Tuning the Bandgap of Photo-Sensitive Polydopamine/Ag$_3$PO$_4$/Graphene Oxide Coating for Rapid, Noninvasive Disinfection of Implants

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Supporting Information

ABSTRACT: Bacterial infection and associated complications are threats to human health especially when biofilms form on biomedical devices and artificial implants. Herein, a hybrid polydopamine (PDA)/Ag$_3$PO$_4$/graphene oxide (GO) coating is designed and constructed to achieve rapid bacteria killing and eliminate biofilms in situ. By varying the amount of GO in the hybrid coating, the bandgap can be tuned from 2.52 to 2.0 eV so that irradiation with 660 nm visible light produces bacteria-killing effects synergistically in concert with reactive oxygen species (ROS). GO regulates the release rate of Ag$^+$ to minimize the cytotoxicity while maintaining high antimicrobial activity, and a smaller particle size enhances the yield of ROS. After irradiation with 660 nm visible light for 15 min, the antimicrobial rates of the PDA/Ag$_3$PO$_4$/GO hybrid coating against Escherichia coli and Staphylococcus aureus are 99.53% and 99.66%, respectively. In addition, this hybrid coating can maintain a repeatable and sustained antibacterial efficacy. The released Ag$^+$ and photocatalytic Ag$_3$PO$_4$ produce synergistic antimicrobial effects in which the ROS increases the permeability of the bacterial membranes to increase the probability of Ag$^+$ to enter the cells to kill them together with ROS synergistically.

INTRODUCTION

Artificial implants for surgical repair or reconstruction of damaged tissues are prone to bacterial infection because the interfaces between the implants and surrounding tissues provide the space for bacterial growth.\(^1\) To solve this problem, antimicrobial agents are introduced,\(^2,3\) but traditional treatment usually requires a long antimicrobial cycle which in turn results in the development of drug-resistant bacteria and prolongs patient suffering.\(^4,5\) Hence, it is important to develop a novel, instantaneous, and efficient antimicrobial method. Reactive oxygen species (ROS) such as peroxide, superoxide, hydroxyl radicals, and singlet oxygen possess rapid bacteria-killing ability,\(^8–10\) because they can damage the DNA, proteins, and membranes of bacteria without producing drug-resistant bacteria.\(^11,12\) Furthermore, ROS can be generated instantaneously to kill bacteria quickly in a short antimicrobial cycle.\(^13\) ROS are normally produced by the combination of O$_2$ with escaping electrons from various photosensitive materials under irradiation with photons of the appropriate wavelength,\(^14–16\) but in the complex in vivo environment, production of ROS is often limited by the lack of oxygen and that only light with a certain wavelength can penetrate skin tissues.

Ag$_3$PO$_4$ has remarkable photocatalytic capability\(^17,18\) and can produce a large amount of ROS during light exposure.\(^19,20\) Ag$_3$PO$_4$ is soluble in water to release Ag$^+$,\(^21\) and so bacteria can be synergistically killed by the generated ROS and released Ag$^+$.\(^22,23\) However, with regard to in vivo antimicrobial application, the
shortcoming is that it is difficult to control the release rate of Ag⁺ and a high silver concentration is detrimental. In addition, Ag₃PO₄ with a bandgap of 2.52 eV can only be excited by visible light that cannot readily penetrate human skin. Therefore, it is necessary to find an appropriate carrier to load Ag₃PO₄ and tune the bandgap so that light with a longer wavelength can be used for in situ antimicrobial therapy. In this respect, graphene oxide (GO) is a desirable host to load nanoparticles due to the large specific surface area and oxygen-containing functional groups. Owing to its excellent electrical conductivity, GO can mitigate recombination of photogenerated electron−hole pairs by rapid transfer of the electron−hole pairs from the photocatalyst to GO to enhance the photocatalytic properties. GO has been utilized to adjust the bandgap of some semiconductor nanomaterials like ZnO and ZnS by forming chemical bonds at the interface between the nanoparticles (NPs) and GO sheets. It has been shown that GO with oxygen-containing functional groups can chelate with Ag⁺ to abate leaching of Ag⁺ and reduce the cytotoxicity, thereby opening the possibility of long-term prevention of bacterial infection if Ag ions are released gradually from the Ag-containing coatings to the surroundings. At the same time, polydopamine (PDA) with excellent biocompatibility also can reduce the cytotoxicity of Ag⁺ and easily combine with other materials.

Herein, we report a controllable, rapid, and efficient in situ disinfection technique by exploiting the synergistic actions of Ag⁺ and ROS produced by the hybrid Ag₃PO₄/GO coating which combines with Ti by PDA under irradiation with 660 nm visible light leading to damage of the bacterial cell membranes, proteins, and DNA.

### RESULTS AND DISCUSSION

**Characterization of Ag₃PO₄/GO Nanofilm.** The X-ray diffraction (XRD) patterns in Figure 1a show the typical (002) diffraction peak assigned to GO at 2θ ≈ 10° and peaks of Ag₃PO₄ at 2θ of 21°, 30°, 34°, 37°, 48°, 53°, 56°, and 58° from PDA/Ag₃PO₄-Ti confirming successful preparation of GO nanosheets and Ag₃PO₄ NPs on Ti. However, after Ag₃PO₄ combines with GO in either PDA/Ag₃PO₄/GO-Ti or PDA/Ag₃PO₄/GO-PEEK, the typical Ag₃PO₄ peaks still exist but that of GO disappears, indicating that Ag₃PO₄ NPs are incorporated into the GO nanosheets and the structure of GO is destroyed. Also, the width of the (110) peak obviously increases because the electrostatic adsorption of GO favors the uniform distribution of Ag₃PO₄ NPs, while for PDA/Ag₃PO₄-Ti, those Ag₃PO₄ NPs may aggregate with each other to form particles with a larger size. Transmission electron microscopy (TEM) results in Figure 1b of GO and Ag₃PO₄/GO-4 (according to the size of Ag₃PO₄, the samples are designated as Ag₃PO₄/GO-1 to -4) show that GO is a translucent sheet with many folds, thus favoring loading of NPs. As for Ag₃PO₄/GO-4, the Ag₃PO₄ NPs are homogeneously distributed on the surface of the GO sheets, and the average size of the nanodots is about 10 nm. According to Figure S1, the weight of GO accounts for 29.19% of Ag₃PO₄/GO-4, and H₂O accounts for 1.71%. So the weight of Ag₃PO₄ accounts for 69.1% of Ag₃PO₄/GO-4, and the mass ratio of Ag₃PO₄ and GO is 2.37:1. The encapsulating efficiency of the system is about 70.32% by mass. The SEM images of PDA/Ag₃PO₄/GO-Ti-4 (according to the size of Ag₃PO₄, the PDA/Ag₃PO₄/GO coatings on Ti are labeled PDA/Ag₃PO₄/GO-Ti-1 to -4) and PDA/Ag₃PO₄/GO-PEEK-4 (the PDA/Ag₃PO₄/GO-4 coating covered on PEEK surface) (Figure 1b) show that PDA/Ag₃PO₄/GO adheres to Ti or PEEK, and the Ag₃PO₄ NPs are homogeneously distributed. Figure S2a shows that the other PDA/Ag₃PO₄/GO-Ti samples contain Ag₃PO₄ NPs with sizes of about 150, 80, 40, and 10 nm.
Figure 1. Structural and physical properties of Ag3PO4/GO. (a) XRD spectra of PDA/GO-Ti, PDA/Ag3PO4-Ti, PDA/Ag3PO4/GO-Ti, and PDA/Ag3PO4/GO-PEEK; (b) TEM images of GO and Ag3PO4/GO with the size of Ag3PO4 NPs being 10 nm and SEM images of PDA/Ag3PO4/GO-Ti and PDA/Ag3PO4/GO-PEEK together with the EDS data; (c) zeta potential of GO, Ag3PO4, as well as Ag3PO4/GO (0.347 mg/mL:0.0625 mg/mL). The error bars indicate means ± SD (n = 3); (d) Ag+ release concentration profiles obtained by immersing five samples in 5 mL of neutral PBS at 37 °C. The error bars indicate means ± SD (n = 3); (e) force–displacement curve acquired by the nanoscratch test and (f) load–displacement curve by the nanoindentation test of PDA/Ag3PO4/GO-Ti and PDA/Ag3PO4/GO-PEEK to show the critical load and Young's modulus.
According to the zeta potential shown in Figure 1c, Ag₃PO₄ is positively charged, while GO is negatively charged. Hence, Ag₃PO₄ can easily bond with GO electrostatically, and the hybrid Ag₃PO₄/GO is negative. Moreover, PDA can combine with GO by intermolecular hydrogen bonds, and the Ag₃PO₄/GO hybrid can be easily deposited on the surface of PDA-modified Ti substrate (sample designated as PDA/Ag₃PO₄/GO-Ti).

Although the released Ag⁺ plays an important role in bacteria killing and prevention of bacterial infection, excessive release of Ag⁺ causes toxic effects. Figure 1d shows that the PDA/Ag₃PO₄/GO-Ti samples exhibit the same Ag⁺ release behavior regardless of the NPs size, and relatively stable release is observed in the initial 18 days. Subsequently, the release rate decreases, but Ag⁺ could still be released even after nearly 30 days. The corresponding total concentration of Ag⁺ is 251.01 μg/L, which was determined by inductively coupled plasma-atomic emission spectrometry (ICP-AES), much higher than those released from PDA/Ag₃PO₄/GO-Ti samples after immersion in PBS for 30 days, indicating that PDA/Ag₃PO₄/GO-Ti samples can provide a sustained Ag⁺ release over 30 days. Compared with PDA/Ag₃PO₄/GO-Ti, the PDA/Ag₃PO₄-Ti group exhibits a larger release of Ag⁺ and accumulative Ag⁺ concentration initially but almost no Ag⁺ release after 18 days. The results suggest that GO mitigates the release of Ag⁺ electrostatically. After immersion in PBS for one month, the surface morphology of PDA/Ag₃PO₄/GO-Ti changes only a little (Figure S2b), but the Ag signal detected by EDS decreases slightly due to the leaching of Ag from the coating surface, indicating that the hybrid nanofilm provides sustained Ag⁺ release, thus bonding well for long-term prevention of bacterial infection.

The thickness of the PDA/Ag₃PO₄/GO coating is about 500 nm according to the cross-sectional image and EDS mappings of Ag in Figure S2c. The binding force between the hybrid nanofilm of PDA/Ag₃PO₄/GO and substrate is determined by the nanoscratch tests (Figure 1e). The critical load is 0.9 mN, indicating that Ag₃PO₄/GO adheres well to the Ti substrate through PDA. The Young’s modulus is 11 GPa (Figure 1f), which is similar to that of natural bone, thus reducing the stress shielding effect and rendering the materials more suitable for bone reconstruction than Ti and Ti alloys (55−110 GPa).
Moreover, Ag₃PO₄/GO can be deposited on PDA-modified PEEK (Figure S2c). The critical load of 1.4 mN (Figure 1e) reveals good bonding strength between the nanofilm and PEEK and the Young’s modulus of PDA/Ag₃PO₄/GO-PEEK is about 5 GPa (Figure 1f), which is also quite close to that of natural bone. Hence, PDA/Ag₃PO₄/GO can be applied onto both metallic and polymeric biomaterials.

**Photocatalytic Properties.** As shown in Figure 2a, PDA/GO-Ti does not exhibit characteristic absorption at wavelengths between 450 and 700 nm. The characteristic absorption wavelength of PDA/Ag₃PO₄-Ti is about 470 nm, which corresponds to the bandgap of 2.52 eV (Figure 2b).²⁻⁴²⁻⁴³ Hence, Ag₃PO₄ does not have photocatalytic antimicrobial ability in vivo because 470 nm visible light cannot penetrate skin tissues. Therefore, it is necessary to adjust the absorption wavelength of Ag₃PO₄ to trigger the photocatalytic ability inside the body. After GO nanosheets are introduced, the absorption wavelength is altered (Figure 2a). For example, the absorption wavelengths of PDA/Ag₃PO₄/GO₁-Ti (Ag₃PO₄/GO = 41.86 mg/mL:0.0625 mg/mL) and PDA/Ag₃PO₄/GO₂-Ti (Ag₃PO₄/GO = 20.93 mg/mL:0.0625 mg/mL) are 490 and 510 nm corresponding to bandgaps of 2.47 and 2.38 eV, respectively (Figure 2b). A larger GO ratio in Ag₃PO₄/GO is observed to red-shift the absorption wavelength of the Ag₃PO₄ NPs. When the ratio between Ag₃PO₄ and GO is 0.347 mg/mL:0.0625 mg/mL (PDA/Ag₃PO₄/GO-Ti), the absorption wavelength shifts to about 660 nm, and the corresponding bandgap is reduced to 2.0 eV (Figure S3), which is not related to the size of Ag₃PO₄. This means that 660 nm visible light can trigger the photocatalytic activity of PDA/Ag₃PO₄/GO-Ti. The change can be ascribed to the structural change at the interface between Ag₃PO₄ and GO as indicated by Raman scattering. As shown in Figure 2c, the Raman peaks of Ag₃PO₄ are at 560, 720, 930, and 1020 cm⁻¹,⁴⁵ but the peaks from Ag₃PO₄ in Ag₃PO₄/GO-4

![Figure 3](image-url)
decrease significantly, suggesting that the structure of Ag₃PO₄ has changed after combining with GO. There are two characteristic peaks, one at 1350 cm⁻¹ corresponding to the D band of sp³ defects and the other at 1595 cm⁻¹ associated with the G band of the sp² plane vibration in GO and Ag₃PO₄/GO.⁴⁶ The intensity ratio of the D band to G band (I_D/I_G) represents the ratio of defects. As shown in Figure 2c, I_D/I_G of GO is 0.886 and increases to 0.914 in Ag₃PO₄/GO-4 due to the strong interfacial interaction between GO and Ag₃PO₄ and change of sp² (C≡C) to sp³. Hence, according to the Raman results and Figure 1a, the structures of both Ag₃PO₄ and GO in Ag₃PO₄/GO-4 have changed with the formation of the Ag–O–C bond at the interface between the Ag₃PO₄ NPs and GO nanosheets. This also explains why the XRD peaks of GO disappear from PDA/Ag₃PO₄/GO-Ti (Figure 1a). The combination of GO nanosheets and Ag₃PO₄ NPs lowers the bottom of the conduction band of Ag₃PO₄ by facilitating interfacial electron transfer and electron–hole pair separation consequently reducing the bandgap of Ag₃PO₄. As a result, the photocatalytic activity of Ag₃PO₄/GO can be triggered by 660 nm visible light irradiation. Furthermore, previous studies have revealed that GO has the up-conversion photoluminescence (UCPL) ability to improve light absorption.⁴⁷–⁴⁹ UCPL occurs when the photon energy of emission is higher than that of excitation (Figure S4).⁵⁰ Hence, GO may absorb 660 nm visible light (2.0 eV) to emit photons with higher energy (2.52 eV) to further enhance the photocatalytic activity of Ag₃PO₄.

ROS are produced from PDA/Ag₃PO₄/GO-Ti during 660 nm visible light irradiation to strengthen the antimicrobial effects.¹⁵,⁵² Figure 2d shows the amounts of ROS generated from different samples. The PDA/Ag₃PO₄/GO-Ti series samples show higher ROS yields than either PDA/GO-Ti or PDA/Ag₃PO₄-Ti, indicating that GO improves the photocatalytic activity of Ag₃PO₄ as discussed above. The ROS yields from PDA/Ag₃PO₄/GO-Ti decrease with increasing size of Ag₃PO₄ NPs because smaller Ag₃PO₄ has a larger specific surface area with more conduction electron oscillation helping to absorb photons and produce more electrons. The electrons are transferred to the GO surface to produce ROS after contacting O₂ giving rise to better photocatalytic properties.

**Antimicrobial Tests.** As shown in the first-row image in Figure S5, the spread plate results indicate almost the same bacterial numbers of *Staphylococcus aureus* for all the groups in the dark for 15 min revealing no antimicrobial effects without light. In contrast, after exposure to 660 nm visible light for 15 min, the PDA/Ag₃PO₄/GO-Ti samples show decreased bacterial numbers, although the pure Ti group still shows the same results as those without light (second row in Figure S5). Hence, 660 nm visible light can stimulate the antimicrobial ability of Ag₃PO₄/GO but not pure Ti. The antimicrobial efficacy of the PDA/Ag₃PO₄/GO-Ti samples is higher than 98% (Figure 3a). Compared to PDA/Ag₃PO₄/GO-Ti, both the PDA/GO-Ti and PDA/Ag₃PO₄-Ti groups have much lower antimicrobial rates of 29.24% and 91.24%. These results are consistent with the ROS yields shown in Figure 2d, which discloses that 660 nm visible light irradiation stimulates Ag₃PO₄/GO to produce more ROS to kill bacteria with a better efficiency.²⁴,⁵⁵ The results suggest that the hybrid of Ag₃PO₄ and GO has better photostimulated antimicrobial ability. As for the PDA/Ag₃PO₄/GO-Ti series samples, the amounts of *S. aureus* decrease gradually with decreasing Ag₃PO₄ size (Figure S5). The antimicrobial rates of PDA/Ag₃PO₄/GO-Ti-1, PDA/Ag₃PO₄/GO-Ti-2, PDA/Ag₃PO₄/GO-Ti-3, and PDA/Ag₃PO₄/GO-Ti-4 against *S. aureus* are 98.18%, 99.2%, 99.66%, and 99.66%.

Figure 4. Surface morphology of the bacteria on the sample surface. (a) Intact bacterial membranes after culturing for 15 min in darkness versus shrunken or broken membranes (marked by red arrows for *E. coli* and blue arrows for *S. aureus*, respectively) after culturing for 1 day in darkness or irradiation for 15 min with 660 nm visible light; (b) SEM images of the biofilm formed on the samples after exposure to 660 nm visible light for 15 min or in darkness for 15 min (dead *S. aureus* marked by purple arrows). The scale bar is 1 μm. Each test was done in triplicate.
respectively (Figure 3a), implying that the antimicrobial efficacy can be improved by reducing the size of the Ag3PO4 NPs and the corresponding higher yields of ROS (Figure 2d). In the case of Escherichia coli, it exhibits a similar trend, and the corresponding antibacterial efficacy is 98.91%, 99.06%, 99.30%, and 99.53% for PDA/Ag3PO4/GO-Ti-1, PDA/Ag3PO4/GO-Ti-2, PDA/Ag3PO4/GO-Ti-3, and PDA/Ag3PO4/GO-Ti-4, respectively. After photodynamic antimicrobial test and subsequent immersion in PBS for 7 days, all the samples in the PDA/Ag3PO4/GO-Ti series show a repeatable antimicrobial rates over 97.79% and 91.27% against E. coli and S. aureus, respectively (Figure 3b), indicating that Ag3PO4/GO can produce repeatable and sustained photocatalytic antimicrobial effects. Compared to the first antimicrobial cycle, the photocatalytic antimicrobial activity of the Ag3PO4-based coatings diminishes slightly afterward due to release of Ag⁺ after immersion in PBS for 7 days.

Although electrostatic adsorption between GO and Ag3PO4 makes Ag3PO4 more stable, Ag⁺ is still slowly released (Figure 1d), and both PDA/Ag3PO4/GO-Ti and PDA/Ag3PO4-Ti release Ag⁺ to kill bacteria. As shown in Figure 5S, after culturing for 1 day in darkness, both PDA/Ag3PO4-Ti and PDA/Ag3PO4/GO-Ti exhibit excellent antimicrobial activity against S. aureus with the former showing better antimicrobial efficiency because PDA/Ag3PO4-Ti can release more Ag⁺ than PDA/Ag3PO4/GO-Ti due to electrostatic adsorption (Figure 1d). In the case of E. coli, spread plates test exhibit similar results (Figure 5S). The physical antimicrobial rates of PDA/Ag3PO4/GO-Ti-4 are 98.91% and 98.64% against E. coli and S. aureus, respectively (Figure 3c).

Formation of biofilms is fatal to implants, and traditional treatment is usually not effective in removing biofilms. As shown in Figure 3d and Figure 5S, although Ag⁺ leached from the coatings can kill bacteria efficiently after culturing for 1 day in darkness, it does not work for biofilms. The bacteria cultured from those peeled from the formed biofilm on samples by ultrasonic vibration spread on the samples after 1 day in the absence of light, and the antimicrobial rate is less than 20% (Figure 3d). After exposure to 660 nm visible light for 15 min, the amounts of bacteria on Ag3PO4 and Ag3PO4/GO decrease obviously, showing antimicrobial rates of over 94.39% against S. aureus, suggesting 660 nm light irradiation for a short time can break the biofilms on both PDA/Ag3PO4-Ti and PDA/Ag3PO4/GO-Ti. When the light exposure time is increased to 30 min, no bacteria are observed (Figure S5), providing evidence that the biofilms are completely destroyed.

During light irradiation, the surface temperature of the samples rises inevitably (Figure 5S). The surface temperature quickly rises at first and then stays at a constant value below 44 °C during exposure for 15 min. The spread plate results in Figure 5S disclose that there is no difference between 45 and 37 °C for both E. coli and S. aureus, indicating that a temperature below 45 °C has no effects on the bacteria within 15 min.

Figure 4a shows the bacterial morphology on the different samples. For the three groups of samples in darkness for 15 min, both E. coli and S. aureus have the normal shape. In contrast, after irradiation for 15 min by 660 nm visible light, the two bacteria are deformed to different degrees as manifested by membrane damage for PDA/GO-Ti, PDA/Ag3PO4-Ti, and serious membrane shrinkage and cracking on PDA/Ag3PO4/GO-Ti (marked by red arrows). Although the membranes of the bacteria cultured in the dark for 1 day are also deformed to some extent due to the action of released Ag ions (marked by blue arrows), the damage is lower than that after 660 nm light irradiation for 15 min, indicating that photocatalytic antimicrobial activity of Ag3PO4/GO is more effective than that resulting from the released Ag⁺ ions. As shown in Figure 4b, the biofilms of S. aureus have almost the same morphology on the three kinds of samples in the dark for 15 min, indicating no antimicrobial activity. After irradiation with 660 nm light for 15 min, the biofilm still exists on the surface of PDA/GO-Ti with few dead bacteria (marked by pink arrows) but those on PDA/Ag3PO4-Ti and PDA/Ag3PO4/GO-Ti disappear as indicated by collapsed bacterial cells (marked by pink arrows). That is, PDA/GO-Ti cannot resist the formation of biofilms but those on PDA/Ag3PO4-Ti and PDA/Ag3PO4/GO-Ti are destroyed with the latter showing better results. These results are consistent with the spread plate results in Figure 5S. The effects of the Ag₃PO₄ size on the bacterial morphology are shown in Figure 5S. Similarly, the bacteria retain a normal shape in the dark for 15 min on all samples irrespective of particle size. After 660 nm light irradiation for 15 min, the deformation degree increases with decreasing particle size decreases due to the different yields of ROS (Figure 2d). Although bacterial deformation appears after culturing for 1 day in darkness, there is almost no difference because the amount of released Ag⁺ is almost the same despite the Ag₃PO₄ size.

**Antimicrobial Mechanism.** ROS kill bacteria by destroying the cell membranes, proteins, and DNA. The extent of damage...
to the bacterial membrane can be determined by detecting the proteins leached from damaged bacterial cells. No protein is released from the intact bacteria during the centrifuge process, and a larger content of released protein means more damaged bacteria. The bacterial membrane damage rate is shown in Figure 5a. As for pure Ti group, it cannot destroy the bacterial membrane, so the amount of protein is defined as zero.

Compared to the pure Ti group, damaged bacterial membrane for the other group is observed after irradiation for 15 min with 660 nm light, and the extent of damage varies with the ROS amounts produced from different samples, i.e., higher ROS yields producing more damage. For example, the most serious membrane damage observed from PDA/Ag$_3$PO$_4$/GO-Ti is caused by the highest ROS yield as shown in Figure 2d. After the bacterial membrane is broken, ROS destroys the intracellular proteins (Figure 5b) and DNA (Figure 5c). The bacterial proteins and genomic DNA are collected and detected by BCA protein assay kit (cat. no. P0010, Beyotime, China) and BIO-RAD (CFX Connect, Real-Time System). Pure Ti group also cannot destroy the proteins and genomic DNA, so it can be collected from the bacteria on the light-illuminated pure Ti group that are intact. But those sampled from the samples irradiated with 660 nm light show damage to a different degree. All in all, a
higher ROS yield produces more serious protein and DNA damage. Synergistic bacteria killing by ROS and Ag⁺. The spread plate and antibacterial ratio histogram in Figure 6a,b disclose that either PDA/Ag₃PO₄/GO-Ti or Ag⁺ alone cannot kill most of the bacteria after irradiation for 10 min by 660 nm visible light. However, when Ag⁺ and ROS are both present (PDA/Ag₃PO₄/GO-Ti + Ag⁺), higher antimicrobial efficacy is achieved. According to our results, ROS produced in 10 min are not enough to kill most of the bacteria (Figure 6a,b). But ROS can change the permeability of the bacterial membranes (Figure 5a), which can be beneficial for Ag⁺ entering into the inside of the bacteria. It can be proven by Figure 6c. The bacterial membranes on the light-irradiated Ti samples are intact and thick, and no Ag signal can be detected from inside the bacteria. The bacterial section images obtained from the light-irradiated PDA/Ag₃PO₄/GO-Ti and Ag⁺ samples show the same morphology, and EDS cannot detect Ag from inside the bacteria. However, for the PDA/Ag₃PO₄/GO-Ti + Ag⁺ group, the membranes of both E. coli and S. aureus are damaged almost completely, and EDS shows Ag penetration into the bacteria. These results confirm that ROS produced by PDA/Ag₃PO₄/GO-Ti after irradiation for 10 min by 660 nm visible light are insufficient to kill most of the bacteria, but with the aid of Ag⁺ penetrating the membranes, they are killed within 10 min after the ROS damage the cell membranes. The Ag⁺ entering the bacteria continue to destroy the membrane, intracellular proteins, and DNA to kill the bacteria. The large white space in the bacteria results from the leakage of damaged proteins and DNA.

**In Vitro Cytocompatibility.** The numbers of cells living on the surface of the samples represent the biocompatibility of the samples. As shown in Figure 7a, the PDA/Ag₃PO₄−Ti samples show increasing cytotoxicity with the increase of culture time in darkness due to the highest concentration of Ag⁺ released from the coating (Figure 1d). In contrast, the PDA/Ag₃PO₄/GO-Ti samples exhibit lower cytotoxicity due to the electrostatic adsorption between Ag₃PO₄ and GO. For example, after culturing for 1 day, the PDA/Ag₃PO₄/GO-Ti samples exhibit the highest cell viability of 88%, while the viability of other groups is between 60 and 80% with the following order PDA/Ag₃PO₄/GO-Ti-2 > PDA/Ag₃PO₄/GO-Ti-3 > PDA/Ag₃PO₄/GO-Ti-4 because Ag₃PO₄ with a smaller size has a larger surface area that leads to relatively higher Ag⁺ release concentration (Figure 1d), thus showing lower cell viability. However, as the culturing time increases, the cell viability of all PDA/Ag₃PO₄/GO-Ti samples is increased. After 7 days of culturing, the cell viability of both PDA/Ag₃PO₄/GO-Ti-1 and PDA/Ag₃PO₄/GO-Ti-2 is close to the level of pure Ti. Even for both PDA/Ag₃PO₄/GO-Ti-3 and PDA/Ag₃PO₄/GO-Ti-4, their cell viability is also enhanced and close to 80%. Besides the reduced releasing rate of Ag⁺ as the culturing time increases, it has been reported that PDA can also increase biocompatibility. In addition, the number of cells on the PDA/Ag₃PO₄/GO-Ti samples increases with cultured time because Ag⁺ release diminishes with time. As shown in Figure 7b, after culturing for 7 and 14 days, all PDA/Ag₃PO₄/GO-Ti samples exhibit higher ALP activity compared to pure Ti, indicating the better osteogenic ability of PDA/Ag₃PO₄/GO-Ti samples. Furthermore, Ag₃PO₄ can be partially decomposed to produce Ag⁺, which is favorable for the growth of osteoblasts by the microgalvanic effect between Ag and Ti. In addition, the cell morphologies on those samples also do not change obviously (Figure 7c).

However, irradiation for 15 min under 660 nm visible light significantly weakens the cytocompatibility of PDA/Ag₃PO₄/GO-Ti samples due to the highest concentration of Ag⁺ released from the coating (Figure 1d). In contrast, the PDA/Ag₃PO₄/GO-Ti samples exhibit lower cytotoxicity due to the electrostatic adsorption between Ag₃PO₄ and GO. For example, after culturing for 1 day, the PDA/Ag₃PO₄/GO-Ti samples exhibit the highest cell viability of 88%, while the viability of other groups is between 60 and 80% with the following order PDA/Ag₃PO₄/GO-Ti-2 > PDA/Ag₃PO₄/GO-Ti-3 > PDA/Ag₃PO₄/GO-Ti-4 because Ag₃PO₄ with a smaller size has a larger surface area that leads to relatively higher Ag⁺ release concentration (Figure 1d), thus showing lower cell viability. However, as the culturing time increases, the cell viability of all PDA/Ag₃PO₄/GO-Ti samples is increased. After 7 days of culturing, the cell viability of both PDA/Ag₃PO₄/GO-Ti-1 and PDA/Ag₃PO₄/GO-Ti-2 is close to the level of pure Ti. Even for both PDA/Ag₃PO₄/GO-Ti-3 and PDA/Ag₃PO₄/GO-Ti-4, their cell viability is also enhanced and close to 80%. Besides the reduced releasing rate of Ag⁺ as the culturing time increases, it has been reported that PDA can also increase biocompatibility. In addition, the number of cells on the PDA/Ag₃PO₄/GO-Ti samples increases with cultured time because Ag⁺ release diminishes with time. As shown in Figure 7b, after culturing for 7 and 14 days, all PDA/Ag₃PO₄/GO-Ti samples exhibit higher ALP activity compared to pure Ti, indicating the better osteogenic ability of PDA/Ag₃PO₄/GO-Ti samples. Furthermore, Ag₃PO₄ can be partially decomposed to produce Ag⁺, which is favorable for the growth of osteoblasts by the microgalvanic effect between Ag and Ti. In addition, the cell morphologies on those samples also do not change obviously (Figure 7c).
GO-Ti (Figure S9a), and as the irradiation time increases, the cytotoxicity becomes more pronounced (Figure S9b). It is believed that ROS is detrimental to cell proliferation, although it does not mean that the cells cannot survive on the samples under light irradiation. As shown in Figure S9c, the cells can still survive on the Ag₃PO₄/GO coating, but compared with those shown in

Figure 8. (a) Immunohistochemical staining for rat tissue slices of epidermal tissues in contact with the samples stained by LY6G for neutrophils and CD3 for lymphocytes. The neutrophils are marked by red arrows and lymphocytes are marked by green arrows; (b) integral optical density (IOD) histogram of neutrophils and lymphocytes, showing the amounts of immune cells, and larger values mean more immune cells. The error bars indicate means ± SD (n = 3): *p < 0.05, **p < 0.01, ***p < 0.001; (c) H&E staining of visceral tissue slices of rats after implantation for 3 days. The scale bar is 50 μm.
Figure 7c, the cell numbers have been significantly reduced. In addition, since light irradiation occurs for a short time, the in vitro cell viability does not reflect the real in vivo tissue toxicity.

**In Vivo Evaluation.** The animal model of specific pathogen-free SD male rats are divided into two groups (pure Ti group and PDA/Ag₃PO₄/GO-Ti-4 group), and each group had four rats (half of the rats in each group are irradiated for 15 min with 660 nm visible light). The samples and 20 μL of S. aureus (1 × 10⁷ CFU/mL) are implanted into the subcutaneous tissues of the rats to build the animal model. These implanted rats are cultured for 1 day or 3 days. Once the animal model has a bacterial infection, the infected site produces immune cells such as neutrophils, lymphocytes, and so on. More bacteria in the tissues indicate more severe inflammatory response, resulting in more immune cells, which can also prove the poor antibacterial activity of the samples.

As shown in Figure 8a, the histological section by immunohistochemical staining of neutrophils and lymphocytes shows that the Ti group has many neutrophils (marked by red arrows) and lymphocytes (marked by the green arrows) in both 660 nm light irradiation for 15 min or in darkness groups. Moreover, as shown in Figure 8b (the immune cells integral optical density (IOD) histogram, larger values mean more immune cells), the immune cells are the same for 660 nm light irradiation for 15 min or in darkness groups, indicating that pure light irradiation has no effects on bacteria. In addition, the inflammation response becomes more serious in 3 days. But for the PDA/Ag₃PO₄/GO-Ti-4 group, only few neutrophils and lymphocytes occur, and the immune cells are decreased with the increase of culture time due to the photocatalytic antimicrobial efficacy of PDA/Ag₃PO₄/GO-Ti-4 irradiated by 660 nm light within a short time. In addition, even in darkness, this group can also exhibit a lower inflammatory response than the pure Ti group, indicating that the released Ag⁺ from the coating can resist bacterial infection. These results confirm that PDA/Ag₃PO₄/GO-Ti-4 samples have not only excellent photocatalytic antibacterial activity but also physical antibacterial activity, which can be further proven by hematoxylin and eosin (H&E) staining (Figure S10a) and Giaios staining results (Figure S10b).

It is noted that the released Ag⁺ can circulate in the body, but according to the histological analysis of the heart, liver, spleen, lung, and kidney of rats cultured for 3 days, no abnormal effects or damage are observed (Figure 8c), proving that the PDA/Ag₃PO₄/GO-Ti is safe in vivo.

**CONCLUSIONS**

PDA/Ag₃PO₄/GO coatings are suitable for biomedical implants due to the excellent antimicrobial ability and elastic modulus close to that of natural bone. They can also be deposited on both metallic and polymeric materials. GO improves the photodynamic performance of Ag₃PO₄ on account of the excellent electrical conductivity which mitigates recombination of photo-generated electron–hole pairs and accelerates electron transport to improve the photocatalytic performance of Ag₃PO₄. GO also alters the bandgap of Ag₃PO₄/GO so that the photodynamic antimicrobial ability can be achieved under 660 nm visible light illumination. The antimicrobial capability of the hybrid PDA/Ag₃PO₄/GO coatings increases with decreasing Ag₃PO₄ nanoparticle size because a larger specific surface area leads to more effective release of Ag⁺ and absorption of more photons to produce ROS. Ag⁺ and ROS function synergistically to damage the DNA, proteins, and bacterial membranes, resulting in bacteria death. The generated ROS change the permeability of the cell membranes, consequently allowing easier passage of Ag⁺ into the bacteria cells to kill them.

**METHODS**

**Synthesis of Ag₃PO₄/GO Composites.** The GO powders, prepared by modified Hummer’s method, were dispersed in deionized (DI) water ultrasonically and 0.034 g of AgNO₃ was added to prepare four groups with different concentrations (AgNO₃/GO = 3.397 mg/mL:0.5 mg/mL, 1.699 mg/mL:0.25 mg/mL, 0.849 mg/mL:0.125 mg/mL, and 0.423 mg/mL:0.0625 mg/mL). After stirring for 30 min, 10 mL of 0.0067 mol/L Na₂HPO₄ were added dropwise to the mixture and the mixture was stirred vigorously for 30 min. Finally, the four groups were adjusted to the same concentration (Ag₃PO₄/GO = 0.347 mg/mL:0.0625 mg/mL).

**Preparation of PDA/Ag₃PO₄/GO-Ti or PDA/Ag₃PO₄/GO-PEEK.** After mechanical polishing with SiC, the biomedical Ti plates (Φ 6 mm × 2.5 mm, Baosteel Group Corp, Shanghai China) were hydrothermally treated according to the procedures reported in our previous work. A layer of PDA was prepared on the surface of Ti, and the samples were immersed in the Ag₃PO₄/GO solutions with different particle size for 1 day under vacuum conditions and then washed with DI water. According to the size of Ag₃PO₄, the samples were labeled PDA/Ag₃PO₄/GO-Ti-1 to -4. Other samples which only had GO (0.0625 mg/mL) or Ag₃PO₄ (0.347 mg/mL) were named PDA/GO-Ti or PDA/Ag₃PO₄-Ti. The PDA/Ag₃PO₄/GO-PEEK samples underwent the same procedure without the hydrothermal treatment.

**Characterization.** Scanning electron microscopy (SEM, JSM-6510LV, JEOL, Japan) was used to examine the sample morphology and EDS; XRD showed the composition and phase. Nanoindentation was employed to assess the adhesion strength between the coatings and substrates. The amount of Ag⁺ released was determined by inductively coupled plasma atomic emission spectrometry (ICP-AES, Optimal 8000, PE, USA). UV–visible spectrophotometry was performed on the UV-3600 (Shimadzu, Japan), and transmission electron microscopy (TEM, FEI, TF20, USA) was performed to examine the morphology. The cell morphology was observed under an inverted fluorescence microscope (IX73, Olympus, Japan).

**Ag⁺ Release Test.** Five samples (PDA/Ag₃PO₄/GO-Ti-1 to -4 and PDA/Ag₃PO₄-Ti, five samples in each group) were immersed in 5 mL of PBS (pH = 7.4) at 37 °C, and the controlled-release solutions were taken out at intervals of 1, 2, 3, 5, 7, 10, 14, 18, 22, and 30 days. The solutions were refreshed each time, and the quantities of Ag⁺ were determined by ICP-AES. In addition, five PDA/Ag₃PO₄/GO-Ti-4 samples were ultrasonically stripped to make Ag₃PO₄ completely free from the sample. The obtained solution was added with an excess of acid to completely dissolve the Ag₃PO₄, and the Ag⁺ concentration was measured using ICP-AES.

**ROS Test.** The amount of ROS determined the antimicrobial capacity of the samples and was measured on a microplate reader using 10 mmol/L 2′,7′-dichlorofluorescein diacetate (DCFH-DA). Once DCFH-DA was combined with ROS, it can generate a fluorescent 2′,7′-dichlorofluorescein (DCF), which can be detected by a microplate reader. First, a microplate reader (the excitation wavelength is 488 to 525 nm) is used to measure the value of 100 μL of DCFH-DA reacted with excess ROS. Next, the samples (PDA/Ag₃PO₄/GO-Ti-1 to 4, PDA/Ag₃PO₄-Ti, PDA-GO-Ti, and pure Ti, three samples for each group, stored under dark conditions) were placed on 96-well plates, and 100 μL of the
capture agent were added to each well. The samples were irradiated for 15 min with 660 nm visible light from a laser with a power of 170 mW (MRL-III-660Dnm-500 mW-16090712, China). The liquid was measured every minute by the microplate reader. The yield of ROS was obtained by comparing the microplate reader values.

**Antimicrobial Tests.** The antimicrobial effects of the samples were assessed based on the ROS and Ag⁺ antimicrobial behavior. They were evaluated by spread plate and SEM. Two types of bacteria, *E. coli* and *S. aureus* (1 × 10⁷ colony-forming units per milliliter (CFU/mL)), were used. The samples were stored in darkness and sterilized with alcohol and ultraviolet light before the experiments. All the experiments were done in triplicate for better statistics.

In the spread plate test, 8 mL of sterile solid agar Luria-Bertani (LB) media were poured into each plate and 20 μL of the bacterial liquid and 20 μL of PBS (pH = 7.4) were taken out to be evenly poured onto each plate. Afterward, the plates were cultured for 1 day at 37 °C and the number of colonies on the plates was recorded on a digital camera. If the plates had no colonies, the spread plate process was repeated again with 200 μL of the bacterial liquid. The number of colonies was recorded using the photos of the spread plate and the antimicrobial ratio was calculated using the following equation (N = number of colonies):

\[
\text{bactericidal ratio (\%)} = \left( \frac{N_{\text{control}} - N_{\text{sample}}}{N_{\text{control}}} \right)
\]

After the antimicrobial test, the bacteria were loaded on the samples that were immersed in 200 μL of 2.5% glutaraldehyde for 2 h and washed three times with PBS. The samples were dehydrated with alcohol (30%, 50%, 70%, 90%, and 100%) for 15 min each and after drying, the bacterial morphology was observed by SEM.

The samples and 100 μL of the bacterial liquid (*E. coli* or *S. aureus*) were added to 96-well plate and irradiated for 15 min with 660 nm visible light. The bacteria liquid was diluted one hundred times for the spread plate test. Three antimicrobial tests were performed and the samples were divided into two groups (pure Ti group and PDA/Ag₃PO₄/GO-Ti-4) and each group had 4 rats (half of the rats in each group sets three parallel samples) are irradiated 10 min by 660 nm visible light. Then the bacterial liquid is collected for spread plate. And the test is repeated five times, the bacteria are collected to make bacterial slices, and observed by TEM.

In the MTT test, the samples and 200 μL of the cell liquid (1 × 10⁵ cells/mL cells) were added into 96-well plates, each sample was set to three parallel groups. After incubation for 1, 3, and 7 days at 37 °C in a 5% CO₂ incubator, the cells (mouse calvarial cell line) were obtained from Tongji Hospital, Wuhan, China. The samples were sterilized with 75% alcohol and then exposed to UV for 30 min and stored under dark condition. All the experiments were done in triplicate.

In the MOTT test, the samples and 200 μL of the cell liquid (1 × 10⁵ cells/mL cells) were added into 96-well plates, each sample was set to three parallel groups. After incubation for 1 day at 37 °C in a 5% CO₂ incubator, the cell liquid (1 × 10⁵ CFU/mL bacterial liquid, and PDA/Ag₃PO₄/GO-Ti-4 or blank well + 90 μL PBS contained Ag⁺ + 10 μL 1 × 10⁷ CFU/mL bacterial liquid, each group sets three parallel samples) are irradiated 10 min by 660 nm visible light. And then the bacterial liquid is collected for spread plate and the test is repeated five times, the bacteria are collected to make bacterial slices, and observed by TEM.

For the evaluation of cell morphology, the samples and 100 mL of the cell liquid (1 × 10⁵ cells/mL cell) were added to 96-well plates. Each sample was set to two parallel groups, and one group of each was irradiated for 15 min with 660 nm visible light. After incubation for 1 day at 37 °C in a 5% CO₂ incubator, the cells were dyed by FITC (100 nM YiSen, Shanghai) as described previously. After drying, the cell morphology was examined by inverted fluorescence microscope.

**In Vivo Tests.** The specific pathogen-free SD male rats (Hubei Provincial Centers for Disease Prevention & Control, 180 g) were cultured in quarantine for acclimatization and detection for 1 week to build a subcutaneous infection model. All the animal experiments and procedures were approved by Hubei Provincial Centers for Disease Prevention & Control. The rats were divided into two groups (pure Ti group and PDA/Ag₃PO₄/GO-Ti-4 group) and each group had 4 rats (half of the rats in each group were irradiated for 15 min with 660 nm visible light). The samples were implanted into the subcutaneous tissue of the rats together with 20 μL of *S. aureus* (1 × 10⁷ CFU/mL⁻¹). After irradiated for 15 min with 660 nm visible light. The DNA liquid was collected and the DNA concentration was measured on the BIO-RAD CFX Connect Real-Time System.

**ROS and Ag⁺ Synergistic Antimicrobial Effect.** Six PDA/Ag₃PO₄/GO-Ti-4 samples and 200 μL PBS are added into 96-well plates. After placed at 37 °C for 2 days’ release of Ag⁺, the PBS solution that contains Ag⁺ is collected. Next, four groups (pure Ti or PDA/Ag₃PO₄/GO-Ti-4 + 100 μL 1 × 10⁷ CFU/mL bacterial liquid, and PDA/Ag₃PO₄/GO-Ti-4 or blank well + 90 μL PBS contained Ag⁺ + 10 μL 1 × 10⁷ CFU/mL bacterial liquid, each group sets three parallel samples) are irradiated 10 min by 660 nm visible light. And then the bacterial liquid is collected for spread plate. And the test is repeated five times, the bacteria are collected to make bacterial slices, and observed by TEM.

**In Vitro Tests.** The biological activity was evaluated by 3-[4,5-dimethylthiazol-2-yl]-2,5-diphenyl tetrazolium bromide (MTT) and cell morphology observation. The MC3T3-E1 cells (mouse calvarial cell line) were obtained from Tongji Hospital, Wuhan, China. The samples were sterilized with 75% alcohol and then exposed to UV for 30 min and stored under dark condition. All the experiments were done in triplicate.

To assess formation of biofilms, the samples and 200 μL of the bacteria liquid (*S. aureus* 1 × 10⁸ CFU/mL) were added to 96-well plates and cultured for 2 days at 37 °C. The bacterial liquid was changed every 12 h and afterward, the bacteria biofilm formed on the surface of samples. The samples and 100 μL of PBS (pH = 7.4) were poured onto new plates and irradiated for 15 min with 660 nm visible light or cultured in dark for 1 day. The bacteria were then collected and diluted 50,000 times for the spread plate test. Three antimicrobial tests were performed and the bacterial morphology was observed by SEM.

To evaluate the Ag⁺ antimicrobial behavior, the samples and 100 μL of the bacterial liquid (*E. coli* or *S. aureus*) were added to 96-well plates. The samples were cultured for 15 min or 1 day in a dark environment at 37 °C. Afterward, the bacterial liquid was diluted a hundred times for the spread plate test. The bacterial morphology was observed and the samples with formed biofilms underwent the spread plate test after culturing for 1 day.

**Antimicrobial Mechanism.** The samples and 100 μL of the bacteria liquid (*S. aureus*) were added to 96-well plates and irradiated for 15 min with 660 nm visible light. The bacterial liquid was collected, centrifuged, and taken out to determine the protein concentration by BCA Protein Assay Kit (cat# P0010, Beyotime, China). All the experiments were done in triplicate.

To assess the role of ROS, 3 mL of the bacteria liquid (*S. aureus*) were crushed to exposure the protein completely. The samples and 100 μL of the bacteria liquid were added to 96-well plates and irradiated for 15 min with 660 nm visible light. The protein concentration in the liquid was determined by the BCA Protein Assay Kit.

The bacteria DNA was extracted using the bacteria DNA kit (Feiyang, Guangzhou, China). 100 μL of the extracted DNA liquid and samples were added to 96-well plates and irradiated for 15 min with 660 nm visible light. The DNA liquid was collected and the DNA concentration was measured on the BIO-RAD CFX Connect Real-Time System.

**ROS and Ag⁺ Synergistic Antimicrobial Effect.** Six PDA/Ag₃PO₄/GO-Ti-4 samples and 200 μL PBS are added into 96-well plates. After placed at 37 °C for 2 days’ release of Ag⁺, the PBS solution that contains Ag⁺ is collected. Next, four groups (pure Ti or PDA/Ag₃PO₄/GO-Ti-4 + 100 μL 1 × 10⁷ CFU/mL bacterial liquid, and PDA/Ag₃PO₄/GO-Ti-4 or blank well + 90 μL PBS contained Ag⁺ + 10 μL 1 × 10⁷ CFU/mL bacterial liquid, each group sets three parallel samples) are irradiated 10 min by 660 nm visible light. And then the bacterial liquid is collected for spread plate. And the test is repeated five times, the bacteria are collected to make bacterial slices, and observed by TEM.
1 and 3 days, the tissues in contact with the samples were collected to make tissue sections (immunohistochemical staining of neutrophils and lymphocytes, H&E staining, and Giemsa staining) to observe bacterial infection. The amounts of neutrophils and lymphocytes were calculated by IOD value, and larger values represent more neutrophils or lymphocytes. The visera of the rats cultured for 3 days were collected to make tissue sections to observe the effects of samples for visera.

**STATISTICAL ANALYSIS**

All the experiments data were analyzed by the one-way ANOVA and expressed as means ± standard deviations with n = 3. p values < 0.05 were considered statistically significant.

**ASSOCIATED CONTENT**

1. Supporting Information

The Supporting Information is available free of charge on the ACS Publications website at DOI: 10.1021/acscentsci.8b00177.

Figures S1–10. TG curves of Ag₃PO₄/GO-4 (S1); structure analysis of GO/Ag₃PO₄ composites and Ag₃PO₄/GO-Ti (S2); absorption wavelength and corresponding bandgap of Ag₃PO₄/GO-Ti (S3); schematic image of up-conversion photoluminescence of Ag₃PO₄/GO (S4); spread plate results of *S. aureus* (S5); spread plate results of *E. coli* (S6); temperature change and corresponding spread plate (S7); bacterial morphology of *E. coli* and *S. aureus* (S8); in vitro evaluation (S9); in vivo evaluation (S10) (PDF)

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**Notes**

The authors declare no competing financial interest.

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**REFERENCES**

(1) Jaggessar, A.; Shahali, H.; Mathew, A.; Yarlagadda, P. K. D. V. Bio-Mimicking Nano and Micro-Structured Surface Fabrication for Antimicrobial Properties in Medical Implants. *J. Nanobiotechnol.* 2017, 15, 64.

(2) Huo, S. D.; Jiang, Y.; Gupta, A.; Jiang, Z. W.; Landis, R. F.; Hou, S. Y.; Liang, X. J.; Rotello, V. M. Fully Zwitterionic Nanoparticle Antimicrobial Agents through Tuning of Core Size and Ligand Structure. *ACS Nano* 2016, 10, 8732−8737.

(3) He, X. J.; Zhang, X. G.; Wang, X.; Qiu, L. Revew of antimicrobial activity of titanium-based implants’ surfaces fabricated by micro-arc oxidation. *Coatings* 2017, 7, 45.

(4) Bradley, P.; Gordon, N. C.; Walker, T. M.; Dunn, L.; Heys, S.; Huang, B.; Earle, S.; Pankhurst, L. J.; Anson, L.; de Cesare, M. D.; Piazza, P.; Votintseva, A. A.; Golubchik, T.; Wilson, D. J.; Wyllie, D. H.; Diel, R.; Niemann, S.; Feuerriegel, S.; Kohl, T. A.; Ismail, N.; Omar, S. V.; Smith, E. G.; Buck, D.; McVean, G. M.; Walker, A. S.; Petö, T. E. A.; Crook, D. W.; Iqbal, Z. Rapid Antibiotic-Resistance Predictions from Genome Sequence Data for Staphylococcus Aureus and Mycobacterium Tuberculosis. *Nat. Commun.* 2016, 7, 11465.

(5) Zhao, Z. W.; Yan, R.; Yi, X.; Li, J. L.; Rao, J. M.; Guo, Z. Q.; Yang, Y. M.; Li, W. F.; Li, Y. Q.; Chen, C. Y. Bacteria-Activated Theranostic Nanoprobe Against Methicillin-Resistant Staphylococcus aureus Infection. *ACS Nano* 2017, 11, 4428−4438.

(6) Tian, J. X.; Zhang, J. Y.; Yang, J. T.; Du, L. Y.; Geng, H.; Cheng, Y. Q. Conjugated Polymers Act Synergistically with Antibiotics to Combat Bacterial Drug Resistance. *ACS Appl. Mater. Interfaces* 2017, 9, 18512−18520.

(7) Pan, P. C.; Yu, H. D.; Liu, Q. L.; Kong, X. T.; Chen, H. H.; Chen, J. A.; Liu, Q.; Li; Kang, Y.; Sun, H. Y.; Zhou, W. F.; Tian, S.; Cui, S. L.; Zhu, F.; Li, Y. Y.; Huang, Y.; Hou, T. J. Combating Drug-Resistant Mutants of Anaplastic Lymphoma Kinase with Potent and Selective Type-I/II Inhibitors by Stabilizing Unique DFG-Shifted Loop Conformation. *ACS Cent. Sci.* 2017, 3, 1208−1220.

(8) Chen, W. Y.; Chang, H. Y.; Lu, J. K.; Huang, Y. C.; Harroun, S. G.; Tseng, Y. T.; Li, Y. J.; Huang, C. C.; Chang, H. T. Self-Assembly of Antimicrobial Polymers on Gold Nanodots: Against Multidrug-Resistant Bacteria and Wound-Healing Application. *Adv. Funct. Mater.* 2015, 25, 7189−7199.

(9) Holmbeck, M. A.; Shadel, G. S. Mitochondria Provide a ‘Complex’ Solution to a Bacterial Problem. *Nat. Immunol.* 2016, 17, 1009−1010.

(10) Zheng, K. Y.; Setyawati, M. I.; Lim, T. P.; Leong, D. T.; Xie, J. P. Antimicrobial Cluster Bombs: Silver Nanoclusters Packed with Daptomycin. *ACS Nano* 2016, 10, 7934−7942.

(11) Ji, D. K.; Zhang, Y.; Yang, Y.; Li, J.; Chen, G. R.; He, X. P.; Tian, H. Targeted Intracellular Production of Reactive Oxygen Species by a 2D Molybdenum Disulfide Glycosheet. *Adv. Mater.* 2016, 28, 9356−9363.

(12) Natan, M.; Gutman, O.; Lavi, R.; Margel, S.; Banin, E. Killing Mechanism of Stable N-Halamine Cross-Linked Polymethacrylamide Nanoparticles that Selectively Target Bacteria. *ACS Nano* 2015, 9, 1175−1188.

(13) Deng, C. H.; Gong, J. L.; Zhang, P.; Zeng, G. M.; Song, B.; Liu, H. Y. Preparation of Melamine Sponge Decorated with Silver Nanoparticles-Modified Graphene for Water Disinfection. *J. Colloid Interface Sci.* 2017, 488, 26−38.

(14) Kawasaki, H.; Kumar, S.; Li, G.; Zeng, C. J.; Kauffman, D. R.; Yoshimoto, J.; Iwaseki, Y.; Jin, R. C. Generation of Singlet Oxygen by Photoexcited Au₅₃(SR)₁₄ Clusters. *Chem. Mater.* 2014, 26, 2777−2788.

(15) Ge, J. C.; Lan, M. H.; Zhou, B. J.; Liu, W. M.; Guo, L.; Wang, H.; Jia, Q. Y.; Niu, G.; Huang, X.; Zhou, H. Y.; Meng, X. M.; Wang, P. F.; Lee, C. S.; Zhang, W. J.; Han, X. D. A Graphene Quantum Dot Photodynamic Therapy Agent with High Singlet Oxygen Generation. *Nat. Commun.* 2014, 5, 4596.

(16) Cho, S. J.; Kim, S. Y.; Park, S. J.; Song, N.; Kwon, H. Y.; Kang, N. Y.; Moon, S. H.; Chang, Y. T.; Cha, H. J. Photodynamic Approach for Teratoma-Free Pluripotent Stem Cell Therapy Using CD11 and Visible Light. *ACS Cent. Sci.* 2016, 2, 604−607.

(17) Chen, Z. H.; Bing, F.; Liu, Q.; Zhang, Z. G.; Fang, X. M. Novel Z-Scheme Visible-Light-Driven Ag₃PO₄/Ago/SiC Photocatalysts with Enhanced Photocatalytic Activity. *J. Mater. Chem. A* 2015, 3, 4652−4658.

(18) Zheng, B. J.; Wang, X.; Liu, C.; Tan, K.; Xie, Z. X.; Zheng, L. High-Efficiently Visible Light-Responsive Photocatalysts: Ag₃PO₄ Tetrahedral Microrystals with Exposed [111] Facets of High Surface Energy. *J. Mater. Chem. A* 2013, 1, 12635−12640.

(19) Xu, J. W.; Gao, Z. D.; Han, K.; Liu, Y. M.; Song, Y. Y. Synthesis of Mechanically Separable Ag₃PO₄/TiO₂/Fe₃O₄ Heterostructure with Enhanced Photocatalytic Performance under Visible Light for Photoinactivation of Bacteria. *ACS Appl. Mater. Interfaces* 2014, 6, 15122−15131.

(20) Deng, C. H.; Gong, J. L.; Ma, L. L.; Zeng, G. M.; Song, B.; Zhang, P.; Huan, S. Y. Synthesis, Characterization and Antimicrobial Perform-
(37) Xie, X. Z.; Mao, C. Y.; Liu, X. M.; Zhang, Y. Z.; Cui, Z. D.; Yang, X. J.; Yeung, K. W. K.; Pan, H. B.; Chu, P. K.; Wu, S. L. Synergistic Bacteria Killing through Photodynamic and Physical Actions of Graphene Oxide/Ag/Collagen Coating. ACS Appl. Mater. Interfaces 2017, 9, 26417−26428.

(38) AshaRani, P. V.; Mun, G. L. K.; Hande, M. P.; Vaiyaveettil, S. Cytotoxicity and Genotoxicity of Silver Nanoparticles in Human Cells. ACS Nano 2009, 3, 279−290.

(39) Neetha, M.; Singh, A. K.; Asokamani, R.; Gogia, A. K. Ti Based Biomaterials, the Ultimate Choice for Orthopaedic Implants. Prog. Mater. Sci. 2009, 54, 397−425.

(40) Biesiekierski, A.; Wang, J.; Gerepel, M. A. H.; Wen, C. A. New Look at Biomedical Ti-Based Shape Memory Alloys. Acta Biomater. 2012, 8, 1661−1669.

(41) Li, J. Q.; Yuan, H.; Zhu, Z. F. In Situ Growth of Ag2PO4 on NiBiO3 Nanorods: A Core-Shell Heterostructure for High Performance Photocatalyst. J. Colloid Interface Sci. 2016, 462, 382−388.

(42) Wei, L.; Karahan, H. E.; Zhai, S. L.; Liu, H. W.; Chen, X. C.; Zhou, Z.; Lei, Y. J.; Liu, Z. W.; Chen, Y. Amorphous Bimetallic Oxide-Based Photocatalysts for Rechargeable Zn-Air Batteries. Adw. Mater. 2017, 29, 1701410.

(43) Chen, Q. Y.; Wang, Y. F.; Wang, Y. W.; Zhang, X. C.; Duan, D. H.; Fan, C. M. Nitrogen-Doped Carbon Quantum Dots/Ag2PO4 Complex Photocatalysts with Enhanced Visible Light Driven Photocatalytic Activity and Stability. J. Colloid Interface Sci. 2017, 491, 238−245.

(44) Chen, Y.; Dong, X. J.; Cao, Y.; Xiang, J. J.; Gao, H. Y. Enhanced Photocatalytic Activities of Low-Bandgap TiO2-Reduced Graphene Oxide Nanocomposites. J. Nanopart. Res. 2017, 19, 200.

(45) Yang, X. F.; Cui, H. Y.; Li, Y.; Qin, J. L.; Zhang, R. X.; Tang, H. Fabrication of Ag2PO4-Graphene Composites with Highly Efficient and Stable Visible Light Photocatalytic Performance. ACS Catal. 2013, 3, 363−369.

(46) Cai, T.; Liu, Y. T.; Wang, L. L.; Zhang, S. Q.; Zeng, Y. X.; Yuan, J. L.; Ma, J. H.; Dong, W. Y.; Liu, C. B.; Luo, S. L. Silver Phosphate-Based Z-Scheme Photocatalytic System with Superior Sunlight Photocatalytic Activities and Anti-Photocorrosion Performance. Appl. Catal., B 2017, 208, 1−13.

(47) Liu, F.; Jiang, M. H.; Ha, H. D.; Kim, J. H.; Cho, Y. H.; Seo, T. S. Facile Synthetic Method for Pristine Graphene Quantum Dots and Graphene Oxide Quantum Dots: Origin of Blue and Green Luminescence. Adv. Mater. 2013, 25, 3657−3662.

(48) Han, Z. X.; Wu, X. L.; Zhou, G. X.; Shen, J. C.; Chu, P. K. Is There Real Upconversion Photoluminescence from Graphene Quantum Dots? Adv. Opt. Mater. 2013, 1, 554−558.

(49) Zhu, S. J.; Song, Y. B.; Zhao, X. H.; Shao, J. R.; Zhang, J. H.; Yang, B. The Photoluminescence Mechanism in Carbon Dots (Graphene Quantum Dots, Carbon Nanodots, and Polymer Dots): Current State and Future Perspective. Nano Res. 2015, 8, 355−381.

(50) Ha, H. D.; Jiang, M. H.; Liu, F.; Cho, Y. H.; Seo, T. S. Upconversion Photoluminescent Metal Ion Sensors Via Two Photon Absorption in Graphene Oxide Quantum Quats. Carbon 2015, 81, 367−375.

(51) Cai, Y. C.; Li, C. L.; Wu, D.; Wang, W.; Tan, F. T.; Wang, X. Y.; Wong, P. K.; Qiao, X. L. Highly Active MgO Nanoparticles for Simultaneous Bacterial Inactivation and Heavy Metal Removal from Aqueous Solution. Chem. Eng. J. 2017, 312, 158−166.

(52) Sirelkhatim, A.; Mahmud, S.; Seeni, A.; Kaus, N. H. M.; Ann, L. C.; Bakhori, S. K. M.; Hasan, H.; Mohamad, D. Review on Zinc Oxide Nanoparticles: Antimicrobial Activity and Toxicity Mechanism. Nano-Micro Lett. 2015, 7, 219−242.

(53) Sun, Y. G.; Xia, Y. N. Gold and Silver Nanoparticles: A Class of Chromophores with Colors Tuneable in the Range from 400 to 750 nm. Analyst 2003, 128, 686−691.

(54) Hao, Y. J.; Liu, B.; Tian, L. J.; Li, F. T.; Ren, J.; Liu, S. J.; Liu, Y.; Zhao, J.; Wang, X. J. Synthesis of [111] Facet-Exposed MgO with Surface Oxygen Vacancies for ROS Generation in the Dark. ACS Appl. Mater. Interfaces 2017, 9, 12687−12693.
(55) Rasool, K.; Helal, M.; Ali, A.; Ren, C. E.; Gogotsi, Y.; Mahmoud, K. A. Antimicrobial Activity of Ti$_3$C$_2$Tx Mxene. ACS Nano 2016, 10, 3674–3684.

(56) Xu, Z. Q.; Li, M.; Li, X.; Liu, X. M.; Ma, F.; Wu, S. L.; Yeung, K. W. K.; Han, Y.; Chu, P. K. Antimicrobial Activity of Silver Doped Titanate Nanowires on Ti Implants. ACS Appl. Mater. Interfaces 2016, 8, 16584–16594.

(57) Liu, Y.; Busscher, H. J.; Zhao, B. G.; Li, Y. F.; Zhang, Z. K.; van der Mei, H. C.; Ren, Y. J.; Shi, L. Q. Surface-Adaptive, Antimicrobially Loaded, Micellar Nanocarriers with Enhanced Penetration and Killing Efficiency in Staphylococcal Biofilms. ACS Nano 2016, 10, 4779–4789.

(58) Duncan, B.; Li, X. N.; Landis, R. F.; Kim, S. T.; Gupta, A.; Wang, L. S.; Ramanathan, R.; Tang, R.; Boerth, J. A.; Rotello, V. M. Nanoparticle-Stabilized Capsules for the Treatment of Bacterial Biofilms. ACS Nano 2015, 9, 7775–7782.

(59) Gehring, J.; Trepka, B.; Klinkenberg, N.; Bronner, H.; Schleheck, D.; Polzar, S. Sunlight-Triggered Nanoparticle Synergy: Teamwork of Reactive Oxygen Species and Nitric Oxide Released from Mesoporous Organosilica with Advanced Antimicrobial Activity. J. Am. Chem. Soc. 2016, 138, 3076–3084.

(60) Lin, G. D.; Qin, H.; Cao, H. L.; Qian, S.; Zhao, Y. C.; Peng, X. C.; Zhang, X. L.; Liu, X. Y.; Chu, P. K. Synergistic Effects of Dual Zn/Ag Ion Implantation in Osteogenic Activity and Antibacterial Ability of Titanium. Biomaterials 2014, 35, 7699–7713.

(61) Liu, R. B.; Mansukhani, N. D.; Guiney, L. M.; Ji, Z. X.; Zhao, Y. C.; Chang, C. H.; French, C. T.; Miller, J. F.; Hersam, M. C.; Nel, A. E.; Xia, T. Identification and Optimization of Carbon Radicals on Hydrated Graphene Oxide for Ubiquitous Antimicrobial Coatings. ACS Nano 2016, 10, 10966–10980.

(62) Giuri, A.; Masi, S.; Colella, S.; Kovtun, A.; Dell’Elce, S.; Treossi, E.; Liscio, A.; Corcione, C. E.; Rizzo, A.; Listorti, A. Cooperative Effect of GO and Glucose on PEDOT:PSS for High VOC and Hysteresis-Free Solution-Processed Perovskite Solar Cells. Adv. Funct. Mater. 2016, 26, 6985–6994.

(63) Liu, Z. H.; Zhu, Y. Z.; Liu, X. M.; Yeung, K. W. K.; Wu, S. L. Construction of Poly(Vinyl Alcohol)/Poly(Lactide-Glycolideacid)/Vancomycin Nanoparticles on Titanium for Enhancing the Surface Self-Antimicrobial Activity and Cytocompatibility. Colloids Surf., B 2017, 151, 165–177.

(64) Li, J.; Tan, L.; Liu, X. M.; Cui, Z. D.; Yang, X. J.; Yeung, K. W. K.; Chu, P. K.; Wu, S. L. Balancing Bacteria-Osteoblast Competition through Selective Physical Puncture and Biofunctionalization of ZnO/Polydopamine/Arginine-Glycine-Aspartic Acid-Cysteine Nanorods. ACS Nano 2017, 11, 11250–11263.

(65) Lin, S.; Liu, X. M.; Tan, L.; Cui, Z. D.; Yang, X. J.; Yeung, K. W. K.; Pan, H. B.; Wu, S. L. Porous Iron-Carboxylate Metal-Organic Framework: A Novel Bioplatform with Sustained Antimicrobial Efficacy and Nontoxicity. ACS Appl. Mater. Interfaces 2017, 9, 19248–19257.
Supporting Information

Tuning the Bandgap of Photo-Sensitive Polydopamine/Ag₃PO₄/Graphene Oxide Coating for Rapid Noninvasive Disinfection of Implants

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