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Bending Mattress and Antibacterial Effect of TiO_2/nAg/Chitosan-nanoparticle-applied Intelligent Patient Bed

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In Taiwan, the hot and humid weather easily leads to a bedsore problem in bedridden patients. Moreover, general patient beds are inconvenient for elderly people with reduced mobility. In this study, to develop a biocompatible mattress that can assist the turning and bending of the elderly and hence reduce the incidence of bedsores, we have proposed an antibacterial and bendable mattress. On the basis of the advice of doctors, we chose titanium dioxide (TiO_2), nanosilver (nAg), and chitosan antibacterial nanoparticles to produce the mattress. By using carbon fibers, the weight of the bed frame can be decreased. The mechanical properties of the mattress and the wear resistances of various foaming formulations and coating materials were determined. The foam material was produced by two methods, namely, the semi-prepolymer method and the one-step method. Moreover, the Ag/TiO_2 powder was experimentally proven to endow excellent biocompatibility and mechanical properties to the preferred foam materials. Silver nitrate was added to prepare the Ag/TiO_2 powder by sintering at 600 °C. The particle size of the Ag/TiO_2 powder was about 1185 nm before sintering. After sintering, the particle size was reduced to 958.3 nm, and the atomic percentage of Cl was 0.15%. Sintering clearly improved the antibacterial effect of the Ag/TiO_2 powder to 99%, which is higher than those of pure TiO_2 and pure Ag/TiO_2 powders. To improve the overall properties of the mattress, various hard materials were added to the bottom of the polyurethane film. The rebound rates of the mattresses with various hardnesses were measured by a physician to obtain the best mattress.

1. Introduction

In this research, an antibacterial and bendable mattress with nanograde titanium dioxide (TiO_2) antibacterial powders has been proposed. To fabricate a mattress, a coating of polyurethane (PU)

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film is necessary. For a biocompatible mattress, the PU film should have high wear resistance, high corrosion resistance, and good biocompatibility. In particular, the elastic modulus of a PU film is very close to that of spongy bone of humans, which confirms that a PU film is highly suitable for mattress applications. In our work, double mattresses were prepared to fabricate an intelligent patient bed. In addition to the PU film, an antibacterial coating is also required for the mattress. Clinical studies have shown that a wound with a high bacterial concentration is less likely to heal. According to the literature, positively charged TiO_2 and chitosan interact with negatively charged lipid bactericidal membranes. As a result, the permeability of the cell membrane changes and the nutrient intake of the cell is blocked.(1) To prepare a lightweight double mattress, PU foam was used. Additionally, to achieve the antibacterial effect, TiO_2, nanosilver (nAg), and chitosan composite material were used to coat the mattress. This material can promote the healing of hemorrhoid wounds. A cost-effective and antibacterial chitosan/TiO_2 composite membrane has been prepared as a dressing material for wound healing.(2) Fibroblast growth in this chitosan/TiO_2 composite membrane is helpful for improving its antibacterial activity. Biocompatible mattresses reduce the pain of patients and their exposure to bacterial infections.

As mentioned above, TiO_2, nAg, and chitosan nanoparticles were used to prepare the mattress for an intelligent patient bed. Our experimental results confirmed that the mattress with TiO_2/Ag-chitosan nanoparticles possesses good antibacterial ability. The antibacterial effect of TiO_2/Ag-chitosan nanoparticles was higher than that of pure TiO_2 nanoparticles, as discussed later. For intelligent patient beds, a sensor system is also very important. Various types of sensor have been applied to intelligent patient beds, and the pressure sensor is one of the most common types. In 2014, Lopes *et al.* proposed protective Ag:TiO_2 nanocomposite thin films for pressure sensors in medical devices (orthopedic prostheses), and these pressure sensors had good response performance.(3) In the future, the TiO_2/nAg/chitosan nanoparticles prepared in our work will also be used as protective coatings in sensor devices of intelligent patient beds. In this way, the TiO_2/nAg/chitosan nanoparticles could have multifunctional uses in intelligent patient beds.

In this study, we develop curved mattresses of foam to reduce the shortcomings of traditional mattresses. A PU foamed material was used as the main structure for production. Our developed mattresses are flexible and difficult to break, enabling their multifunctional use for different patients. Nurses divide the human body into the upper body, buttocks, thighs, and calves on the basis of their clinical experience. To fabricate the bendable mattress, the mattress was cut and divided into eight equal parts. Thus, a mattress with bottom grooves was formed, and the patient can be easily turned over by bending the mattress.

2. Experimental Method

Because a wound is very sensitive to the environment, a TiO_2 nanomaterial with an antibacterial effect can be used to avoid infection. However, a pure TiO_2 nanomaterial has inherent shortcomings, such as a large band gap, recombination of charge carriers, and difficult separation in solutions.(4) Thus, we developed antibacterial TiO_2, nAg, chitosan powder, and a PU material. Nanoparticles have been used as a supporting material for Ag. The Ag/TiO_2 nanocomposite has proved to be a promising antibacterial material and shows low toxicity in nature.[5,6] Potential materials of the double mattress with different antibacterial formulas were tested to determine whether the product has a bacteriostatic effect, and whether it has a significant effect on patients with bedsores (Fig. 1).

A bendable and bacteriostatic double mattress was co-developed by Taichung Veterans General Hospital in cooperation with the Da-Yeh University development team. In our work, the preparation of the foam material, the technique of bacteriostatic coating, and the appearance of the patient bed were mainly focused on. The PU foam material is used as the main structure to make the double mattress easy to bend and difficult to break while having a bacteriostatic effect. Tensile and impact tests were carried out on the materials of the double mattress to determine their mechanical properties and obtain the optimum fabrication conditions of the foam material of a mattress that can be used to turn over patients and address the shortcomings of traditional beds. The double mattress can be equipped with left-hand and right-hand functions, which can prevent the problem of hemorrhoids. Therefore, the double mattress has a ventilation and bacteriostatic effect. The back pressure and load on patients can be minimized, allowing them to sleep well.

3. Results and Discussion

3.1 Mattress manufacturing and testing

PU foam was produced as the main body of the mattress. The polyols, PUs, additives, and other materials were added to a mold. Then, these materials were mixed by stirring at a high speed. Finally, a foaming experiment was performed on the mixed material to produce the PU foam.

Hydroxyapatite [$Ca_{10}(PO_4)_6(OH)_2$] is the main mineral constituent of calcified tissues such as bones and teeth. It has been widely used as a carrier for drug delivery, a bone substitute for filling bone defects, a scaffold matrix for tissue engineering, and a coating material on biomedical implants owing to its excellent biocompatibility and bioactivity. Over the past few decades, a number of methods have been developed to synthesize hyaluronic acid (HA) nanocrystals of various sizes and morphologies.[7] In addition to excellent biocompatibility, the HA material also has good mechanical properties. Thus, HA powders are suitable for inclusion in the foam material for mattresses.

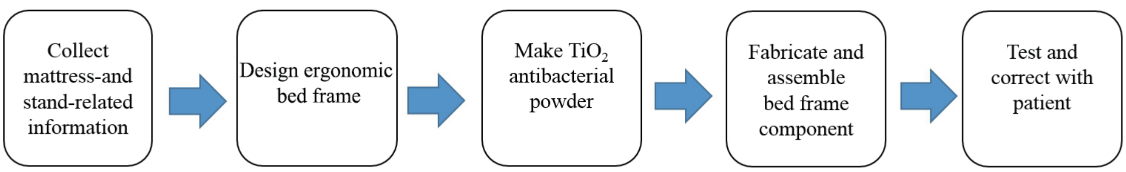

Fig. 1. (Color online) Experimental method.

A double mattress was produced by the PU one-step method. The foam raw materials were HR200 and 295 in a ratio of 1:0.4. Then, we added various hydroxyapatites as additives. A mechanical test involving cutting the foam sample was carried out to determine the best powder and amount of each raw material to make the mattress. Table 1 shows the test results of these powders with particles of different shapes. It was found that the HA powder with granular particles had the highest Young's modulus. The double mattress is made of two layers, the upper layer of which is made of an inert foam material. When a patient is lying on the double mattress, pressure will be distributed evenly. The lower layer is a PU foam. The double mattress was cut into eight pieces, and the patient can be easily turned over by bending the mattress (Fig. 2).

3.2 Nano-TiO_2 bacteriostatic powder

After preparing the TiO_2 powder by the sol-gel method, it was sintered in a high-temperature furnace to investigate the particle size and the atomic percentage of chlorine at various sintering temperatures. Chlorine is harmful to the human body, so it is hoped that the chlorine atomic percentage determined by dynamic light scattering (DLS) analysis will be zero. In the process of preparing the TiO_2 powder by the sol-gel method, we found that the powder particle size was the smallest when the sintering temperature was 600 °C. Therefore, silver nitrate was added to prepare the Ag/TiO_2 powder, and the sintering temperature was also 600 °C.

In our work, eggshells were used to produce the HA powder through a number of experimental steps (Fig. 3). The optimum manufacturing conditions to produce the HA powder

Table 1
Characteristics of powders with different shapes.

	1	2	3	4
Powder	No	Eggshell	HA	HA
Particle shape	**No**	**Granule**	**Flake**	**Granule**
Foaming ratio	1:0.4	1:0.4	1:0.4	1:0.4
Powder (wt %)	**0**	**5**	**5**	**5**
Density (g/cm^3)	0.425	0.431	0.447	0.451
Density SD	**0.006**	**0.0283**	**0.0234**	**0.0245**
Young's (MPa)	1.38	2.20	2.73	2.82
Young's SD	**0.06**	**0.072**	**0.092**	**0.0668**

Note. SD = Standard deviation.

Fig. 2. (Color online) Bendable double mattress.

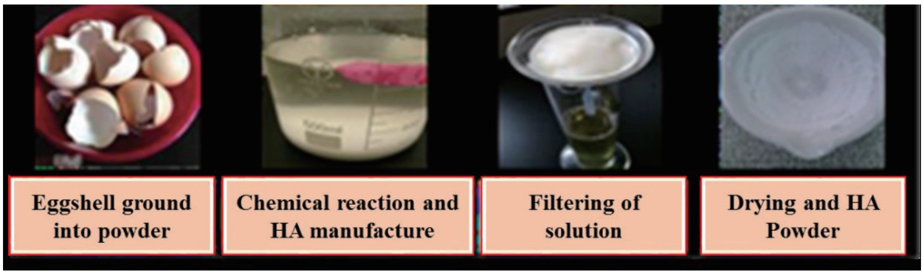

Fig. 3. (Color online) Experimental procedure for preparing HA powder.

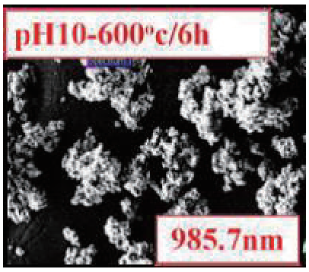

Fig. 4. (Color online) HA particles.

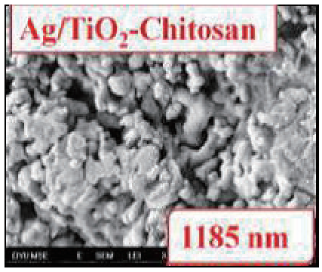

Fig. 5. (Color online) Bacteriostatic particles.

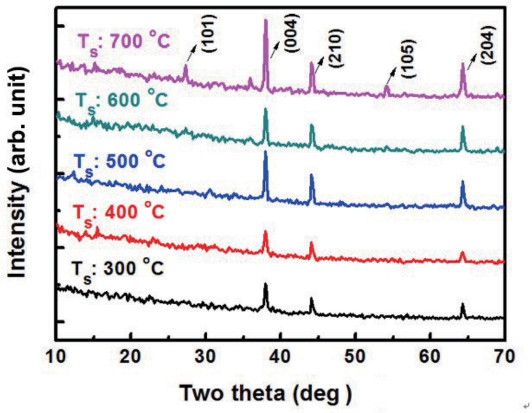

Fig. 6. (Color online) XRD results of TiO_2.

were pH 10 and 600 °C/6 h, and the average particle size was 985.7 nm (as shown in Fig. 4). Moreover, the HA did not contain elemental Cl (measured by DLS analysis).

The SEM image in Fig. 5 reveals that the particle size of the Ag/TiO_2 powder is about 1185 nm before sintering. The particle size of the Ag/TiO_2 powder is larger than that of the TiO_2 powder. Moreover, the atomic percentage of Cl in the Ag/TiO_2 powder is 0.34%. However, after sintering the Ag/TiO_2 powder, its particle size is about 958.3 nm and the atomic percentage of Cl is reduced to 0.15%. Both grain refinement and a decrease in the atomic percentage of elemental Cl can be observed in the Ag/TiO_2 powder after sintering.

Figure 6 shows the results of a θ–2θ XRD scan of Ag/TiO_2 powders after sintering at 300–700 °C. When the sintering temperature was 300–600 °C, the test samples showed diffraction peaks of TiO_2 (004), TiO_2 (210), and TiO_2 (204). When the sintering temperature was increased to 700 °C, these three peaks still appeared and two new diffraction peaks of TiO_2

(101) and TiO_2 (105) also appeared. From these results, it can be confirmed that the powders are indeed crystalline phases belonging to TiO_2. Furthermore, when the sintering temperature is higher, the diffraction peaks are stronger. Clearly, the crystallinity of the powders is increased with increasing sintering temperature, indicating that the powders have a larger grain size.

3.3 Bacteriostatic ring experiment on nano-TiO_2 bacteriostatic powder

First, 10 g of Luria-Bertani and 8 g of agar were placed in a beaker, and then 500 ml of DI water was poured into the beaker. After stirring and sterilizing for 1 h, a sterile medium was obtained. Then, the sterilized medium was dispensed onto a Petri dish. Moreover, it was also treated by cooling and solidifying processes. To further sterilize the medium, it was exposed to ultraviolet light. After the OD value of *Staphylococcus aureus* reached 0.8, a sterilized cotton stick was used to pick up the bacterial liquid. Then, the bacteria were prepared on a Petri dish by the streak plate method.

Bacteriostatic ring experiments were performed using various solutions consisting of pure water, alcohol, water mixed with TiO_2 powder, alcohol mixed with TiO_2 powder, water mixed with TiO_2/Ag-chitosan powder, and alcohol mixed with TiO_2/Ag-chitosan powder. The concentration of TiO_2/Ag-chitosan powder was 4×10^{-4} μg/ml. The samples in the incubator were divided into an unilluminated group and an illuminated group. The illuminated group was illuminated every 15 min. After one day, the bacteriostatic rates were determined from the control and test groups. The results of the experiments showed that the bacteriostatic rate of pure water is 10% (Fig. 7), and the inhibition rate of pure alcohol is 50% (Fig. 8). The

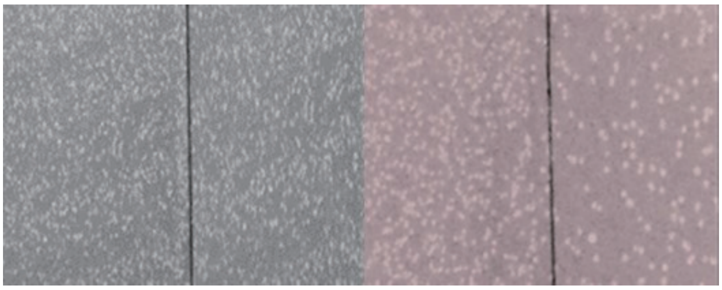

Fig. 7. (Color online) Bacteriostatic ring experiments using pure water (left) and alcohol (right). The bacteriostatic rates were 10% (left) and 50% (right).

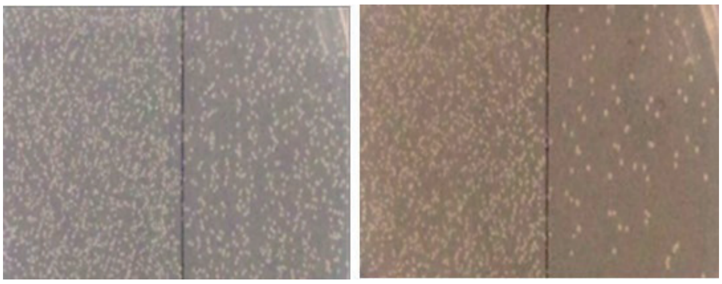

Fig. 8. (Color online) Bacteriostatic ring experiments using pure water (left) and alcohol (right), both mixed with TiO_2 powders. The bacteriostatic rates were 67% (left) and 83% (right).

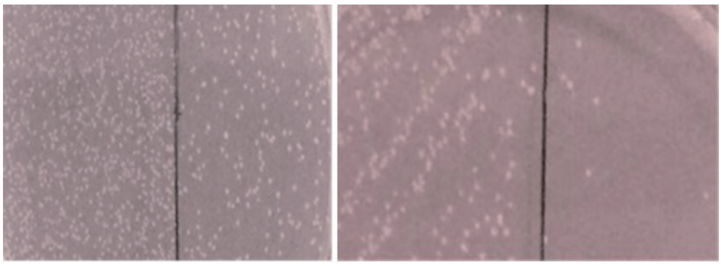

Fig. 9. (Color online) Bacteriostatic ring experiments using pure water (left) and alcohol (right), both mixed with TiO_2/Ag-chitosan powders. The bacteriostatic rates were 69% (left) and 99% (right).

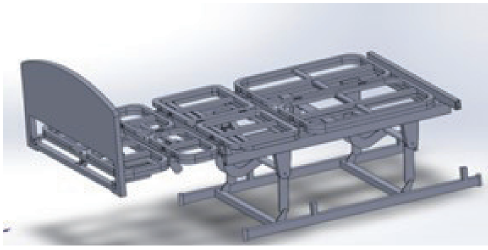

Fig. 10. (Color online) Bendable double mattress frame designed with Solidworks.

Fig. 11. (Color online) Demonstration of turning over the bed.

bacteriostatic rate of the illuminated group is clearly better than that of the unilluminated group. Additionally, the bacteriostatic rate of TiO_2/Ag-chitosan powder is significantly higher than those of pure TiO_2 and nAg/TiO_2 powders. As shown in Fig. 9, a bacteriostatic effect of 99% was obtained in alcohol mixed with TiO_2/Ag-chitosan powder under illumination.

3.4 Bed frame design

The aim of this research is to develop the first ever clinical mattress with equal parts by cutting (Fig. 10). Carbon fibers are pasted onto the surface of a mold to make a bedstead; then, the mold is placed in an oven to harden the material.(8) The bedstead was prepared using carbon fibers to reduce the weight of the bed, and thus reduce the burden on nurses and occupational injuries. The double mattress prepared in our work possesses both left and right turnover functions, and the patient can adjust his or her posture without requiring help from a nurse. The mattress has the following characteristics.

(1) The bendable and antibacterial double mattress comprises eight equal parts. Such a bending double mattress allows a patient to be easily turned over, has a good bacteriostatic property, and causes no anaphylactic reaction.
(2) The headboard of the smart bed with the bendable and antibacterial double mattress can be raised by the patient. Moreover, the bed also turns the patient left and right to avoid the bedsore problem arising in patients and bedridden elderly (Fig. 11).
(3) The double layer (PU foam and inert foam) and the optimized cutting groove depth can evenly support the body weight to relieve pressure and increase comfort, and injury to the patient when the double mattress is flipped and bent can be avoided.

Fig. 12. (Color online) Bendable double mattress frame.

Table 2
Patient opinion survey.

	Excellent (%)	Good (%)	Average (%)	Poor (%)
Comfort	90	10	0	0
Permeability	85	10	5	0
Practicality	85	10	5	0
Convenience	90	5	5	0

Note. The total number of respondents was 50.

(4) The bendable and antibacterial double mattress combined with the bacteriostatic powder is a novel technology. The bacteriostatic powder has excellent adhesion and a good bacteriostatic effect of 99%.

3.5 Patient opinion survey

After producing the double mattress frame (Fig. 12), it was randomly assigned to 50 patients and a questionnaire survey was carried out. According to the results of the survey, most patients gave a high evaluation of this double mattress (Table 2); 90% of the patients as well as the nurses hope that the bendable and antibacterial double mattress will be available soon.

4. Conclusion

In this work, we developed a nano-TiO_2/nAg/chitosan powder that was coated on a bendable and antibacterial double mattress. The bacteriostatic rate of the mattress is 99%, and it can reduce the incidence of bedsores in patients. We studied the bacteriostatic powder containing trace amounts of nAg and found it to have a very high bacteriostatic effect. Because the TiO_2 only enhances the bacteriostatic effect under light, we expect that the bacteriostatic ability at night to be improved by adding chitosan and nAg. Therefore, the bendable and antibacterial double mattress can possess bacteriostatic ability over 24 h without light. The experimental results of this research showed that the TiO_2 powder with a small particle size possesses good bacteriostatic ability. The optimal sintering temperature and time for the bacteriostatic powder are 600 °C and 4 h, respectively, and its average particle size is 688.5 nm. After sintering, the bacteriostatic effect is improved. Additionally, when the nAg and chitosan are added, the bacteriostatic power of the TiO_2 powder is maintained. The bed coated with TiO_2 has a 50% antibacterial effect. This can reduce the frequency of mattress disinfection, which decreases the cost of mattress cleaning. Our experimental results showed that TiO_2/nAg/chitosan nanoparticles possess a better antibacterial effect (99%), which can further reduce the cost of mattress cleaning. With the growing shortage of nurses, smart beds can reduce their workload and also reduce the risk of infections in patients and their families during wound care. The bilateral rollover function of smart beds can greatly reduce the burden on the care provider.

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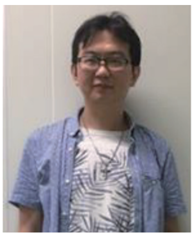

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