop intrinsically dual modal semiconducting polymers. Doping PDA works to reduce the optical bandgap energy of different semiconducting conjugated polymers. In the PPy–PDA hybrid prepared by this method, the Raman scattering and PA brightness were enhanced 3.2- and 2.4-fold, respectively, compared with those of PPy. These two enhanced signals can be used for both in vitro and in vivo imaging and detection. Moreover, the substantial functionality of this hybrid holds great promise for further development of multifunctional theranostic agents.

Most studies about semiconducting polymers in bioimaging focus on two competing optical processes, fluorescence imaging and PA amplitude, which cannot be enhanced simultaneously. The method proposed here can promote a different optical process, Raman scattering, for bioimaging without interference with the PA amplitude. Moreover, for Raman imaging the PDA dopant can realize the potential of semiconducting polymers in bioimaging by increasing their signal-to-noise ratio. With better understanding of the molecular structures and chain packing in semiconducting polymers, this method can be adopted further to develop other PDA-doped materials with more enhanced imaging abilities.

**REFERENCES**


**ASSOCIATED CONTENT**

4 Supporting Information

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Detailed experimental procedures and supplementary results (PDF)

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**Notes**

The authors declare no competing financial interest.

**ABBREVIATIONS**

PPy, polypyrrole; PDA, polydopamine; PANI, polyaniline; MRI, magnetic resonance imaging; PAI, photoacoustic imaging; PA, photoacoustic; SERS, surface-enhanced Raman spectroscopy; RRS, resonance Raman spectroscopy; SiO2, silica; CS, chondroitin sulfate; SWCNT, single-walled carbon nanotubes


