

Review

## Chitin, Chitosan, and Its Derivatives for Wound Healing: Old and New Materials

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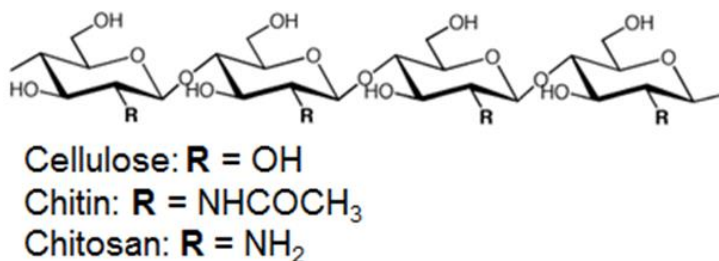
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**Abstract:** Chitin ( $\beta$ -(1-4)-poly-*N*-acetyl-D-glucosamine) is widely distributed in nature and is the second most abundant polysaccharide after cellulose. It is often converted to its more deacetylated derivative, chitosan. Previously, many reports have indicated the accelerating effects of chitin, chitosan, and its derivatives on wound healing. More recently, chemically modified or nano-fibrous chitin and chitosan have been developed, and their effects on wound healing have been evaluated. In this review, the studies on the wound-healing effects of chitin, chitosan, and its derivatives are summarized. Moreover, the development of adhesive-based chitin and chitosan are also described. The evidence indicates that chitin, chitosan, and its derivatives are beneficial for the wound healing process. More recently, it is also indicate that some nano-based materials from chitin and chitosan are beneficial than chitin and chitosan for wound healing. Clinical applications of nano-based chitin and chitosan are also expected.

**Keywords:** chitin; chitosan; wound healing; chitin nanofiber; chitosan nanofiber; animal experiments; adhesive

## 1. Introduction

Chitin (Figure 1,  $\beta$ -(1-4)-poly-*N*-acetyl-D-glucosamine) is widely distributed in nature and is the second most abundant polysaccharide after cellulose [1]. Chitin occurs in nature as ordered microfibrils and is the major structural component in the exoskeletons of crab and shrimp shells and the cell walls of fungi and yeast. As chitin is not readily dissolved in common solvents, it is often converted to its more deacetylated derivative, chitosan [2–4]. Chitin and chitosan are biocompatible, biodegradable, and non-toxic. Chitin and chitosan are also antimicrobial and hydrating agents [5,6]. Chitin and chitosan are also used in various types of biomedical applications such as drug and gene delivery, wound healing, tissue engineering, and stem cell technology [7]. Chitin and chitosan can be easily processed into various products, including hydrogels [8–10], membranes [11–16], nanofibers [17–21], beads [22], micro/nanoparticles [23–26], scaffolds [27–30], and sponges [31,32].



**Figure 1.** Chemical structure of linear polysaccharides: cellulose, chitin, and chitosan.

Wound healing is a specific biological process related to the general phenomenon of growth and tissue regeneration [33]. The wound healing process consists of a series of interdependent and overlapping stages in which a variety of cellular and matrix components act together to reestablish the integrity of damaged tissue and replacement of lost tissue [34]. The wound healing process has been described as being comprised of five overlapping stages, which involve complex biochemical and cellular processes. These phases are described as homeostasis, inflammation, migration, proliferation, and maturation [35].

Several reports have described the beneficial effects of chitin and chitosan for wound healing using *in vitro*, animal, and clinical studies. Recently, techniques for the isolation and manufacturing of nanofibrillar chitin and chitosan have been developed. Due to the development of this technology, applications of nano-chitin and nano-chitosan have also become more widespread. In the present review, biological properties of chitin and chitosan for wound healing are summarized. Moreover, recent investigations and developments using nano-chitin and nano-chitosan for wound healing are also described.

## 2. Chitin for Wound Healing

### 2.1. In Vitro Studies

Several reports have described the beneficial effects of chitin for wound healing using *in vitro* studies (Table 1). Mori *et al.* evaluated the effects of chitin and its derivatives on the proliferation of fibroblasts and on the production of cytokines *in vitro* [36]. Chitin and its derivatives showed almost no acceleratory effect on the proliferation of cultured fibroblasts. Interleukin-8 (IL-8) was observed in the supernatants of rat primary cultured dermal fibroblasts stimulated with chitin and its derivatives. Chitin and its derivatives did not stimulate the production of IL-6 by mouse dermal primary cultured fibroblasts. IL-1 $\alpha$ , IL-1 $\beta$ , and tumor necrosis factor- $\alpha$  were not detected in the fibroblast supernatants. These observations support the notion that cell proliferation is accelerated indirectly by chitin and its derivatives when these materials are used *in vivo*. Okamoto *et al.* investigated the effects of chitin and their oligomers/monomers on the migration of fibroblasts (3T6) and vascular endothelial cells (human umbilical vascular endothelial cell: HUVEC) *in vitro* [37]. In a direct migratory assay using the blind well chamber method, migratory activity of 3T6 cells was reduced by chitin. The migratory activity of HUVECs was enhanced by chitin and the chitin monomer (GlcNAc). The supernatant of 3T6 cells preincubated with chitin reduced the migratory activity of 3T6 cells. The supernatant preincubated with chitin had no effect.

**Table 1.** The summary of *in vitro* studies of chitin for wound healing.

Preparation	Cells	Major results	Ref.
Chitin, its derivatives	Fibroblast	Chitin and its derivatives showed almost no acceleratory effects on proliferation	[36]
Chitin/their oligomer/monomer	3T6	The migratory activity was reduced by chitin, chitosan and GlcN	[37]
Chitin/their oligomer/monomer	HUVECs	The migratory activity was enhanced by chitin, chitosan and GlcNAc	[37]
Chitin	Bovine PMNs	Chitin and chitosan activated bovine PMNs	[38]
Chitin	Canine PMNs	Chitin and chitosan activated canine PMNs	[39]
Chitin	Canine PMNs	Chitin and chitosan induced complement-mediated chemotactic activities	[40]
Chitin	Canine PMNs	Supernatants of canine PMNs incubated with chitin and chitosan contained high enough LTB4 and PGE2 concentrations	[41]
Chitin	Macrophage	Chitin is a size-dependent stimulator of macrophage IL-17A production and IL-17AR expression and demonstrated that these responses are TLR-2 and MyD88-dependent	[42]

Usami *et al.* reported that chitin and chitosan induced the activation of bovine and canine polymorphonuclear cells (PMNs) *in vitro* [38,39]. They also described complement-mediated chemotactic activities (CA) that were only induced by chitin and not by GlcNAc and their oligomers [40]. Moreover, they investigated the effects of chitin on the release of arachidonic acid products. Supernatants of

suspensions of canine PMN incubated with chitin contained a leukotriene B4 (LTB4) concentration high enough to induce canine PMN migration *in vitro*. The supernatants also contained the same concentration of prostaglandin E2 (PGE2) as normally found in the peripheral blood of dogs [41].

Da silva *et al.* characterized the ability of chitin fragments to regulate murine macrophage cytokine production *in vitro* [42]. They showed that chitin is a size-dependent stimulator of macrophage IL-17A production and IL-17AR expression and demonstrated that these responses are TLR-2 and MyD88-dependent.

## 2.2. Animal Studies

Many reports by animal experiments also indicate the beneficial effects of chitin for wound healing (Table 2). Okamoto *et al.* histologically evaluated the effects of chitin, which was obtained from squid pen, in dogs [43]. In the chitin group, the implant was organized gradually and its organization was completed on post-implantation day (PID) 18, when obvious angiogenesis toward the non-woven fabric of polyester (NWF) was observed. Numbers of mononuclear (MN) and polymorphonuclear (PMN) cells concentrated around the implants on PID 2 were larger in the chitin group than in the control group. In the chitin group, formation of granulating tissue around the implant was identified on PID 4, whereas such a phenomenon was not observed in the control group. Moreover, Okamoto *et al.* described the sponge-, cotton-, and flake-type remedies made of chitin (chitin-sponge, chitin-cotton, and chitin-flake, respectively), and NWF composited with chitin (chitin-NWF) was applied to various types of trauma, abscess, surgical tissue defect, and herniorrhaphy in 147 clinical cases including 72 dogs, 38 cows, 33 cats, two rabbits, one monkey, and one horse [44]. Chitin-sponges were applied in 30 cases as filling agents for surgical tissue defects, in 25 trauma cases, and in 31 cases of abscess as a wound dressing or tissue defect-filling agent. In 77 out of 86 cases (89.5%), good healing developed. When the chitin-sponge was buried in surgical tissue defects due to oncotomy in 20 cases, post-operative recurrence of the tumor was observed in one case after one month, but was not recognized for a period of 3–24 months in the rest of the 19 cases. Chitin-NWF was applied in two cases of trauma and 12 cases of abscess as a wound dressing or tissue defect-filling agent, six cases as a filling agent for surgical tissue defects, and 12 cases of umbilical hernia as a prosthesis for the suture site of a hernia ring. In 28 out of 32 cases (87.5%), good healing developed. Chitin-cotton was applied in eight cases of trauma and 12 cases of abscess as a wound dressing or tissue defect-filling agent. In 18 out of 20 cases (90.0%), good healing developed. Chitin-flake was applied in nine cases of trauma as a wound dressing or tissue defect-filling agent. In eight out of nine cases (88.9%), good healing developed. In all cases, no side effects were observed. Minami *et al.* reported the level of prostaglandin E2 (PGE2) in the exudate induced by subcutaneous implantation of a complex formed from NWF and polymeric chitin (chitin/NWF) or by implantation of NWF in dogs measured by radioimmunoassay [45]. The amount of PGE2 in the exudate induced by chitin/NWF was about five times as high as that in the exudate induced by NWF, while the level of PGE2 in the exudate was similar to that in serum. Minami *et al.* described that chitin and chitosan activated the complement components C3 and C5, but not C4. The intensity of complement activation was greater with CS than with chitin. Chitin and CS both activated the complement system via the alternative pathway [46]. Suzuki *et al.* reported the influence of the physicochemical properties of chitin and chitosan on complement activation [47]. They described that the activation of the complement

system disappeared with increasing hydrophilicity (increase in the deacetylation ratio, use of low-molecular-weight compounds).

A study using an incisional skin wound in a rat model was carried out by Kojima *et al.* to evaluate the effect of chitin on collagen synthesis in wound healing [48]. Collagen synthesis was evaluated by measuring prolyl hydroxylase activity in rat granulation tissue. It was found that, compared to chitosan, chitin at the higher concentration (10 mg/mL) induced stable collagen synthesis without scatter in the early wound-healing process.

**Table 2.** The summary of *in vivo* studies of chitin for wound healing.

Preparation	Animal	Major results	Ref.
Chitin	Dog	Numbers of MN and PMN cells were larger in the chitin group than in the control group. Formation of granulating tissue around the implant was identified in the chitin group	[43]
Chitin-sponge	Dog, cow, cats, <i>etc.</i>	Chitin-sponges were applied in 30 cases as filling agents for surgical tissue defects, in 25 trauma cases, and in 31 cases of abscess as a wound dressing or tissue defect-filling agent. In 77 out of 86 cases (89.5%), good healing developed	[44]
Chitin-cotton	Dog, cow, cats, <i>etc.</i>	Chitin-cotton was applied in 8 cases of trauma and 12 cases of abscess as a wound dressing or tissue defect-filling agent. In 18 out of 20 cases (90.0%), good healing developed	[44]
Chitin-flake	Dog, cow, cats, <i>etc.</i>	Chitin-flake was applied in 9 cases of trauma as a wound dressing or tissue defect-filling agent. In 8 out of 9 cases (88.9%), good healing developed	[44]
Chitin/NWF	Dog	The amount of PGE2 in the exudate induced by chitin/NWF was about 5 times as high as that in the exudate induced by NWF	[45]
Chitin	Dog	Chitin activated the complement components C3 and C5, but not C4	[46]
Chitin	Rat	Compared to chitosan, chitin at the higher concentration (10 mg/mL) induced stable collagen synthesis without scatter in the early wound-healing process	[47]

### 3. Chitosan for Wound Healings

#### 3.1. *In Vitro* Study

Wiegand *et al.* reported the cytotoxic effects of two types of chitosan with similar degrees of deacetylation (DDA) but different molecular weights, 120 and 5 kDa, on the human keratinocyte cell line HaCaT (Table 3) [49]. The results indicated that chitosan exhibited a molecular weight-dependent negative effect on HaCaT cell viability and proliferation *in vitro*. The chitosan tested also stimulated the release of inflammatory cytokines by HaCaT cells depending on incubation time and concentration. Chitosan-120 kDa and chitosan-5 kDa induced apoptotic cell death, which was mediated by activation of the effector caspases 3/7. For the 120 kDa chitosan, the involvement of both extrinsic and intrinsic signal pathways was shown by the activation of caspases 8 and 9. Howling *et al.* examined the effect of chitin and chitosan with different degrees of deacetylation (DDA) but similar molecular weights on the proliferation of human skin fibroblasts and keratinocytes *in vitro* [50]. It was reported that chitosan with

relatively high DDA (89%) strongly stimulated fibroblast proliferation, while samples with lower DDA showed less activity. The stimulatory effect on fibroblast proliferation required the presence of serum in the culture medium, suggesting that the chitosan may be interacting with growth factors present in the serum and potentiating their effect. In contrast to the stimulatory effects on fibroblasts, chitosan inhibited human keratinocyte mitogen. These data demonstrated that high DDA chitosan can modulate human skin cell mitogen *in vitro*.

**Table 3.** The summary of *in vitro* studies of chitosan for wound healing.

Preparation	Cells	Major results	Ref.
Chitosan	HaCaT	Chitosan exhibited a molecular weight-dependent negative effects on cell viability and proliferation	[49]
Chitosan	Fibroblast	Chitosan with high DDA strongly stimulated proliferation	[50]
Chitosan, their oligomer/monomer	3T6	The migratory activity was reduced by chitosan and GlcN	[37]
Chitosan, their oligomer/monomer	HUVECs	The migratory activity was enhanced by chitosan	[37]
Chitosan-based membranes	Human PMNs	PMNs, in the presence of chitosan, secrete lysozyme. The materials do not stimulate the production of ROS	[51]
Chitosan	Human PMNs	PMNs, stimulated with G-CSF and chitosan, accumulated osteopontin mRNA and released osteopontin	[52]
Chitosan	Macrophage	Chitosan had a stimulatory effect on both macrophage nitric oxide (NO) production and chemotaxis	[53]

Okamoto *et al.* investigated the effects of chitosan and their oligomers/monomers on the migration of fibroblasts (3T6) and vascular endothelial cells (HUVEC) *in vitro* [37]. In a direct migratory assay using the blind well chamber method, migratory activity of 3T6 cells was reduced by chitosan and the chitosan monomer (GlcN). The migratory activity of HUVECs was enhanced by chitosan and was reduced by chitosan oligomers and GlcN. The supernatant of 3T6 cells preincubated with chitin or chitosan reduced the migratory activity of 3T6 cells. The supernatant of HUVECs preincubated with chitosan also reduced the migratory activity of HUVECs.

Santos *et al.* investigated the effect of chitosan-based membranes on the activation of human PMNs [51]. Isolated human PMNs were cultured in the presence of newly-developed membranes of chitosan or chitosan/soy. The effect of the chitosan on the activation of PMNs was assessed by the quantification of lysozyme and reactive oxygen species (ROS). The results showed that PMNs, in the presence of chitosan, secrete similar amount of lysozyme like the controls (PMNs without material), also that the materials do not stimulate the production of ROS. Ueno *et al.* reported that osteopontin was produced in human PMNs treated with chitosan [52]. Osteopontin is a glycosylated phosphoprotein that promotes the attachment or spread of a variety of cell types. In addition, osteopontin may play a role in granulomatous inflammation. The *in vitro* results showed that PMNs, stimulated with granulocyte-colony

stimulating factor (G-CSF) and chitosan, accumulated osteopontin mRNA and released osteopontin into their culture supernatants. These findings suggest that osteopontin is synthesized by migrating PMNs, elucidating a novel role of chitosan in regulating the evolution of wound healing at the early phase of healing. The macrophage NO secretion was attributed to the *N*-acetyl-glucosamine unit of the chitosan molecule rather than to the glucosamine residue. Moreover, the immunostimulatory effect of chitosan was very specific, since other glycosaminoglycans, such as *N*-acetyl-D-mannosamine and *N*-acetyl-D-galactosamine, had no effects on NO production [53].

An important aspect of materials used as wound dressings is their antimicrobial activities [7]. It has been proposed that interactions between positively charged chitosan molecules and negatively charged microbial cell membranes lead to the disruption of the microbial membrane and subsequently the leakage of proteinaceous and other intracellular constituents [54–57]. At lower concentrations (<0.2 mg/mL), the polycationic chitosan binds to the negatively charged bacterial surface to cause agglutination, while at higher concentrations, the larger number of positive charges impart a net positive charge to the bacterial surfaces to keep them in suspension [54]. It has also been proposed that chitosan interacts with the membrane of the cell to alter cell permeability [54,57,58]. Studies using fluorescent probes, 1-*N*-phenylnaphthylamine, Nile red and propidium iodide, and field emission scanning electron microscopy suggested that chitosan-arginine's antibacterial activity is at least in part due to its interaction with the cell membrane, in which it increases membrane permeability [58].

No *et al.* compared the antibacterial activities of chitosan and chitosan oligomers against both gram-negative and gram-positive bacteria [59]. Chitosan showed higher antibacterial activities than chitosan oligomers and markedly inhibited the growth of most bacteria tested, although inhibitory effects differed with molecular weights of chitosan and the particular bacterium. Chitosan generally showed stronger bactericidal effects with gram-positive bacteria than with gram-negative bacteria in the presence of 0.1% chitosan. As a chitosan solvent, 1% acetic acid was effective in inhibiting the growth of most of the bacteria tested, except for lactic acid bacteria that were more effectively suppressed with 1% lactic or formic acids. Raafat *et al.* investigated the antimicrobial mode of action of chitosan using a combination of approaches [57]. It was found that chitosan exhibited a dose-dependent growth-inhibitory effect. A simultaneous permeabilization of the cell membrane to small cellular components, coupled with a significant membrane depolarization, was detected. A concomitant interference with cell wall biosynthesis was not observed. Chitosan treatment of 22 *Staphylococcus simulans* cells did not give rise to cell wall lysis; the cell membrane also remained intact. Muzzarelli *et al.* tested the antimicrobial efficacy of *N*-carboxybutyl chitosan, which was prepared from crustacean chitosan (DDA = 73%), against 298 strains of gram-positive and gram-negative pathogens and *Candida* spp. [60]. It was found that *N*-carboxybutyl chitosan was particularly active against *Candida* and gram-positive bacteria. Seyfarth *et al.* studied the antifungal activities of water-soluble low- and high-molecular weight chitosan hydrochloride, carboxymethyl chitosan, chitosan oligosaccharide, and *N*-acetyl-D-glucosamine against *Candida albicans*, *Candida krusei*, and *Candida glabrata* [61]. The investigators observed a concentration-dependent antifungal activity of low- and high-molecular-weight chitosan hydrochloride against the fungal species in acid medium. In addition, the investigators found an influence of molecular weight on the antifungal activity: a low-molecular weight was associated with low antifungal activity. Another interesting fact was the low activity of carboxymethyl chitosan against the fungal species.

### 3.2. In Vivo Study

Ueno *et al.* evaluated the effects of cotton fiber-type chitosan (DDA = 18%) on the accelerated granulation in experimental open skin wounds on beagles during the early phase of wound healing (Table 4) [62]. It was reported that, on day 3 post-wounding, the chitosan-treated wounds showed histologically severe infiltration of PMN cells and an increase in effusion compared with the control. Granulation was pronounced on days 9 and 15 post-wounding in the chitosan treatment group. In the study described by Okamoto *et al.*, square, full-thickness skin wounds ( $2 \times 2 \text{ cm}^2$ ) were created on both sides of the dorsal midline of each dog and treated every two days with chitin powder, chitosan powder, or not treated [63]. Macroscopic and histological observations indicated that, at 28 days post-wounding, re-epithelialization tended to be greater in chitin and chitosan groups than in the non-treated control group. The number of inflammatory cells was statistically greater in the control group than in the chitin and chitosan groups. Mi *et al.* prepared an asymmetric chitosan membrane using the immersion-precipitation phase inversion method and evaluated it as a wound covering [64]. The chitosan wound dressing consisted of a skin surface on the top layer supported by a macro-porous sponge-like sublayer. The asymmetric chitosan membrane demonstrated controlled evaporative water loss, excellent oxygen permeability, and promoted fluid drainage ability, and could inhibit the invasion of exogenous microorganisms owing to the dense skin layer and inherent antimicrobial property of chitosan. Open skin wounds in rats covered with the asymmetric chitosan membrane were hemostatic and healed quickly. Histological examination confirmed that the epithelialization rate was increased and the deposition of collagen in the dermis was well organized as a result of covering the wounds with this asymmetric chitosan membrane. The effect of a chitosan acetate bandage (HemCom bandage) on healing of excisional wounds in mice with and without *S. aureus* infection was investigated by Burkatovskaya *et al.* [65]. In order to study the conflicting clamping and stimulating effects of the chitosan acetate bandage on normal wounds, the bandages were removed from wounds at times after application ranging from 1 h to 9 days. Application for three days resulted in the earliest wound closure, and all application times resulted in a faster healing slope after removal compared with control wounds. In addition, the chitosan acetate bandage reduced the number of inflammatory cells in the wound at days 2 and 4 and had an overall beneficial effect on wound healing, especially during the early period where its antimicrobial effect is most important.

In a study using a rat model, Jin *et al.* compared the effects of chitosan with heparin on the early extension of burns [66]. Chitosan powder, heparin powder, and the mixture of chitosan and heparin were applied to burns created on the backs of rats. Histological examination after 72 h showed that the burn degree of the chitosan-treated group was less severe than that of the control group, and chitosan greatly prevented the extension of burns in the early phase. In contrast, heparin had no protective effect on the early extension of burns. Use of chitosan and heparin together attenuated chitosan's protective effect. Alsarra investigated the wound-healing efficacy of chitosan with different molecular weights and DDA ranges on rat burns [67]. The highest wound-healing rate was found in the group treated with high-molecular weight and high-DDA chitosan. Burns treated with high molecular weight chitosan had significantly more epithelial tissue, and the best re-epithelialization and fastest wound closure were obtained in the high-molecular-weight chitosan treatment group. Histological examination and studies on collagenase activity revealed advanced granulated tissue formation and epithelialization in wounds



treated with high molecular weight chitosan. A chitosan hydrogel (white, opaque, and presented a dense outer layer, a highly porous and interconnected interior structure, high DDA: 86%) was developed by Ribeiro *et al.* and its applicability as a wound dressing for burn wounds in rats was evaluated [68]. Macroscopic analysis revealed that the wound beds of the animals treated with the chitosan hydrogel were considerably smaller than those of the untreated controls. Histological analysis revealed a lack of a reactive or a granulomatous inflammatory reaction in skin lesions treated with the chitosan hydrogel and the absence of pathological abnormalities in the organs obtained by necropsy, which supported the local and systemic histocompatibility of the biomaterial. In a similar study, bio-inspired bilayered physical hydrogels (only used intermolecular physical cross-links of low energy ( $\leq kT$ ): hydrogen bonding and hydrophobic interactions to elaborate a three-dimensional network of polymer chains) composed of only chitosan and water were processed and applied for the treatment of full-thickness burn injuries in dogs [69]. The first layer consisted of a rigid protective gel to ensure good mechanical properties and gas exchanges. A second soft and flexible layer allowed the material to follow the geometry of the wound and ensured a good superficial contact. The results showed that chitosan materials were well-tolerated and promoted good tissue regeneration. They induced inflammatory cell migration and angiogenic activity favoring a high vascularization of the neotissue. Moreover, collagen types I and IV were synthesized under the granulation tissue and the formation of the dermal-epidermal junction was observed. After 100 days, the new tissue was quite similar to native skin, especially by its aesthetic aspect and its great flexibility. A study was carried out by Diegelmann *et al.* to analyze the effect of chitosan on the subcutaneous wound-healing response in rats [70]. The polyvinyl alcohol sponge implant model was used as a means to deliver either chitosan or its vehicle to standardized subcutaneous wounds on the back of rats. It was shown that the presence of chitosan significantly delayed the appearance of macrophages and also reduced capillary ingrowth, fibroblast infiltration, and mature collagen fiber deposition. Okamoto *et al.* investigated the effects of chitosan on experimental *S. aureus* infected abscesses in dogs [71]. The abscesses were treated with suspensions of finely granulated chitosan in varying doses (0.01, 0.1, or 1.0 mg). It was found that, in comparison with the ampicillin treated and non-treated control group, the group treated with chitosan at doses of 0.1 and 1.0 mg had a faster wound-healing rate. Histologically, the granulation tissue formed had abundant vascularization in the 0.1 and 1.0 mg chitosan groups on day 8.

Burkatovskaya *et al.* compared the antimicrobial ability of the HemCon™ bandage, a chitosan acetate bandage, with an alginate sponge bandage and silver sulfadiazine cream in mouse models with infected open wounds [72]. An excisional wound in BALB/c mice was inoculated with 50–250 million bacterial cells. After 30 min of inoculation, it was followed by the application of the HemCon™ bandage, alginate sponge bandage, silver sulfadiazine cream, or no treatment. All chitosan acetate-treated mice infected with *P. aeruginosa* and *P. mirabilis* survived, while groups receiving no treatment, alginate, and silver sulfadiazine demonstrated 25%–100% mortality. Chitosan acetate was much more effective than other treatments in rapidly reducing bacterial luminescence, which was correlated to the colony forming units of bacteria isolated from the wounds. *S. aureus* formed only nonlethal localized infections after temporary immunosuppression of the mice, but HemCon™ was again more effective in reducing bacterial luminescence. Ong *et al.* refined the chitosan dressing by incorporating polyphosphate and silver for improved hemostatic and antimicrobial effects [73]. *In vivo* animal tests demonstrated that the silver dressing also significantly reduced mortality from 90% to 14.3% in a *P. aeruginosa* wound

infection model in mice. Although the dressing exerted severe cytotoxicity against cultured fibroblasts, wound healing was not inhibited. The sterility is a prerequisite for preparations to use on injured skin. Biomaterials based on chitin and chitosan can be used after gamma irradiation, thermal treatment in autoclave and ethylene oxide [7,74,75].

**Table 4.** The summary of *in vivo* studies of chitosan for wound healing.

Preparation	Animal	Major results	Ref.
Cotton fiber-type chitosan	Dog	Cotton fiber-type chitosan showed the accelerated granulation in experimental open skin wounds on beagles during the early phase of wound healing	[62]
Chitosan membrane	Rat	Open skin wounds in rats covered with the asymmetric chitosan membrane were hemostatic and healed quickly	[64]
Chitosan acetate bandage (HemCom)	Mouse	Chitosan acetate bandage had an overall beneficial effect on wound healing, especially during the early period where its antimicrobial effect is most important	[65]
Chitosan powder	Rats	Chitosan greatly prevented the extension of burns in the early phase	[66]
Chitosan	Rats	The highest wound-healing rate was found in the group treated with high-molecular weight and high-DDA chitosan. Burns treated with high molecular weight chitosan had significantly more epithelial tissue, and the best re-epithelialization and fastest wound closure were obtained in the high-molecular-weight chitosan treatment group	[67]
Chitosan hydrogel	Rats	The wound beds of the animals treated with the chitosan hydrogel were considerably smaller than those of the untreated controls	[68]
Chitosan	Dogs	Chitosan was well-tolerated and promoted good tissue regeneration	[69]
Chitosan	Dogs	Chitosan was well-tolerated and promoted good tissue regeneration	[69]

### 3.3. Clinical Study

In patients undergoing plastic surgery, Biagini *et al.* treated the donor sites with soft pads of freeze-dried *N*-carboxybutyl chitosan to promote ordered tissue regeneration [76]. It observed that, compared to the control donor sites, better histoarchitectural order, better vascularization, and the absence of inflammatory cells were observed at the dermal level, whilst fewer aspects of proliferation in the malpighian layer were reported at the epidermal level. Accordingly, it was suggested that *N*-carboxybutyl chitosan leads to the formation of regularly organized cutaneous tissue and reduces anomalous healing. Stone *et al.* evaluated the healing at skin graft donor sites dressed with chitosan [77]. A total of 20 patients requiring a split-skin graft during the seven-month period were enrolled in the study. Half of the skin graft donor sites were dressed with chitosan and the other half with a conventional

dressing. Chitosan proved to be an easy dressing material to apply and maintain and was painless to remove. Histologically, skin occluded by the chitosan dressing showed marked differences from the skin occluded by conventional dressing at the newly healed stages. Chitosan biopsies showed a looser connective tissue stroma in the papillary dermis, which was richer in both glycosaminoglycan matrix and capillaries than control biopsies. Small dermal nerve fibers were also more numerous in chitosan biopsies and showed marked differences to skin occluded by the conventional dressing at the newly healed time point. In addition, digital color separation analysis of donor site scars demonstrated an earlier return to normal skin color at chitosan-treated areas. Another similar clinical study was conducted by Azad *et al.* to investigate a design for a chitosan membrane as a wound-healing dressing [78]. Membranes were prepared from shrimp chitosan (DDA = 75%) with less than 1% protein and mineral content and a molecular weight of  $1.5 \times 10^6 \pm 0.1 \times 10^6$  Dalton. The chitosan membranes, in mesh or non-mesh form, were applied to dress the fresh wound that resulted at a skin graft donor site after removal of a skin layer of 0.010–0.015 inches. Half of the wound was dressed with chitosan membrane and the other half with the control Bactigras<sup>®</sup>, a chlorhexidine acetate impregnated *tulle gras*. The clinical data indicated that the mesh chitosan membrane promotes efficient adherence, hemostasis, healing, and re-epithelialization of the wound. Itching and pain sensitivity were lessened. The histopathology preparations showed that under the chitosan membrane, cells stimulate repair of the skin cell layers and help to re-establish tissue architecture. The application of a non-mesh membrane was not advised. The use of non-mesh chitosan membranes resulted in the accumulation of blood under the membrane. A randomized controlled study aimed to determine the efficacy of a chitosan/dextran gel on hemostasis and wound healing after endoscopic sinus surgery was carried out by Valentine *et al.* [79]. A total of 40 patients undergoing endoscopic sinus surgery for chronic rhinosinusitis were enrolled in the study. Chitosan/dextran gel achieved rapid hemostasis with the mean time to hemostasis at 2 min compared with 10 min for the control. There were significantly less adhesions at all time points when chitosan/dextran gel was used than in the control. However, no significant difference was observed between chitosan/dextran gel and the control with respect to crusting, mucosal edema, infection, or granulation tissue formation.

Akncbay *et al.* reported the clinical effectiveness of chitosan, both as a carrier in gel form and as an active agent in the treatment of chronic periodontitis (CP) [80]. A total of 15 patients with moderate to severe CP were selected for this study. The chitosan gel (1% W/W) with or without 15% metronidazole was prepared and applied in combination with scaling and root planing and compared to scaling and root planing alone (control group) in CP patients. In all groups, significant improvements were observed in clinical parameters between baseline and week 24. No complications related to the chitosan were observed in patients throughout the study period. The authors suggested that chitosan itself is effective as well as its combination with metronidazole in CP treatment owing to its antimicrobial properties. In a similar study, Boynuegri *et al.* evaluated the effects of chitosan on periodontal regeneration. A total of 20 patients with CP were recruited for the study [81]. The chitosan gel (1% W/V) was applied alone or in combination with demineralized bone matrix or collagenous membrane. Radiographic data revealed that, in comparison with the non-treated control group, all treated groups showed statistically significant bone fills when compared with baseline, indicating that the use of chitosan gel alone or its combination with demineralized bone matrix/collagenous membrane is a promising method for periodontal regeneration.

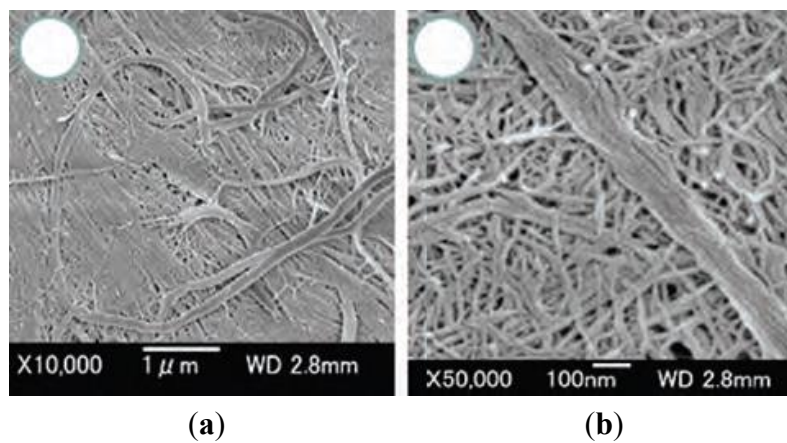
## 4. Materials Based on Chitin and Chitosan for Wound Healing

### 4.1. Chitin and Chitosan Nanofibers

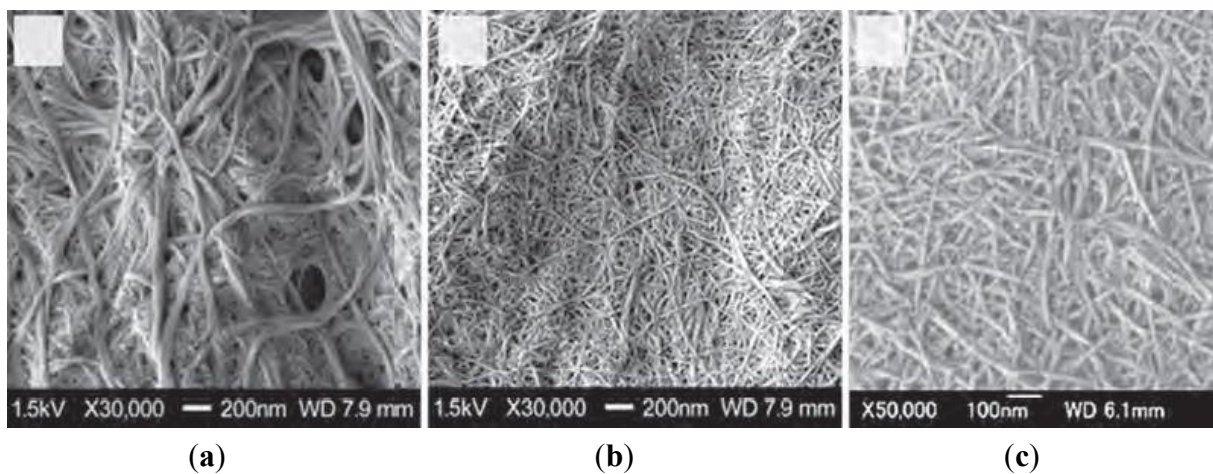
Nanofibers are fibers of less than 100 nm thickness with an aspect ratio of more than 100 [82,83]. Because of their characteristic morphology, extremely high surface-to-volume ratio, unique optical properties, and high mechanical strength, the development of methods for the preparation of nanofibers has become an important subject [84,85]. Chitin nanofibers (Chitin-NFs) are mainly prepared from crustacean and diatomaceous chitin powders according to newly adopted approaches and protocols. In particular, recent articles deal with the following advances: chitin-NFs isolated after hydrolysis in diluted HCl, chitin-NF isolated mechanically in the presence of minor amounts of acetic acid, chitosan-NF obtained from partially deacetylated chitin, mechanical fibrillation, fibrillation with the aid of sonication, manufacturing of chitin nanofibers by e-spinning, preparation and spinning of chitin solutions in ionic liquids, and manufacturing of aerogels [86]. Araki described the recent results on electrostatic and steric stabilizations of nanofibrils, together with brief and basic descriptions of their stabilization mechanisms [87]. Chitin nanofibers were isolated from the cell walls of five types of mushrooms by the removal of glucans, minerals, and proteins, followed by a simple grinding treatment under acidic conditions. The width of the nanofibers depended on the type of mushrooms from which they were obtained and varied between 20 and 28 nm; the crystalline structure was maintained and glucans remained on the nanofiber surface [21]. By similar means, chitin nanofibers ( $\Phi$  10–20 nm) were isolated from prawn shells under mild conditions (Figure 2) [88]. These nanofibers are considered to have great potential for various applications because they have several useful properties such as high specific surface area and high porosity [7]. Figure 3 shows field emission scanning electron microscopic (FE-SEM) images of the crab shell surface after removal of proteins and calcium carbonate. Chitin nanofibers of approximately 10-nm thickness were observed. Thicker chitin-protein fibers with a diameter of approximately 100 nm were also observed and confirmed to be bundles of nanofibers of 10-nm width. The obtained chitin slurry (in neutral water) was passed through a grinder. The width of the fibers derived from crab shells after grinder treatment was distributed over a wide range, *i.e.*, from 10 to 100 nm (Figure 4a). The twisted plywood structure seems disintegrated after application of a one-time grinder treatment. As a result, 100-nm-thick fibers were isolated from chitin-protein fibers. However, thicker fibers were not successfully disintegrated by grinder treatment, even though the protein layers were removed under a never dried condition. The chitin slurry thus obtained formed a gel after a single grinder treatment, suggesting that nano-fibrillation was accomplished because of the high dispersion property in acidic water and the high surface-to-volume ratio of the nanofiber. The disintegrated chitin was observed as highly uniform nanofibers with a width of 10 nm, suggesting that the fibrillation process was facilitated in acidic water (Figure 4b,c).



**Figure 2.** Chitin nanofiber.



**Figure 3.** FE-SEM micrographs of the crab shell surface after removal of the matrix. The length of the scale bars are (a) 1000 nm and (b) 100 nm, respectively. Copyright 2009 American Chemical Society [88].



**Figure 4.** FE-SEM micrographs of chitin nanofibers from crab shells after one pass through the grinder. (a) Without acetic acid (pH 7); (b) and (c) with acetic acid (pH 3). The length of the scale bar is (a) 200 nm, (b) 200 nm, and (c) 100 nm, respectively. Copyright 2009 American Chemical Society [88].

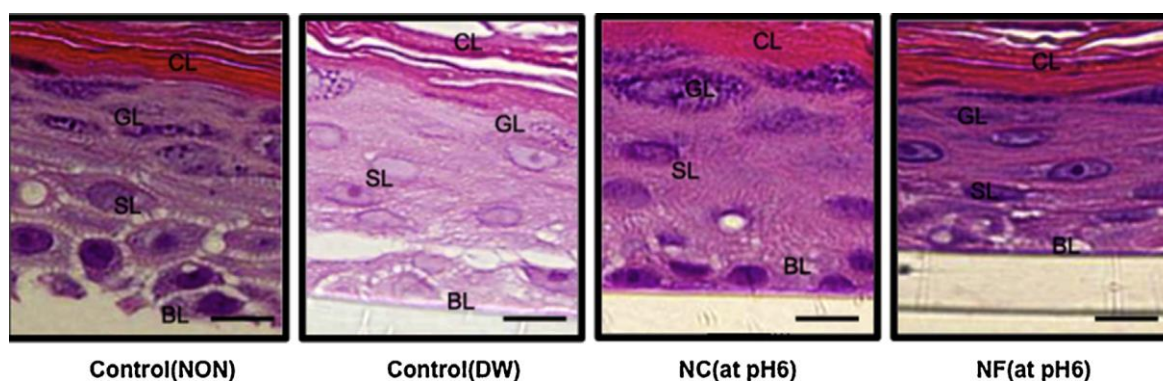
There are 3 categories of wound dressing: biologic, synthetic, and biologic-synthetic dressings. Biologic dressings are commonly used; however, they have some disadvantages, including high antigenicity, poor adhesiveness, and risk of cross contamination. Synthetic dressings have a long shelf life, induce a minimal inflammatory reaction, and carry almost no risk of pathogen transmission. Biologic-synthetic dressings are bi-layered and consist of high polymer and biologic materials [89–91]. Dressing materials must maintain a moist environment at the wound interface, allow gaseous exchange, act as a barrier to microorganisms, and remove excess exudates. The dressing should also be non-toxic, non-allergenic, nonadherent, and easily removable without causing trauma. Moreover, it should be made from readily available biomaterials that require minimal processing, possess antimicrobial properties, and promote wound healing [6]. Recent advances in process chemistry made it possible to prepare chitin-NF and chitosan-NF materials that are more flexible and useful for the development of new bio-related products. In fact, some reports discussed new generation of chitosan-based wound dressing materials [92,93].

Muzzarelli *et al.* reported that chitin nanofibrils that Talymed<sup>®</sup> manufactured from marine diatoms by Marine Polymer Tech., MA, USA, had been developed. Treatment of cutaneous wounds with the said FDA-approved chitin-NF resulted in more rapid wound closure in diabetic animal models, owing to increased expression of several cytokines, growth factors, and innate immune activation, besides activating angiogenesis, cell proliferation, and re-epithelialization [94]. The efficacy, safety, and tolerability of Talymed<sup>®</sup> among patients with leg ulcers was evaluated [95]. In a randomized, multi-center study, 86.4% of patients experienced complete wound healing when receiving multilayer compression plus Talymed<sup>®</sup> compared to 45% when receiving multilayer compression alone. The pilot study suggested that chitin-NF is well tolerated and effective. Fischer *et al.* reported that chitin-NF activates platelets, accelerates the clotting of blood, and is the best way to achieve surface hemostasis when patients are coagulopathic because of shock or treatment with antiplatelet drugs [96]. It was also reported that chitin-NF promotes the expression of  $\alpha$ - and  $\beta$ -defensins in endothelial cells and  $\beta$ -defensins in keratinocytes. Lindner *et al.* assessed the antimicrobial efficacy of chitin-NF [97]: *S. aureus*-infected wounds were either treated with chitin-NF or left untreated for three and five days. Gram staining showed that animals treated with chitin-NF showed significant reduction in bacterial counts five days post-wounding than the untreated wounds. Given that defensins are part of the innate immune system, activation of these pathways precludes the generation of resistant organisms, and also allows for the antibiotic-independent clearance of bacterial infection. Thus, they concluded that chitin-NF enhances wound healing while concomitantly limiting wound infection.

Mattioli-Belmonte *et al.* evaluated a spray, gel, and gauze that were prepared from chitin nanofibrils/chitosan glycolate by macroscopic assessment, light microscopy, and immunohistochemistry. The wound repair provided by these materials is clearly evident even without the synergistic effects of the laser co-treatment. These findings confirmed the effectiveness of chitin nanofibrils/chitosan glycolate-based products in restoring subcutaneous architecture [98]. Dibutylchitin (DBC) is a water-soluble chitin derivative with confirmed biological properties. DBC is obtained in the reaction of chitin with butyric anhydride, under heterogeneous conditions, in which perchloric acid is used as a catalyst [6]. Previously, DBC fibrous materials were used for wound healing applications. After  $\gamma$ -sterilization, DBC non-woven fabrics were applied to a group of nine patients with different indications [99]. Blasinka and Drobnik reported that implantation of DBC in the subcutaneous area of

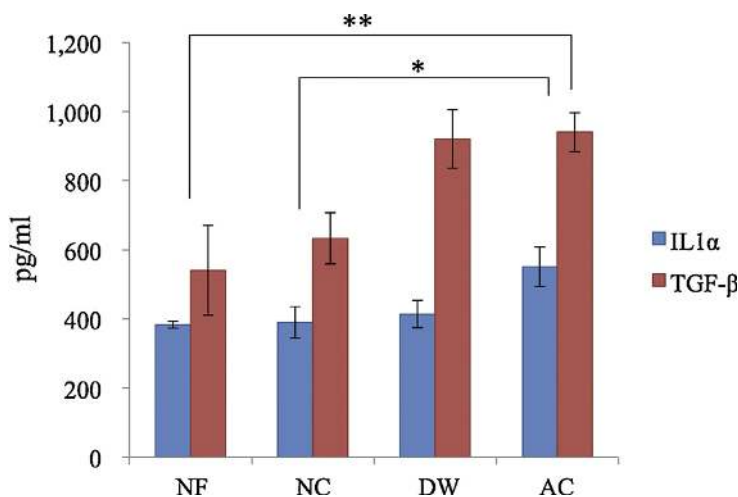
rats induced an increase in the weight of the granulation tissue [100]. This study revealed that the number of cells isolated from the wound and cultured on DBC films increased. DBC elevates the glycosaminoglycan level in the granulation tissue. This study documents the beneficial influence on tissue repair, which could be explained by the modification of the extracellular matrix (ECM) and cell number [100]. Jang *et al.* evaluated the effects of electrospun non-woven DBC/PLA-blended mats on wound healing. Topical application of the mats significantly reduced skin wound rank sores and increased skin remodeling of wounded hairless mice in a dose-dependent manner. Furthermore, the mats notably increased the expression of type I collagen and filaggrin. These results indicate that the application of the mats resulted in increased ECM synthesis and remodeling of the skin [101].

Ito *et al.* verified the effect of chitin nanofibrils and nanocrystals on skin using a 3D skin culture model and Franz cells [102]. In the experiment using a 3D culture model, histological images for the non-treatment, diluted water, chitin nanocrystal (pH 6), and chitin-NF (pH 6) groups at 24 h post-application are shown in Figure 5. The observations include large intercellular gaps in the non-treatment group, low granule density in the diluted water group, and high granule density in the chitin nanocrystal (pH 6) and chitin-NF (pH 6) groups. For both interleukin (IL)-1 $\beta$  and transforming growth factor- $\beta$  (TGF- $\beta$ ), the cytokine production increased in the following order: chitin-NF < chitin nanocrystals < diluted water < acetic acid. The TGF- $\beta$  levels differed significantly between the chitin-NF and acetic acid groups and the chitin nanocrystal and acetic acid groups (Figure 6). These results indicate that the application of nanofibrils and nanocrystals to skin improved the epithelial granular layer and increased granular density. Furthermore, application of nanofibrils and nanocrystals to the skin resulted in a lower production of TGF- $\beta$  compared to that of the control group. Thus, chitin-NF and nanocrystals might have protective effects on skin.



**Figure 5.** The effect of chitin-NF on histological changes in a 3D skin culture model. The number of layers and granule density were assessed in the granular layer (GL). Intercellular gaps and nucleus clarity were assessed in the spinosum layer (SL). Characteristic observations included large intercellular gaps in the NON group, low granule density in the DW group, and high granule density in the chitin nanocrystal (NC) (pH 6) and chitin-NF (NF) (pH 6) group. (Bar = 100  $\mu$ m). Copyright 2014 Elsevier [102].





**Figure 6.** The effect of chitin-NF on cytokine production in Franz cells. For both IL-1 $\beta$  and TGF- $\beta$ , the cumulative cytokine production increased in the following order: NF < NC < DW < AC. A highly significant difference was confirmed between the NF and DW groups (IL-1 $\beta$  and TGF- $\beta$ ) and the NF and AC groups (for TGF- $\beta$ ), whereas a significant difference was confirmed between the NC and AC groups (IL-1 $\beta$  and TGF- $\beta$ ). The error bars indicate mean  $\pm$  SE. Significantly different from the AC group (\*\* $P$  < 0.01; \* $P$  < 0.05). Copyright 2014 Elsevier [102].

An important aspect of materials used as wound dressing, is their antimicrobial activities. It is known that chitosan derivatives with quaternary ammonium groups possess antimicrobial properties [6]. It is now widely accepted that the target site of these cationic polymers is the cytoplasmic membrane of bacterial cells [103]. Photo cross-linked electrospun mats containing quaternary chitosan (QCS) were efficient in inhibiting the growth of gram-positive and gram-negative bacteria [104]. Similarly, photo-cross-linked electrospun nanofibrous QCS/poly-vinyl alcohol (PVA) mats had good antibacterial activities against *Escherichia coli* (*E. coli*, gram-negative) and *Staphylococcus aureus* (gram-positive) [105]. These characteristic features of electrospun mats indicate their great potential for wound dressing applications. Recently, biocompatible carboxyethyl CS (CECS)/PVA nanofibers were prepared by electrospinning of aqueous CECS/PVA solutions [106]. The potential use of CECS/PVA electrospun fiber mats as scaffold materials for skin regeneration was evaluated *in vitro* using mouse fibroblasts. Results from the indirect cytotoxicity assessment of the fiber mats indicated that CECS/PVA electrospun mats were non-toxic to mouse fibroblasts. Furthermore, cell culture results indicated that fibrous mats promoted mouse fibroblast attachment and proliferation. Charernsriwilaiwat *et al.* reported the wound healing effects of lysosome-loaded electrospun CS-based nanofiber mats. A blended mixture of CS ethylenediaminetetraacetic acid (weight ratio: 30/70) and PVA solution was electrospun to produce fibrous mats containing lysozyme. In the *in vivo* study, lysozyme-loaded CS-ethylenediaminetetraacetic acid nanofiber mats accelerated the rate of wound healing compared to gauze [107]. Zhou *et al.* evaluated composite nanofibrous membranes of water-soluble N-carboxyethyl CS/PVA/silk for use as wound dressings. The nanofibrous materials showed good biocompatibility [108].

Huang *et al.* evaluated a novel amphipathic derivative of chitosan (carboxymethyl-hexanoyl chitosan) as a wound dressing. The results showed that carboxymethyl-hexanoyl chitosan NFs preserved their antimicrobial activity and exhibited high biocompatibility for fibroblasts [109]. Li *et al.* prepared

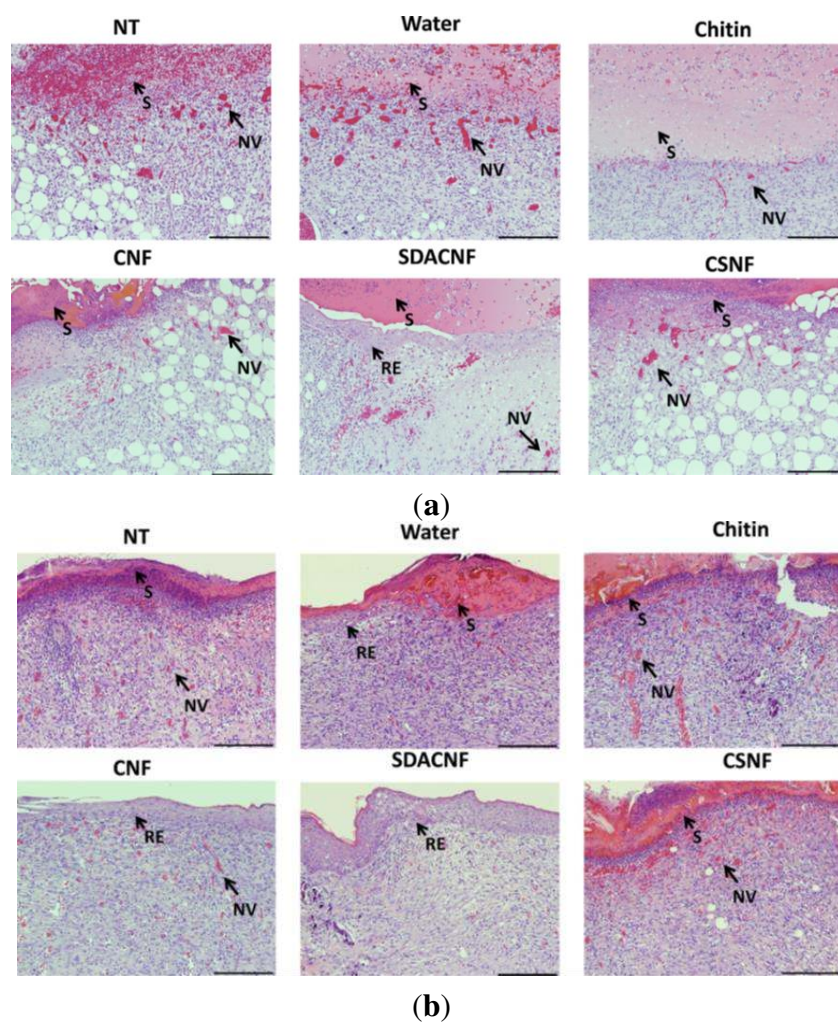


PLA/chitosan NFs with a core-shell structure by electrospinning. The electrospun nanofibrous materials promoted cell growth and attachment [110]. Wound dressing biomaterials should be bio-compostable and promote the growth of dermis and epidermis layers. Chen *et al.* evaluated composite nanofibrous membranes of chitosan/collagen, which are known for their beneficial effects on wound healing. The membranes were found to promote wound healing and induce cell migration and proliferation. In animal studies, the nanofibrous membranes were found to perform better in wound healing than gauze and commercial collagen sponges [111]. Wang *et al.* developed a poly(L-lactide-co-glycolide) (PLGA)-knitted mesh-reinforced collagen-chitin scaffold. Following transplantation of this scaffold, wound contraction was inhibited and neo-tissue formation and blood vessel in-growth were effectively promoted [112]. Cai *et al.* reported the preparation of composite nanofibrous membranes from chitosan and SF by electrospinning [113]. In this study, the antibacterial activities against *E. coli* (gram-negative) and *S. aureus* (gram-positive) were evaluated by measuring the turbidity. The results suggested that the antibacterial effects of the materials varied depending on the type of bacteria. Moreover, the biocompatibility of the prepared materials was investigated *in vitro* using murine fibroblasts with hematoxylin and eosin (HE) staining and MTT assays. The membranes were found to promote cell attachment and proliferation. These results suggested that chitosan/SF composite nanofibrous membranes are wound dressing candidates. Recently, chitosan-based electrospun nanofibrous materials have been proposed as burn dressings [114]. Chitosan-NF mats were prepared and evaluated as wound dressing for IIIa- and IIIb-degree burns. The results showed that chitosan-NF dressings provided effective absorption of exudates, ventilation of the wound, protection from infections, and stimulation of the process of skin tissue regeneration. Degradation of these materials prevented mechanical damage to the wound during removal.

Abdelgawad *et al.* described a green route to produce antibacterial nanofiber mats loaded with silver nanoparticles (Ag-NPs, 25 nm diameter) enveloped in chitosan after reduction with glucose. The results showed superior properties and synergistic antibacterial effects by combining chitosan with Ag-NPs [115]. Gomes *et al.* performed a study in order to compare the performance of electrospun nanofiber mats from three different polymers concerning cell-scaffold interaction and wound healing promotion. A polyester (polycaprolactone, PCL), a protein (gelatin from cold water fish skin, GEL), and a polysaccharide (chitosan) were the polymers chosen. *In vitro* tests revealed that cells adhered and proliferated in all scaffolds. However, cells deep into the scaffold were only observed in the PCL and chitosan scaffolds. In *in vivo* tests, chitosan scaffolds had the highest impact on the healing process by decreasing the extent of wound contraction and enhancing the production of a neodermis and re-epithelialization of the wound [116]. Xu *et al.* reported the successful development of biocompatible tannic acid (TA)/chitosan (CS)/pullulan (PL) composite nanofibers (NFs) with synergistic antibacterial activity against the gram-negative bacteria *Escherichia coli*. The ternary composite membrane exhibits good water absorption ability with a rapid uptake rate. This novel membrane favors fibroblast cell attachment and growth by providing a 3D environment, which mimics the ECM in skin and allows cells to move through the fibrous structure. This results in interlayer growth throughout the membrane, thus favoring potential for deep and intricate wound healing [117].

More recently, the wound healing effects of superficially deacetylated chitin nanofibrils (SDACNFs) were evaluated using an experimental model [118]. The results of the present study indicate SDACNF quickly and effectively induce both re-epithelialization and proliferations of fibroblasts and collagen

compared than chitin, chitin nanofibrils (CNFs) and chitosan nanofibrils (CSNFs). The results of the histopathological assessments on day 8 are shown in Figure 7. Re-epithelization under the scab was observed in only the SDACNF group on day 4, whereas re-epithelization was not observed in the other groups on day 4. In the SDACNF group, complete re-epithelization was observed on day 8. In the CNF group, adequate re-epithelization was also observed on day 8. In the other groups, however, incomplete re-epithelization was observed. In the SDACNF group, fibroblast proliferation was well observed on day 8 and was superior to that of the other groups. Adequate collagen depositions were observed in the chitin, SDACNF, and CSNF groups on day 8. Although many mononuclear cells were observed in the NT, vehicle, chitin, and CSNF groups, only a few mononuclear cells were observed in the CNF and SDACNF groups on day 8.



**Figure 7.** Histopathological changes on day 4 and 8 in the circular excision wound model. All images are from one of four rats in each group on day 4 (a) and 8 (b). The arrows point to events during wound healing. S: scab, RE: re-epithelization, NV: neovascularization. NT: non-treatment control, Water: vehicle control, CNFs: chitin nanofibrils treatment, SDACNFs: superficially deacetylated chitin nanofibrils treatment, CSNFs: chitosan nanofibrils treatment. Bar: 200  $\mu$ m (a), 100  $\mu$ m (b). Copyright 2015 Elsevier [118].

The wound healing process consists of a series of interdependent and overlapping stages in which a variety of cellular and matrix components act together to reestablish the integrity of damaged tissue and replacement of lost tissue [34]. The wound healing process has been described as being comprised of five overlapping stages, which involve complex biochemical and cellular processes. These stages are described as homeostasis, inflammation, migration, proliferation, and maturation [35].

The results in this study indicate that SDACNF quickly progress the earlier stages of wound healing (homeostasis, inflammation and migration). Furthermore, it is also indicated that SDACNF strongly induced the later stages of wound healing (proliferation, and maturation) than CNF, chitin and CSNF. In the SDACNF group, many positive areas of MT staining were observed compared with those of the other groups on day 8. Following the histopathological examination, wound-healing stages were summarized in each experimental group (Table 5). The wound healing process consisted of three phases, namely inflammation, proliferation, and re-modeling. As a defense mechanism of the tissue, the first response is inflammation, which provides resistance to microbial contaminations. However, a long duration in the inflammatory phase causes a delay in the healing process [119]. The results of the present study indicate that SDACNFs strongly induced proliferation and re-modeling phases than CNFs and CSNFs (Table 5). Especially, the sign of the proliferation was observed in only the SDACNFs group on day 4. On the other hand, the remodeling phase was not observed in the other groups. In only the SDACNFs group, the complete regeneration of the epithelium was observed on day 8. In the CNF group, mild proliferation and re-modeling phases were observed on day 8. However, the regeneration of the epithelium was not completed. This result also indicates that SDACNFs quickly progress the inflammation phase and induced proliferation and re-modeling phases.

**Table 5.** Wound healing phases on day 4 and 8 in the circular excision wound model. HE and MT stained sections on day 4 and 8 were scored as none (–), mild (+), moderate (++) and severe (+++) for epidermal and/or dermal re-modeling. I: inflammation phase; P: proliferation phase; R: re-modeling phase. NT: non-treatment control; Water: vehicle control; CNFs: chitin nanofibrils treatment; SDACNFs: superficially deacetylated chitin nanofibrils treatment; CSNFs: chitosan nanofibrils treatment.

	<b>I</b>	<b>P</b>	<b>R</b>
<i>Day 4</i>			
NT	+++	+	–
Water	+++	+	–
Chitin	++/+++	++	–
CNF	++/+++	++	–
SDACNF	++	++	+
CSNF	++/+++	++	–
<i>Day 8</i>			
NT	++	+	+
Water	++	++	+
Chitin	++	++	–/+
CNF	+	++	++
SDACNF	+	+++	+++
CSNF	++/+++	++/+++	+

The application of CNFs to skin improved the epithelial granular layer and increased granular density [102]. It is reported that CNFs treatment causes increased expression of both  $\alpha$ - and  $\beta$ -type defensins in endothelial cells and  $\beta$ -type defensins in keratinocytes [97]. These observations indicate CNFs have beneficial effects for epidermal cells in wound healing process. Moreover, Erba *et al.* described that membranes consisting entirely of chitin nanofibers were applied to dorsal excisional wounds of db/db mice followed by application of a vacuum device [120]. Results included significant expression of platelet-derived growth factor, transforming growth factor, epidermal growth factor, and superior granulation tissue formation rich in collagen-I as well as epithelialization and wound contraction. In this study, we dropped small amount of materials for the wound. Thereby, the wound healing effects of chitin was not enough. In the CNFs groups, enough regeneration of the epidermal was observed. However, the proliferation of fibroblast is inadequate. In CSNFs group, adequate proliferation of fibroblast was observed. But the regeneration of the epidermal was poor. In the SDACNFs group, on the other hand, well regeneration of epidermal and proliferation of fibroblast were observed. These results might be indicating SDACNFs promote wound healing with the efficiency. If any material exhibits a combination of antioxidant, antimicrobial, and anti-inflammatory activities, it can be concluded that this material will promote wound healing and contribute to skin regeneration [121]. Antimicrobial activity is important during wound healing since wounds are exposed to an external environment and are more prone to microbial attacks, usually resulting in a delay in the healing process. Lindner *et al.* reported that CNFs membranes promoted the expression of  $\alpha$ - and  $\beta$ -defensins in endothelial cells and that of  $\beta$ -defensins in keratinocytes [97]. The results also indicated that wounds infected with *S. aureus* and treated with CNFs membranes showed a significant reduction in gram-positive staining, enhancing wound healing while concomitantly limiting wound infection. Previously, the antimicrobial effects of SDACNFs were reported [122]. Antioxidant materials provide wound-healing effects via free radical scavenging activities and inhabitation of lipid peroxidation, preventing cell damages [123,124]. We also reported the suppressive effects of CNFs on myeloperoxidase activation in inflammatory conditions of the colon [125]. These evidences might indicate that SDACNFs or CNFs are efficient as new functional biomaterials for the wound healing process [118].

These nanofibers are considered to have great potential for various applications because they have several useful properties such as high specific surface area and high porosity [126–128]. However, the reason why these nanofibers specifically enhance the wound healing process is unclear. Further study must be performed to understand the mechanisms of nano-chitin and nano-chitosan for wound healing.

#### 4.2. Other Formulations Based on Chitin and Chitosan

Many previous reports have indicated that materials based on chitin and chitosan are beneficial for wound healing. One is the hydrogel. Cho *et al.* prepared a water-soluble chitin hydrogel (deacetylation degree of 0.50 and molecular weight of 800 kDa). The water-soluble chitin hydrogel was found to be more efficient than chitin or chitosan powders as a wound-healing accelerator. Also, the chitin hydrogel-treated skin had the highest tensile strength and the arrangement of collagen fibers in the skin was similar to normal skin [129]. Loke *et al.* developed a non-adherent wound dressing with sustained anti-microbial capability. The wound dressing consists of two layers: the upper layer is a carboxymethyl

chitin hydrogel material, while the lower layer is an anti-microbial impregnated biomaterial. The hydrogel layer acts as a mechanical and microbial barrier, and is capable of absorbing wound exudate. In physiological fluid, the carboxymethylated chitin hydrogel swells considerably, imbibing up to four times its own weight in water, and is also highly porous to water vapor. The moisture permeability of the dressing prevents the accumulation of fluid in heavily exuding wounds seen in second-degree burns. The lower layer, fabricated from chitosan acetate foam, is impregnated with chlorhexidine gluconate. From the *in vitro* release studies, the loading concentration was optimized to deliver a sufficient amount of anti-microbial drugs into the wound area to sustain the anti-microbial activity for 24 h [130]. The effects of topical formulations based on water-soluble chitin were evaluated in a rabbit ear model. The application of water-soluble chitin ointments significantly accelerated wound healing and wound contraction. The areas of epithelialization and granulation tissue in the water-soluble chitin ointment group were found to be remarkably larger than those in the control group (no treatment) and in the placebo group (treated with ointment-based materials). Grown granulation tissue, including dense fibroblast deposition was observed under the thickened epithelium of the wound treated with water-soluble chitin ointments. The number of inflammatory cells in the water soluble chitin ointment group was significantly decreased compared with those in the control and placebo groups, indicating that water soluble chitin would give low stimuli to wounds and prevent excessive scar formation [131]. It has been reported that treatment of full-thickness cutaneous wounds in a diabetic mouse model with chitin-containing membranes resulted in an increased wound closure rate correlated with an impressive rise in angiogenesis. Serum-starved endothelial cells were treated with vascular endothelial growth factor (VEGF) or with different concentrations of chitin. As compared with the total number of cells plated (control), at 48 h after serum starvation, there was a twofold reduction in the number of cells but this reduction was reversed after the addition of VEGF or chitin at either 5 or 10 mg/mL. These results indicate that, like VEGF, chitin treatment prevents cell death induced by serum deprivation [132]. Jayakumar *et al.* developed  $\alpha$ - and  $\beta$ -chitin membranes using  $\alpha$ - and  $\beta$ -chitin hydrogel for wound dressing applications. The bioactivity and cell adhesion studies of these membranes were studied using MG63 osteoblast cells [15]. The cells adhered and spread over the membrane after 24 h of incubation. In another study, the  $\alpha$ -chitin/gelatin composite hydrogels were prepared by mixing  $\alpha$ -chitin hydrogel with gelatin [133]. In this work, mechanical, swelling, enzymatic degradation, thermal, and bioactivity studies were examined. Biocompatibility of the  $\alpha$ -chitin/gelatin hydrogel was performed in human MG63 osteoblast-like cells. After 48 h, the cells were attached and completely spread over the membrane surface. In the same way, the biological properties of the  $\alpha$ -chitin hydrogels were also reported [134].

Boucard *et al.* processed bio-inspired bi-layered physical hydrogels that only consisted of chitosan and water and applied them to the treatment of full-thickness burn injuries. To compare, highly viscous solutions of chitosan were also considered. Animal experiments were performed on pigskin and biopsies performed on days 9, 17, 22, 100, and 293 were analyzed by histology and immunohistochemistry. Only one chitosan material was used at each time point. All the results showed that chitosan materials were well-tolerated and promoted good tissue regeneration. They induced inflammatory cell migration and angiogenetic activity favoring high vascularization of the neo-tissue. At day 22, collagen types I and IV were synthesized under the granulation tissue and the formation of a dermal-epidermal junction was observed. After 100 days, the new tissue was quite similar to native skin, especially by its aesthetic aspect and its great flexibility [68]. Ribeiro *et al.* evaluated the applicability of chitosan hydrogel as a

wound dressing [69]. The results showed that chitosan hydrogel was able to promote cell adhesion and proliferation. Chitosan's positive charge allows for electrostatic interactions with glycosaminoglycans, which attract growth factors that enhance cell growth and proliferation [135]. Cell viability studies showed that the hydrogel and its degradation by-products are non-cytotoxic. The evaluation of the applicability of chitosan in the treatment of dermal burns in Wistar rats was performed by induction of full-thickness transcutaneous dermal wounds. Macroscopic analysis revealed that the wound beds of the animals treated with chitosan were considerably smaller than those of the controls. Histological analysis revealed a lack of a reactive or granulomatous inflammatory reaction in skin lesions with chitosan and the absence of pathological abnormalities in the organs obtained by necropsy, which supported the local and systemic histocompatibility of the biomaterial [69]. Application of ultraviolet light irradiation to a photocrosslinkable aqueous chitosan solution resulted in an insoluble and flexible hydrogel [136,137]. In order to evaluate its accelerating effect on wound healing, full-thickness skin incisions were made on the backs of mice and subsequently a photocross-linkable chitosan aqueous solution was added into the wound and irradiated with ultraviolet light for 90 seconds. Application of the chitosan hydrogel significantly induced wound contraction and accelerated wound closure and healing compared with the untreated controls. Histological examination showed an advanced contraction rate on the first two days and tissue fill rate on days 2 to 4 in the chitosan hydrogel-treated wounds. Furthermore, in cell culture studies, chitosan hydrogel culture medium supplemented with 5% fetal-bovine serum was found to be a chemo-attractant for human dermal fibroblasts in an invasion chamber assay using filters coated with Matrigel and in a cell migration assay.

Kweon *et al.* described how a water-soluble chitosan/heparin complex was prepared using water-soluble chitosan with wound healing ability and heparin with the ability to attract or bind to growth factors related to the wound healing process [138]. To evaluate the wound healing effect, a full thickness skin excision was performed on the backs of the rat. Grossly, in the untreated control group the wound had a well-defined margin and was covered by crust. The second group treated with water-soluble chitosan ointment revealed a small wound size with less crust and an ill-defined margin, which appeared to regenerate from the margin. The third group treated with water-soluble chitosan/heparin complex ointment appeared to be nearly completely healed. The third group (water-soluble chitosan/heparin) showed nearly complete regeneration of the appendage structure and was similar to normal in the dermis. In contrast, the control and second groups exhibited an absence and decreased number of skin appendages, respectively. In order to create a moist environment for rapid wound healing, a hydrogel sheet composed of a blended powder of alginate, chitin/chitosan, and fucoidan (ACF-HS; 60:20:2:4 W/W) has been developed as a functional wound dressing [139]. On application, ACF-HS was expected to effectively interact with and protect the wound in rats, providing a good moist healing environment with exudates. In addition, the wound dressing has properties, such as ease of application and removal as well as good adherence. Histological examination demonstrated significantly advanced granulation tissue and capillary formation in the healing-impaired wounds treated with ACF-HS on day 7. Yang *et al.* developed hydrogels based on PVA, water-soluble chitosan, and glycerol made by irradiation followed by freeze-thawing [140]. MTT assay suggested that the extract of hydrogels was non-toxic towards L929 mouse fibroblasts. Compared to gauze dressing, the hydrogel based on PVA, water-soluble chitosan, and glycerol accelerates the healing process of full-thickness wounds in a rat model. Wounds treated with hydrogel healed at the 11th day postoperatively and histological observation showed that mature

epidermal architecture was formed. Sung *et al.* developed a minocycline-loaded wound dressing with an enhanced healing effect [141]. The cross-linked hydrogel films were prepared with PVA and chitosan using the freeze-drying method. In a wound-healing test, this minocycline-loaded PVA-chitosan hydrogel showed faster healing of the wound made in the rat dorsum than the conventional product or the control (sterile gauze) due to the antifungal activity of chitosan. In particular, from the histological examination, the healing effect of minocycline-loaded hydrogel was greater than that of the drug-loaded hydrogel, indicating the potential healing effect of minocycline. Liu *et al.* describes novel hydrogel nanofiber mats fabricated via solution blowing of chitosan and PVA solution, with various contents of ethylene glycol diglycidyl ether (EGDE) as a cross-linker [142]. The mat quickly hydrated in an aqueous environment to form a hydrogel. Their value of equilibrium water absorption varied from 680% to 459% based on the EGDE content. The nanofiber mats showed good bactericidal activity against *Escherichia coli*.

Aoyagi *et al.* prepared novel wound dressings composed of chitosan film and minocycline hydrochloride using commercial polyurethane film (Tegaderm) [143]. Various formulations were applied to severe burn wounds in rats in the early stage, and the wound status and change in the wound surface area were examined. The use of 10 mg of minocycline hydrochloride and complete sealing with Tegaderm had a negative effect. Minocycline hydrochloride ointment was not effective but Geben cream was fairly effective. However, chitosan (83% degree of deacetylation) with a cut of Tegaderm film containing 2 mg of minocycline hydrochloride and chitosan (83% degree of deacetylation) films showed a positive effect. Chitosan and hyaluronic acid were used to fabricate a novel wound dressing material [144]. Chitosan/hyaluronic acid composite films with high transparency could be fabricated on glass or poly(methyl methacrylate) substrates. *In vivo* animal tests revealed that, compared with the vaseline gage, the chitosan/hyaluronic acid film more effectively accelerated wound healing and reduced the occurrence of re-injury when peeling off the dressing. Membranes made of chitosans in combination with alginates as polyelectrolyte complexes have also been prepared [145]. They display greater stability to pH changes and are more effective as controlled release membranes than either the chitosan or alginate separately. The membranes based on chitosan/alginate could be used on highly exuding wounds to prevent bacterial infections. Moreover, films formed by a complex between  $\beta$ -glucan and chitosan were also prepared.  $\beta$ -glucan and chitosan complex film was expected to promote the therapeutic efficacy of the dressing by increasing the wound healing response [146].  $\beta$ -glucan-chitosan complex films demonstrated therapeutic effects comparable or superior to those of Beschitin<sup>®</sup> W, a commercial wound dressing made from chitosan. Additionally, the  $\beta$ -glucan-chitosan complex film did not dissolve during the application period, did not adhere to wounds, and was easy to remove. These results indicate that  $\beta$ -glucan-chitosan complex films are a promising wound-dressing material [144].

Silver (Ag) has been used as an antimicrobial agent for a long time in the form of metallic silver and silver sulfadiazine ointments. Recently Ag nanoparticles have been considered a potent antimicrobial agent and have been used in diverse medical applications ranging from silver-based dressings to silver-coated medical devices [147]. In recent years, to improve antimicrobial activity, researchers have focused on Ag-loaded chitosan nanoparticles [148,149]. Wound dressings composed of nano Ag and chitosan were fabricated using chitosan films [150]. In the animal experiments, the healing rate of the Ag-chitosan dressing group was higher than the rates of the control groups at 99% compared with 82%, respectively, for the Ag sulfadiazine group on day 13. The healing time was  $13.51 \pm 4.56$  days for the

Ag-chitosan group and  $17.45 \pm 6.23$  days for the Ag sulfadiazine group. Observations made on the histological sections on day 9 indicated that in the nano Ag dressing group a continuous epithelial lamina was formed together with some sebaceous glands. The Ag sulfadiazine group showed no epithelial laminae, while the chitosan film group exhibited patchy epithelial laminae with a few sebaceous glands. At 13 days, the blood silver content was five times that of normal. On the 45th day post-operatively, the Ag content of the liver, kidney, and brain had increased in both nano-silver and Ag sulfadiazine groups but more so in the latter, where the liver silver content was 100 times greater than that of normal. Zinc oxide (ZnO) has attracted wide interest because of its good photocatalytic activity, high stability, antibacterial property, and non-toxicity [151–153]. Novel chitosan/Ag/ZnO blend films were prepared via a new method of sol-cast transformation [154]. The results revealed that ZnO and Ag nanoparticles with spherical and granular morphology had uniform distribution within the chitosan polymer. The product had excellent antimicrobial activities against *Bacillus subtilis*, *E. coli*, *S. aureus*, *Penicillium*, *Aspergillus*, *Rhizopus*, and yeast. In another study, ZnO nanoparticles were prepared by the Pechini method from polyester by reacting citric acid with ethylene glycol in which the metal ions are dissolved and incorporated into blend films of chitosan and PVA with different concentrations of polyoxyethylene sorbitan monooleate, Tween 80 [155]. The films containing ZnO nanoparticles showed antibacterial activity towards *S. aureus*. More recently, the beneficial effects of Chitosan/nAg, chitin or Chitosan/nZnO, Chitosan/Nano fibrin and micro-Porous Chitosan Hydrogel/Nano Fibrin Composites were also reported [156–159].

## 5. Tissue Adhesives Based on Chitin and Chitosan

Tissue adhesives are gaining popularity in diverse clinical applications including wound closure, healing, drug delivery, implantation of medical devices, tissue engineering, and bone and dental applications [160–162]. Tissue adhesives and sealants are particularly important in situations where other techniques such as suturing are impractical or ineffective [160,162]. The ideal adhesive should have strong and rapid adhesion, low immunogenicity, biocompatibility, and biodegradability. Thus far, many adhesives have been developed including naturally derived tissue (fibrin glue and gelatin-resorcin-formaldehyde-glutaraldehyde) [163–166], synthetic tissue (cyanoacrylates and polyethylene glycol (PEG)-based hydrogel sealants) [160,162], urethane-based [160], and nature-inspired adhesives (mussel adhesive proteins and gecko-inspired adhesives) [167]. However, current adhesives have both beneficial and adverse effects. For example, adhesives with thrombin from a bovine source can trigger allergic reactions in some patients. There is also a risk of transmission of zoonotic disease to humans when bovine-sourced thrombin is used [168]. Although cyanoacrylate has fast polymerization and strong adhesion, it may lack the required flexibility, especially for soft tissue adhesion [169]. Moreover, Smith *et al.* reported that the ethyl-2-cyanoacrylate induced granulomatous inflammation, embolization, hemorrhage, and necrosis of the vascular walls in cats [170].

Previously, many researchers developed tissue adhesives and evaluated their efficiencies. Ono *et al.* prepared a photocrosslinkable chitosan to which both azide and lactose moieties were introduced (Az-CH-LA) as a biological adhesive for soft tissues and its effectiveness was compared with that of fibrin glue [171]. Introduction of the lactose moieties resulted in a much more water-soluble chitosan at neutral pH. Application of ultraviolet light (UV) irradiation to photocrosslinkable Az-CHLA produced



an insoluble hydrogel within 60 s. This hydrogel firmly adhered two pieces of sliced ham with each other, depending upon the Az-CH-LA concentration. The binding strength of the chitosan hydrogel prepared from 30–50 mg/mL of Az-CH-LA was similar to that of fibrin glue. Compared to the fibrin glue, the chitosan hydrogel more effectively sealed air leakage from pinholes on isolated small intestine and aorta and from incisions on isolated trachea. Neither Az-CH-LA nor its hydrogel showed any cytotoxicity in cell culture tests of human skin fibroblasts, coronary endothelial cells, and smooth muscle cells. Furthermore, all mice studied survived for at least one month after implantation of 200  $\mu$ L of photocrosslinked chitosan gel and intraperitoneal administration of up to 1 mL of 30 mg/mL of Az-CHLA solution. Renbutsu *et al.* synthesized UV-curable chitosans (UVCC-7-10) using less-toxic agents [172]. The UVCC-7 was completely cured by UV spot irradiation for 4 s. The UVCC-7 was implanted into murine subcutaneous tissues and was observed by histological examination at seven days after implantation. In the histological findings, the implant was surrounded by thin fibrous granulating tissue with no inflammatory cellular infiltration. Fibroblasts infiltrated between the cured implant. The novel synthesized UVCC-7 showed good biocompatibility.

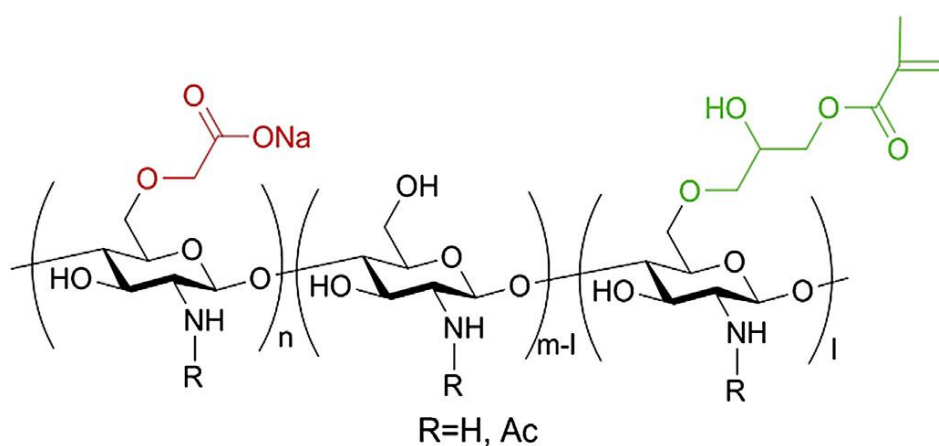
Nie *et al.* developed a novel polysaccharides/polypeptide hydrogel composed of naturally-derived materials for application as an adhesive sealant and hemostatic material. This hydrogel was developed via Michael addition crosslinking [173]. Thiol-modified chitosan (CSS) was crosslinked quickly *in situ* by an efficient polypeptide crosslinker (EPLM), which was prepared by introducing maleimide groups onto  $\epsilon$ -polylysine. Gelation can happen swiftly within 15–215 s depending on the CSS concentration, the degree of substitution (DS) of maleimide groups, and the molar ratio of maleimide groups to thiol groups. Results indicated that the storage modulus of the hydrogel increased dramatically with the increase of CSS concentration and DS of maleimide. The obtained adhesive hydrogel had an adhesion strength four times higher than that of the commercial fibrin glue. Notably, it is non-toxic to L929 cells and exhibits excellent prompt hemostatic properties. The polysaccharides/polypeptide structure designed here improves both the biocompatibility and the adhesive properties. Lih *et al.* reported that chitosan-poly(ethylene glycol)-tyramine (CPT) hydrogels were rapidly formed *in situ* using horseradish peroxidase and hydrogen peroxide in order to explore their performance as efficient tissue adhesives [174]. A poly(ethylene glycol) modified with tyramine was grafted onto a chitosan backbone to enhance the solubility of the chitosan and to crosslink it into a three-dimensional networks. The elastic modulus of the hydrogels could be controlled by changing the crosslinking conditions, and the mechanical strength influenced the tissue adhesiveness of the hydrogels. The hydrogels showed adhesiveness ranging from 3- to 20-fold that of fibrin glue (Greenplast<sup>®</sup>). The hemostatic ability of the hydrogels was evaluated on the basis that bleeding from liver defects was significantly arrested by the combined effect of the adhesiveness of the hydrogels and the hemostatic property of the chitosan materials. The enzymatic crosslinking method enabled the water-soluble chitosan to rapidly form hydrogels within 5 s of an incision into the skin of rats. Histological results demonstrated that the CPT hydrogels showed superior healing effects in the skin incision when compared to suture, fibrin glue, and cyanoacrylate. By two weeks post-implantation, the wound was completely recovered, with a newly formed dermis, due to the presence of the CPT hydrogels in the incision.

Barton *et al.* reported photochemical-tissue-bonding (PTB) using rose Bengal (RB) integrated into a chitosan bioadhesive as an alternative nerve repair device that removes the need for sutures [175]. Rats were arranged into three groups: RB-chitosan adhesives-repair, end-to-end epineural suture-repair

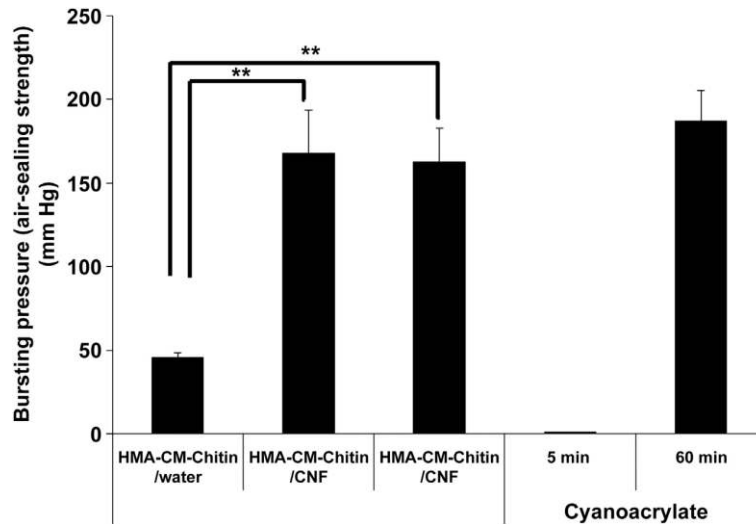
(surgical standard), and sham laser-irradiated control. Groups were compared through histological assessment, electrophysiological recordings, and grip motor strength. RB-chitosan adhesive-repaired nerves displayed comparable results when compared to the standard suture-repair based on histological and electrophysiological findings. Functionally, RB-chitosan adhesive was associated with a quicker and more pronounced recovery of grip force when compared to the suture-repair. Moreover, they reported that chitosan adhesive films have also been shown to strongly adhere to sheep intestine without any chemical modification to chitosan [176]. In this study, we continued to investigate chitosan adhesive films and explored the impact on tissue repair strength and tensile strength characteristics of four types of adhesive films based on chitosan with different molecular weights and degrees of deacetylation. The results showed that adhesives based on chitosan with medium molecular weight achieved the highest bonding strength, tensile strength, and elastic modulus when compared to the other adhesives.

More recently, we reported that novel biological adhesives made from chitin derivatives were prepared and evaluated for their adhesive properties and biocompatibility [177]. Chitin derivatives with acrylic groups, such as 2-hydroxy-3-methacryloyloxypropylated carboxymethyl chitin (HMA-CM-chitin; Figure 8), were synthesized and cured by the addition of an aqueous hydrogen peroxide solution as a radical initiator.

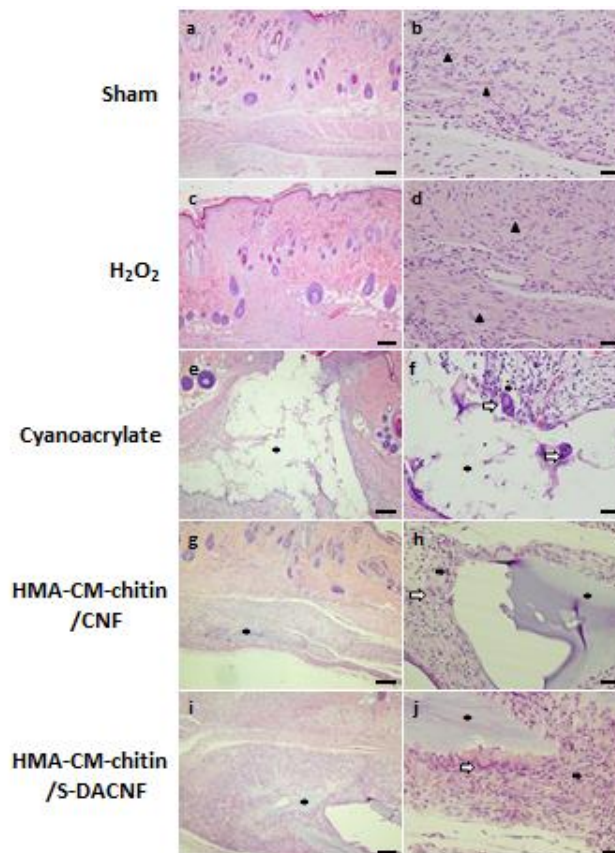
The adhesive strength of HMA-CM-chitin increased when it was blended with chitin nanofibers (CNFs) or surface-deacetylated chitin nanofibers (S-DACNFs). HMA-CM-chitin/CNFs or HMA-CM-chitin/S-DACNFs have almost equal adhesive strength compared to that of a commercial cyanoacrylate adhesive (Figure 9). Moreover, quick adhesion and induction of inflammatory cell migration were observed in HMA-CM-chitin/CNF and HMA-CM-chitin/S-DACNF. At 14 days after implantation, many multinucleated giant cells were observed in the cyanoacrylate group. On the other hand, less multinucleated giant cells were observed in the HMA-CM-chitin/CNF and HMA-CM-chitin/S-DACNF groups (Figure 10). These findings indicate that the composites prepared in this study are promising new biological adhesives.



**Figure 8.** Chemical structure of 2-hydroxy-3-methacryloyloxypropylated carboxymethyl chitin (HMA-CM-chitin). Copyright 2015 Elsevier [177].



**Figure 9.** Bursting pressure test of HMA-CM-chitin. Tests were performed using rat skin. Data represent the mean  $\pm$  S.D. in each group. The statistical analysis was performed using Scheffe’s F test. Copyright 2015 Elsevier [177].



**Figure 10.** Histopathological changes. All images are from one of six rats in each group on day 14. The arrows indicate neutrophils. The arrowheads indicate fibroblasts. The asterisks indicate the adhesions. The clear arrows indicate multinucleated giant cells. Results on the low power fields (a,c,e,g,i) and high power fields (b,d,f,h,j) are shown. Scale bar: 200 mm (a,c,e,g,i) and 40 mm (b,d,f,h,j). Copyright 2015 Elsevier [177].

## 6. Conclusions

Many reports have indicated the accelerating effects of chitin, chitosan, and its derivatives on wound healing. More recently, chemically modified or nanofibrous chitin and chitosan have been developed, and their effects on wound healing have also been evaluated. In this review, the current studies on the wound healing effects of chitin, chitosan, and its derivatives are summarized. Moreover, the development of adhesive-based chitin and chitosan are also described. There is a great deal of evidence indicating that chitin, chitosan, and its derivatives are beneficial for the wound healing process. More recently, much evidence indicate the beneficial effects of nano-chitin and nano-chitosan for wound healing process. The development of the materials based on the nano-chitin and nano-chitosan will be processing in near future.

## Author Contributions

K.A. planned and wrote the manuscript. R.I., T.O., S.I., M.M., H.S., S.M., and Y.O. commented on and modified the manuscript.

## Conflicts of Interest

The authors declare no conflict of interest.

## References

1. Muzzarelli, R.A.A. Chitin nanostructures in living organisms. In *Chitin: Formation and Diagenesis*; Gupta, N., Ed.; Springer: Dordrecht, The Netherlands, 2011; Volume 34, pp. 1–34.
2. Kurita, K. Controlled functionalization of the polysaccharide chitin. *Prog. Polym. Sci.* **2001**, *269*, 1921–1971.
3. Rinaudo, M. Chitin and chitosan: Properties and applications. *Prog. Polym. Sci.* **2006**, *31*, 603–632.
4. Pillai, K.S.; Paul, W.; Sharma, C.P. Chitin and chitosan polymers: Chemistry, solubility and fiber formation. *Prog. Polym. Sci.* **2009**, *34*, 641–678.
5. Jayakumar, R.; Prabakaran, M.; Nair, S.V.; Tamura, H. Novel chitin and chitosan nanofibers in biomedical applications. *Biotechnol. Adv.* **2010**, *28*, 142–150.
6. Jayakumar, R.; Prabakaran, M.; Sudheesh Kumar, P.T.; Nair, S.V.; Tamura, H. Biomaterials based on chitin and chitosan in wound dressing applications. *Biotechnol. Adv.* **2011**, *29*, 322–337.
7. Azuma, K.; Ifuku, S.; Osaki, T.; Okamoto, Y.; Minami, S. Preparation and Biomedical Applications of Chitin and Chitosan Nanofibers. *J. Biomed. Nanotechnol.* **2014**, *10*, 2891–2920.
8. Nagahama, H.; Kashiki, T.; Nwe, N.; Jayakumar, R.; Furuike, T.; Tamura, H. Preparation of biodegradable chitin/gelatin membranes with GlcNAc for tissue engineering applications. *Carbohydr. Polym.* **2008**, *73*, 456–463.
9. Nagahama, H.; Nwe, N.; Jayakumar, R.; Koiwa, S.; Furuike, T.; Tamura, H. Novel biodegradable chitin membranes for tissue engineering applications. *Carbohydr. Polym.* **2008**, *73*, 295–302.
10. Tamura, H.; Furuike, T.; Nair, S.V.; Jayakumar, R. Biomedical applications of chitin hydrogel membranes and scaffolds. *Carbohydr. Polym.* **2011**, *84*, 820–824.

11. Yusof, N.L.B.M.; Wee, A.; Lim, L.Y.; Khor, E. Flexible chitin films as potential wound-dressing materials: Wound model studies. *J. Biomed. Mater. Res. A* **2003**, *66*, 224–232.
12. Marreco, P.R.; Moreira, P.L.; Genari, S.C.; Moraes, A.M. Effects of different sterilization methods on the morphology, mechanical properties and cytotoxicity of chitosan membranes used as wound dressings. *J. Biomed. Mater. Res. B Appl. Biomater. B* **2004**, *71*, 268–277.
13. Jayakumar, R.; Nwe, N.; Tokura, S.; Tamura, H. Sulfated chitin and chitosan as novel biomaterials. *Int. J. Biol. Macromol.* **2007**, *40*, 175–181.
14. Jayakumar, R.; Nwe, N.; Nagahama, H.; Tamura, H. Synthesis, characterization and biospecific degradation behavior of sulfated chitin. *Macromol. Symp.* **2008**, *264*, 163–167.
15. Jayakumar, R.; Divya Rani, V.V.; Shalumon, K.T.; Sudheesh Kumar, P.T.; Nair, S.V.; Furuike, T.; Tamura, H. Bioactive and osteoblast cell attachment studies of novel  $\alpha$ - and  $\beta$ -chitin membranes for tissue engineering applications. *Int. J. Biol. Macromol.* **2009**, *45*, 260–264.
16. Madhumathi, K.; Binulal, N.S.; Nagahama, H.; Tamura, H.; Shalumon, K.T.; Selvamurugan, N.; Nair, S.V.; Jayakumar, R. Preparation and characterization of novel  $\alpha$ -chitin-hydroxyapatite composite membranes for tissue engineering applications. *Int. J. Biol. Macromol.* **2009**, *44*, 1–5.
17. Shalumon, K.T.; Binulal, N.S.; Selvamurugan, N.; Nair, S.V.; Menon, D.; Furuike, T.; Tamura, H.; Jayakumar, R. Electrospinning of carboxymethyl chitin/poly(vinyl alcohol) nanofibrous scaffolds for tissue engineering applications. *Carbohydr. Polym.* **2009**, *77*, 863–869.
18. Shalumon, K.T.; Anulekha, K.H.; Girish, C.M.; Nair, S.V.; Jayakumar, R. Single step electrospinning of chitosan/poly(caprolactone) nanofibers using formic acid/acetone solvent mixture. *Carbohydr. Polym.* **2010**, *80*, 413–419.
19. Gopalan, N.K.; Dufresne, A. Crab shell chitin whisker reinforced natural rubber nanocomposites. 1. Processing and swelling behavior. *Biomacromolecules* **2003**, *4*, 657–665.
20. Fan, Y.; Saito, T.; Isogai, A. Preparation of chitin nanofibers from squid pen beta-chitin by simple mechanical treatment under acid conditions. *Biomacromolecules* **2008**, *9*, 1919–1923.
21. Ifuku, S.; Nogi, M.; Abe, K.; Yoshioka, M.; Morimoto, M.; Saimoto, H.; Yano, H. Preparation of chitin nanofibers with a uniform width as alpha-chitin from crab shells. *Biomacromolecules* **2009**, *10*, 1584–1588.
22. Yusof, N.L.B.M.; Lim, L.Y.; Khor, E. Preparation and characterization of chitin beads as a wound dressing precursor flexible chitin films as potential wound-dressing materials: Wound model studies. *J. Biomed. Mater. Res.* **2001**, *54*, 59–68.
23. Jayakumar, R.; Reis, R.L.; Mano, J.F. Phosphorous containing chitosan beads for controlled oral drug delivery. *J. Bioact. Compat. Polym.* **2006**, *21*, 327–340.
24. Prabakaran, M. Chitosan derivatives as promising materials for controlled drug delivery. *J. Biomater. Appl.* **2008**, *23*, 5–36.
25. Anitha, A.; Divya Rani, V.V.; Krishna, R.; Sreeja, V.; Selvamurugan, N.; SNair, S.V.; Tamura, H.; Jayakumar, H. Synthesis, characterization, cytotoxicity and antibacterial studies of chitosan, *O*-carboxymethyl and *N,O*-carboxymethyl chitosan nanoparticles. *Carbohydr. Polym.* **2009**, *78*, 672–677.
26. Anitha, A.; Deepa, N.; Chennazhi, K.P.; Nair, S.V.; Tamura, H.; Jayakumar, R. Development of mucoadhesive thiolated chitosan nanoparticles for biomedical applications. *Carbohydr. Polym.* **2010**, *83*, 66–73.

27. Peter, M.; Sudheesh Kumar, P.T.; Binulal, N.S.; Nair, S.V.; Tamura, H.; Jayakumar, R. Development of novel chitin/nano bioactive glass ceramic nanocomposite scaffolds for tissue engineering applications. *Carbohydr. Polym.* **2009**, *78*, 926–931.
28. Peter, M.; Binulol, N.S.; Soumya, S.; Nair, S.V.; Tamura, H.; Jayakumar, R. Nanocomposite scaffolds of bioactive glass ceramic nanoparticles disseminated chitosan matrix for tissue engineering applications. *Carbohydr. Polym.* **2010**, *79*, 284–289.
29. Prabakaran, M.; Jayakumar, R. Chitosan-graft- $\beta$ -cyclodextrin scaffolds with controlled drug release capability for tissue engineering applications. *Int. J. Biol. Macromol.* **2009**, *44*, 320–325.
30. Maeda, Y.; Jayakumar, R.; Nagahama, H.; Furuike, T.; Tamura, H. Synthesis, characterization and bioactivity studies of novel  $\beta$ -chitin scaffolds for tissue-engineering applications. *Int. J. Biol. Macromol.* **2008**, *42*, 463–467.
31. Muramatsu, K.; Masuda, S.; Yoshihara, Y.; Fujisawa, A. *In vitro* degradation behavior of freeze-dried carboxymethyl-chitin sponges processed by vacuum-heating and gamma irradiation. *Polym. Degradat. Stabil.* **2003**, *81*, 327–332.
32. Portero, A.; Teijeiro-Osorio, D.; Alonso, M.J.; Remunan-Lopez, C. Development of chitosan sponges for buccal administration of insulin. *Carbohydr. Polym.* **2007**, *68*, 617–625.
33. Dai, T.; Tanaka, M.; Huang, Y.Y.; Hamblin, M.R. Chitosan preparations for wounds and burns: Antimicrobial and wound-healing effects. *Exp. Rev. Anti Infect. Ther.* **2011**, *9*, 857–879.
34. Boateng, J.S.; Matthews, K.H.; Stevens, H.N.; Eccleston, G.M. Wound healing dressings and drug delivery systems: A review. *J. Pharm. Sci.* **2008**, *97*, 2892–2923.
35. Beanes, S.R.; Dang, C.; Soo, C.; Ting, K. Skin repair and scar formation: The central role of TGF- $\beta$ . *Exp. Rev. Mol. Med.* **2003**, *5*, 1–22.
36. Mori, T.; Okumura, M.; Matsuura, M.; Ueno, K.; Tokura, S.; Okamoto, Y.; Minami, S.; Fujinaga, T. Effects of chitin and its derivatives on the proliferation and cytokine production of fibroblasts *in vitro*. *Biomaterials* **1997**, *18*, 947–951.
37. Okamoto, Y.; Watanabe, M.; Miyatake, K.; Morimoto, M.; Shigemasa, Y.; Minami, S. Effects of chitin/chitosan and their oligomers/monomers on migrations of fibroblasts and vascular endothelium. *Biomaterials* **2002**, *23*, 1975–1979.
38. Usami, Y.; Okamoto, Y.; Minami, S.; Matsushashi, A.; Kumazawa, N.H.; Tanioka, S.; Shigemasa, Y. Chitin and chitosan induce migration of bovine polymorphonuclear cells. *J. Vet. Med. Sci.* **1994**, *56*, 761–762.
39. Usami, Y.; Okamoto, Y.; Minami, S.; Matsushashi, A.; Kumazawa, N.H.; Tanioka, S.; Shigemasa, Y. Migration of canine neutrophils to chitin and chitosan. *J. Vet. Med. Sci.* **1994**, *56*, 1215–1216.
40. Usami, Y.; Minami, S.; Okamoto, Y.; Matsushashi, A.; Shigemasa, Y. Influence of chain length of *N*-acetyl-D-glucosamine and D-glucosamine residues on direct and complement-mediated chemotactic activities for canine polymorphonuclear cells. *Carbohydr. Polym.* **1997**, *32*, 115–122.
41. Usami, Y.; Okamoto, Y.; Takayama, T.; Shigemasa, Y.; Minami, S. Chitin and chitosan stimulate canine polymorphonuclear cells to release leukotrien B4 and prostaglandin E2. *J. Biomed. Mater. Res.* **1998**, *42*, 517–522.
42. Da Silva, C.A.; Hartl, D.; Liu, W.; Lee, C.G.; Elias, J.A. TLR-2 and IL-17A in chitin-induced macrophage activation and acute inflammation. *J. Immunol.* **2008**, *181*, 4279–4286.

43. Okamoto, Y.; Minami, S.; Matsushashi, A.; Sashiwa, H.; Saimoto, H.; Shigemasa, Y.; Tanigawa, T.; Tanaka, Y.; Tokura, S. Polymeric *N*-acetyl-D-glucosamine (chitin) induces histionic activation in dogs. *J. Vet. Med. Sci.* **1993**, *55*, 739–742.
44. Okamoto, Y.; Minami, S.; Matsushashi, A.; Sashiwa, H.; Saimoto, H.; Shigemasa, Y.; Tanigawa, T.; Tanaka, Y.; Tokura, S. Application of polymeric *N*-acetyl-D-glucosamine (chitin) to veterinary practice. *J. Vet. Med. Sci.* **1993**, *55*, 743–747.
45. Minami, S.; Okamoto, Y.; Matsushashi, A.; Sashiwa, H.; Saimoto, H.; Shigemasa, Y.; Tanigawa, T.; Suzuki, T.; Tanioka, S.; Tanaka, Y. Polymeric *N*-acetyl-D-glucosamine (chitin) induces prostaglandin E2 in dogs. *J. Vet. Med. Sci.* **1995**, *57*, 377–378.
46. Minami, S.; Suzuki, H.; Okamoto, Y.; Fujinaga, T.; Shigemasa, Y. Chitin and chitosan activate complement via the alternative pathway. *Carbohydr. Polym.* **1998**, *36*, 151–155.
47. Suzuki, Y.; Okamoto, Y.; Morimoto, M.; Sashiwa, H.; Saimoto, H.; Tanioka, S.; Shigemasa, Y.; Minami, S. Influence of physicochemical properties of chitin and chitosan on complement activation. *Carbohydr. Polym.* **2000**, *42*, 307–310.
48. Kojima, K.; Okamoto, Y.; Kojima, K.; Miyatake, K.; Fujise, H.; Shigemasa, Y.; Minami, S. Effects of chitin and chitosan on collagen synthesis in wound healing. *J. Vet. Med. Sci.* **2004**, *66*, 1595–1598.
49. Wiegand, C.; Winter, D.; Hipler, U.C. Molecular-weight-dependent toxic effects of chitosans on the human keratinocyte cell line HaCaT. *Skin Pharmacol. Physiol.* **2010**, *23*, 164–170.
50. Howling, G.I.; Dettmar, P.W.; Goddard, P.A.; Hampson, F.; Dornish, M.; Wood, E.J. The effect of chitin and chitosan on the proliferation of human skin fibroblasts and keratinocytes *in vitro*. *Biomaterials* **2001**, *22*, 2959–2966.
51. Santos, T.C.; Marques, A.P.; Silva, S.S.; Oliveira, J.M.; Mano, J.F.; Castro, A.G.; Reis, R.L. *In vitro* evaluation of the behaviour of human polymorphonuclear neutrophils in direct contact with chitosan-based membranes. *J. Biotechnol.* **2007**, *132*, 218–226.
52. Ueno, H.; Murakami, M.; Okumura, M.; Kadosawa, T.; Uede, T.; Fujinaga, T. Chitosan accelerates the production of osteopontin from polymorphonuclear leukocytes. *Biomaterials* **2001**, *22*, 1667–1673.
53. Rabea, E.I.; Badawy, M.E.; Stevens, C.V.; Smagghe, G.; Steurbaut, W. Chitosan as antimicrobial agent: Applications and mode of action. *Biomacromolecules* **2003**, *4*, 1457–1465.
54. Li, P.; Poon, Y.F.; Li, W.; Zhu, H.Y.; Yeap, S.H.; Cao, Y.; Qi, X.; Zhou, C.; Lamrani, M.; Beuerman, R.W.; *et al.* A polycationic antimicrobial and biocompatible hydrogel with microbe membrane suctioning ability. *Nature Mater.* **2011**, *10*, 149–156.
55. Kong, M.; Chen, X.G.; Xing, K.; Park, H. Antimicrobial properties of chitosan and mode of action: a state of the art review. *Int. J. Food Microbiol.* **2010**, *144*, 51–63.
56. Andres, Y.; Giraud, L.; Gerente, C.; Le Cloirec, P. Antibacterial effects of chitosan powder: Mechanisms of action. *Environ. Technol.* **2007**, *28*, 1357–1363.
57. Raafat, D.; von Bargaen, K.; Haas, A.; Sahl, H.G. Insights into the mode of action of chitosan as an antibacterial compound. *Appl. Environ. Microbiol.* **2008**, *74*, 3764–3773.
58. Tang, H.; Zhang, P.; Kieft, T.L.; Ryan, S.J.; Baker, S.M.; Wiesmann, W.P.; Rogelj, S. Antibacterial action of a novel functionalized chitosan-arginine against Gram-negative bacteria. *Acta Biomater.* **2010**, *6*, 2562–2571.

59. No, H.K.; Park, N.Y.; Lee, S.H.; Meyers, S.P. Antibacterial activity of chitosans and chitosan oligomers with different molecular weights. *Int. J. Food Microbiol.* **2002**, *74*, 65–72.
60. Muzzarelli, R.; Tarsi, R.; Filippini, O.; Giovanetti, E.; Biagini, G.; Varaldo, P.E. Antimicrobial properties of *N*-carboxybutyl chitosan. *Antimicrob. Agents Chemother.* **1990**, *10*, 2019–2023.
61. Seyfarth, F.; Schliemann, S.; Elsner, P.; Hipler, U.C. Antifungal effect of high- and low-molecular-weight chitosan hydrochloride, carboxymethyl chitosan, chitosan oligosaccharide and *N*-acetyl-D-glucosamine against *Candida albicans*, *Candida krusei* and *Candida glabrata*. *Int. J. Pharmaceut.* **2008**, *353*, 139–148.
62. Ueno, H.; Yamada, H.; Tanaka, I.; Kaba, N.; Matsuura, M.; Okumura, M.; Kadosawa, T.; Fujinaga, T. Accelerating effects of chitosan for healing at early phase of experimental open wound in dogs. *Biomaterials* **1999**, *20*, 1407–1414.
63. Okamoto, Y.; Shibazaki, K.; Minami, S.; Matsushashi, A.; Tanioka, S.; Shigemasa, Y. Evaluation of chitin and chitosan on open wound healing in dogs. *J. Vet. Med. Sci.* **1995**, *57*, 851–854.
64. Mi, F.L.; Shyu, S.S.; Wu, Y.B.; Lee, S.T.; Shyong, J.Y.; Huang, R.N. Fabrication and characterization of a sponge-like asymmetric chitosan membrane as a wound dressing. *Biomaterials* **2001**, *22*, 165–173.
65. Burkatovskaya, M.; Castano, A.P.; Demidova-Rice, T.N.; Tegos, G.P.; Hamblin, M.R. Effect of chitosan acetate bandage on wound healing in infected and noninfected wounds in mice. *Wound Repair Regen.* **2008**, *16*, 425–431.
66. Jin, Y.; Ling, P.X.; He, Y.L.; Zhang, T.M. Effects of chitosan and heparin on early extension of burns. *Burns.* **2007**, *33*, 1027–1031.
67. Alsarra, I.A. Chitosan topical gel formulation in the management of burn wounds. *Int. J. Biol. Macromol.* **2009**, *45*, 16–21.
68. Ribeiro, M.P.; Espiga, A.; Silva, D.; Baptista, P.; Henriques, J.; Ferreira, C.; Silva, J.C.; Borges, J.P.; Pires, E.; Chaves, P.; Correia, I.J. Development of a new chitosan hydrogel for wound dressing. *Wound Repair Regen.* **2009**, *17*, 817–824.
69. Boucard, N.; Viton, C.; Agay, D.; Mari, E.; Roger, T.; Chancerelle, Y.; Domard, A. The use of physical hydrogels of chitosan for skin regeneration following third-degree burns. *Biomaterials* **2007**, *28*, 3478–3488.
70. Diegelmann, R.F.; Dunn, J.D.; Lindblad, W.J.; Cohen, I.K. Analysis of the effects of chitosan on inflammation, angiogenesis, fibroplasia, and collagen deposition in polyvinyl alcohol sponge implants in rat wounds. *Wound Repair Regen.* **1996**, *4*, 48–52.
71. Okamoto, Y.; Tomita, T.; Minami, S.; Matsushashi, A.; Kumazawa, N.H.; Tanioka, S.; Shigemasa, Y. Effects of chitosan on experimental abscess with *Staphylococcus aureus* in dogs. *J. Vet. Med. Sci.* **1995**, *57*, 765–767.
72. Burkatovskaya, M.; Tegos, G.P.; Swietlik, E.; Demidova, T.N.; Castano, A.P.; Hamblin, M.R. Use of chitosan bandage to prevent fatal infections developing from highly contaminated wounds in mice. *Biomaterials* **2006**, *27*, 4157–4164.
73. Ong, S.Y.; Wu, J.; Moochhala, S.M.; Tan, M.H.; Lu, J. Development of a chitosan-based wound dressing with improved hemostatic and antimicrobial properties. *Biomaterials* **2008**, *29*, 4323–4332.



74. França, R.; Mbeh, D.A.; Samani, T.D.; Le Tien, C.; Mateescu, M.A.; Yahia, L.; Sacher, E. The effect of ethylene oxide sterilization on the surface chemistry and *in vitro* cytotoxicity of several kinds of chitosan. *J. Biomed. Mater. Res. B Appl. Biomater.* **2013**, *101*, 1444–1455.
75. Mayol, L.; De Stefano, D.; Campani, V.; De Falco, F.; Ferrari, E.; Cencetti, C.; Matricardi, P.; Maiuri, L.; Carnuccio, R.; Gallo, A.; *et al.* Design and characterization of a chitosan physical gel promoting wound healing in mice. *J. Mater. Sci. Mater. Med.* **2014**, *25*, 1483–1493.
76. Biagini, G.; Bertani, A.; Muzzarelli, R.; Damadei, A.; Di Benedetto, G.; Belligolli, A.; Riccotti, G.; Zucchini, C.; Rizzoli, C. Wound management with *N*-carboxybutyl chitosan. *Biomaterials* **1991**, *12*, 281–286.
77. Stone, C.A.; Wright, H.; Clarke, T.; Powell, R.; Devaraj, V.S. Healing at skin graft donor sites dressed with chitosan. *Br. J. Plast. Surg.* **2000**, *53*, 601–606.
78. Valentine, R.; Athanasiadis, T.; Moratti, S.; Hanton, L.; Robinson, S.; Wormald, P.J. The efficacy of a novel chitosan gel on hemostasis and wound healing after endoscopic sinus surgery. *Am. J. Rhinol. Allergy* **2010**, *24*, 70–75.
79. Azad, A.K.; Sermsintham, N.; Chandkrachang, S.; Stevens, W.F. Chitosan membrane as a wound-healing dressing: Characterization and clinical application. *J. Biomed. Mater. Res. B Appl. Biomater.* **2004**, *69*, 216–222.
80. Akncbay, H.; Senel, S.; Ay, Z.Y. Application of chitosan gel in the treatment of chronic periodontitis. *J. Biomed. Mater. Res. B Appl. Biomater.* **2007**, *80*, 290–296.
81. Boynueğri, D.; Ozcan, G.; Senel, S.; Uç, D.; Uraz, A.; Oğuş, E.; Cakilci, B.; Karaduman, B. Clinical and radiographic evaluations of chitosan gel in periodontal intraosseous defects: A pilot study. *J. Biomed. Mater. Res. B Appl. Biomater.* **2009**, *90*, 461–466.
82. Xia, Y.; Yang, P.; Sun, Y.; Wu, Y.; Mayers, B.; Gates, B.; Yin, Y.; Kim, F.; Yan, H. One-dimensional nanostructures: Synthesis, characterization, and applications. *Adv. Mater.* **2003**, *15*, 353–389.
83. Li, D.; Xia, Y. Electrospinning of nanofibers: Reinventing the wheel? *Adv. Mater.* **2004**, *16*, 1151–1170.
84. Huang, Z.M.; Zhang, Y.Z.; Kotaki, M.; Ramakrishna, S. A review on polymer nanofibers by electrospinning and their applications in nanocomposites. *Compos. Sci. Technol.* **2003**, *63*, 2223–2253.
85. Ramakrishna, S.; Fujihara, K.; Teo, W.E.; Yong, T.; Ma, Z.; Ramaseshan, R. Electrospun nanofibers: Solving global issues. *Mater. Today* **2006**, *9*, 40–50.
86. Muzzarelli, R.A.; Mehtedi, M.E.; Mattioli-Belmonte, M. Emerging biomedical applications of nano-chitins and nano-chitosans obtained via advanced eco-friendly technologies from marine resources. *Mar. Drugs* **2014**, *12*, 5468–5502.
87. Araki, J. Electrostatic or steric? Preparations and characterizations of well-dispersed systems containing rod-like nanowhiskers of crystalline polysaccharides. *Soft Matter* **2013**, *9*, 4125–4141.
88. Ifuku, S.; Nogi, M.; Abe, K.; Yoshioka, M.; Morimoto, M.; Saimoto, H.; Yano, H. Simple preparation of chitin nanofibers with a width of 10–20 nm from prawn shell under neutral conditions. *Carbohydr. Polym.* **2011**, *84*, 762–764.
89. Bruin, P.; Jonkman, M.F.; Meijer, H.J.; Pennings, A.J. A new porous polyetherurethane wound covering. *J. Biomed. Mater. Res.* **1990**, *24*, 217–226.

90. Matsuda, K.; Suzuki, S.; Isshiki, N.; Yoshioka, K.; Wada, R.; Okada, T.; Ikeda, Y. Influence of glycosaminoglycans on the collagen sponges component of a bilayer artificial skin. *Biomaterials* **1990**, *11*, 351–355.
91. Suzuki, S.; Matsuda, K.; Isshiki, N.; Tamada, Y.; Ikada, Y. Experimental study of newly developed bilayer artificial skin. *Biomaterials* **1990**, *11*, 356–360.
92. Naseri, N.; Algan, C.; Jacobs, V.; John, M.; Oksman, K.; Mathew, A.P. Electrospun chitosan-based nanocomposite mats reinforced with chitin nanocrystals for wound dressing. *Carbohydr. Polym.* **2014**, *109*, 7–15.
93. Naseri, N.; Mathew, A.P.; Girandon, L.; Fröhlich, M.; Oksman, K. Porous electrospun nanocomposite mats based on chitosan–cellulose nanocrystals for wound dressing: Effect of surface characteristics of nanocrystals. *Cellulose* **2015**, *22*, 521–534.
94. Muzzarelli, R.A.A. Biochemical significance of exogenous chitins and chitosans in animals and patients. *Carbohydr. Polym.* **1993**, *20*, 7–16.
95. Kelechi, T.J.; Mueller, M.; Hankin, C.S.; Bronstone, A.; Samies, J.; Bonham, P.A. A randomized, investigator-blinded, controlled pilot study to evaluate the safety and efficacy of a poly-N-acetyl glucosamine-derived membrane material in patients with venous leg ulcers. *J. Am. Acad. Dermatol.* **2012**, *66*, E209–E215.
96. Fischer, T.H.; Hays, W.E.; Valeri, C.R. Poly-N-acetyl glucosamine fibers accelerate hemostasis in patients treated with antiplatelet drugs. *J. Trauma.* **2011**, *71*, S176–S182.
97. Lindner, H.B.; Zhang, A.G.; Eldridge, J.; Demcheva, M.; Tsihilis, P.; Seth, A.; Vournakis, J.; Muise-Helmericks, R.C. Anti-bacterial effects of poly-N-acetyl-glucosamine nanofibers in cutaneous wound healing: Requirement for Akt1. *PLoS One* **2011**, *6*, e18996.
98. Mattioli-Belmonte, M.; Zizzi, A.; Lucarini, G.; Giantomassi, F.; Biagini, G.; Tucci, F. Orlando, G.; Provinciali, M.; Carezzi, F.; Morganti, P. Chitin nanofibrils linked to chitosan glycolate as spray, gel and gauze preparations for wound repair. *J. Bioact. Comp. Polym.* **2007**, *22*, 525–553.
99. Chilarski, A.; Szosland, L.; Krucińska, I.; Kiekens, P.; Błasińska, A.; Schoukens, G.; Cisko, R.; Szumilewicz, J. Novel dressing materials accelerating wound healing made from dibutylchitin. *Fibers Tex. East. Eur.* **2007**, *15*, 77–81.
100. Blasinska, A.; Drobnik, J. Effects of nonwoven mats of Di-O-butyrylchitin and related polymers on the process of wound healing. *Biomacromolecules* **2008**, *9*, 776–782.
101. Jang, S.I.; Mok, J.Y.; Jeon, I.H.; Park, K.H.; Nguyen, T.T.; Park, J.S.; Hwang, H.M.; Song, M.S.; Lee, D.; Chai, K.Y. Effect of electrospun non-woven mats of dibutyl chitin/poly(lactic acid) blends on wound healing in hairless mice. *Molecules* **2012**, *17*, 2992–3007.
102. Ito, I.; Osaki, T.; Ifuku, S.; Saimoto, H.; Takamori, Y.; Kurozumi, S.; Imagawa, T.; Azuma, K.; Tsuka, T.; Okamoto, Y.; *et al.* Evaluation of the effects of chitin nanofibrils on skin function using skin models. *Carbohydr Polym.* **2014**, *101*, 464–470.
103. Tashiro, T. Antibacterial and bacterium adsorbing macromolecules. *Macromol. Mater. Eng.* **2001**, *286*, 63–87.
104. Ignatova, M.; Manolova, N.; Rashkov, I. Novel antibacterial fibers of quaternized chitosan and poly(vinyl pyrrolidone) prepared by electrospinning. *Eur. Polym. J.* **2007**, *43*, 1112–1122.

105. Ignatova, M.; Starbova, K.; Markova, N.; Manolova, N.; Rashkov, I. Electrospun nano-fibre mats with antibacterial properties from quaternized chitosan and poly(vinyl alcohol). *Carbohydr. Res.* **2006**, *341*, 2098–2107.
106. Zhou, Y.; Yang, D.; Chen, X.; Xu, Q.; Lu, F.; Nie, J. Electrospun water-soluble carboxyethyl chitosan/poly(vinyl alcohol) nanofibrous membrane as potential wound dressing for skin regeneration. *Biomacromolecules* **2008**, *9*, 349–354.
107. Charernsriwilaiwat, N.; Opanasopit, P.; Rojanarata, T.; Ngawhirunpat, T. Lysozyme-loaded, electrospun chitosan-based nanofiber mats for wound healing. *Int. J. Pharm.* **2012**, *427*, 379–384.
108. Zhou, Y.; Yang, H.; Liu, X.; Mao, J.; Gu, S.; Xu, W. Electrospinning of carboxyethyl chitosan/poly(vinyl alcohol)/silk fibroin nanoparticles for wound dressings. *Int. J. Biol. Macromol.* **2013**, *53*, 88–92.
109. Huang, L.Y.; Liu, T.Y.; Liu, K.H.; Liu, Y.Y.; Chao, C.S.; Tung, W.L.; Yang, M.C. Electrospinning of amphiphathic chitosan nanofibers for surgical implants application. *J. Nanosci. Nanotechnol.* **2012**, *12*, 5066–5070.
110. Li, Y.; Chen, F.; Nie, J.; Yang, D. Electrospun poly(lactic acid)/chitosan core-shell structure nanofibers from homogeneous solution. *Carbohydr. Polym.* **2012**, *90*, 1445–1451.
111. Chen, Z.; Mo, X.; He, C.; Wang, H. Intermolecular interactions in electrospun collagen-chitosan complex nanofibers. *Carbohydr. Polym.* **2008**, *72*, 410–418.
112. Wang, X.; You, C.; Hu, X.; Zheng, Y.; Li, Q.; Feng, Z.; Sun, H.; Gao, C.; Han, C. The roles of knitted mesh-reinforced collagen-chitosan hybrid scaffold in the one-step repair of full-thickness skin defects in rats. *Acta. Biomater.* **2013**, *9*, 7822–7832.
113. Kossovich, L.Y.; Salkovskiy, Y.; Kirillova, I.V. Electrospun chitosan nanofiber materials as burn dressing. *IFMBE Proc.* **2010**, *31*, 1212–1214.
114. Cai, Z.X.; Mo, X.M.; Zhang, K.H.; Fan, L.P.; Yin, A.L.; He, C.L.; Wang, H.S. Fabrication of chitosan/silk fibroin composite nanofibers for wound-dressing applications. *Int. J. Mol. Sci.* **2010**, *11*, 3529–3539.
115. Abdelgawad, A.M.; Hudson, S.M.; Rojas, O.J. Antimicrobial wound dressing nanofiber mats from multicomponent (chitosan/silver-NPs/polyvinyl alcohol) systems. *Carbohydr Polym.* **2014**, *100*, 166–178.
116. Gomes, S.R.; Rodrigues, G.; Martins, G.G.; Roberto, M.A.; Mafra, M.; Henriques, C.M.; Silva, J.C. *In vitro* and *in vivo* evaluation of electrospun nanofibers of PCL, chitosan and gelatin: A comparative study. *Mater. Sci. Eng. C Mater. Biol. Appl.* **2015**, *46*, 348–358.
117. Xu, F.; Weng, B.; Gilkerson, R.; Materon, L.A.; Lozano, K. Development of tannic acid/chitosan/pullulan composite nanofibers from aqueous solution for potential applications as wound dressing. *Carbohydr Polym.* **2015**, *115*, 16–24.
118. Izumi, R.; Komada, S.; Ochi, K.; Karasawa, L.; Osaki, T.; Murahata, Y.; Tsuka, T.; Imagawa, T.; Itoh, N.; Okamoto, Y.; *et al.* Favorable effects of superficially deacetylated chitin nanofibrils on the wound healing process. *Carbohydr. Polym.* **2015**, *123*, 461–467.
119. Kondo, T. Timing of skin wounds. *Legal Med.* **2007**, *9*, 109–114.
120. Erba, P.; Adini, A.; Demcheva, M.; Valeri, C.R.; Orgill, D.P. Poly-N-acetyl glucosamine fibers are synergistic with vacuum-assisted closure in augmenting the healing response of diabetic mice. *J. Trauma.* **2011**, *71*, S187–S193.

121. Pesin Suntar, I.; Kupeli Akkol, E.; Yilmazer, D.; Baykal, T.; Alper, M.; Kirmizibekmez, H.; Yesilada, E. Investigations on the *in vivo* wound healing potential of *Hypericum perforatum* L. *J. Ethnopharmacol.* **2010**, *127*, 468–477.
122. Ifuku, S.; Ikuta, A.; Egusa, M.; Kaminaka, H.; Izawa, H.; Morimoto, M.; Saimoto, H. Preparation of high-strength transparent chitosan film reinforced with surface-deacetylated chitin nanofibers. *Carbohydr. Polym.* **2013**, *98*, 1198–1202.
123. Getie Gebre, M.; Mariam, T.; Reitz, R.; Neubert, R.H. Evaluation of the release profiles of flavonoids from topical formulations of the crude extract of the leaves of *Dodonea viscosa* (Sapindaceae). *Pharmazie* **2002**, *57*, 320–322.
124. Shetty, S.; Udupa, S.; Udupa, L. Evaluation of antioxidant and wound healing effects of alcoholic and aqueous extract of *Ocimum sanctum* Linn in rats. *Evid. Based Complement. Alternat. Med.* **2008**, *5*, 95–101.
125. Azuma, K.; Osaki, T.; Eakuda, T.; Ifuku, S.; Saimoto, H.; Imagawa, T.; Okamoto, Y.; Minami, S. Beneficial and preventive effect of chitin nanofibrils in a dextran sulfate sodium-induced acute ulcerative colitis model. *Carbohydr. Polym.* **2012**, *87*, 1399–1403.
126. Nalwa, H.S. *Handbook of Nanostructured Biomaterials and Their Applications in Nanobiotechnology*; American Scientific Publishers: Los Angeles, CA, USA, 2005; Volumes 1–2.
127. Nalwa, H.S. *Encyclopedia of Nanoscience and Nanotechnology*; American Scientific Publishers: Los Angeles, CA, USA, 2004; Volumes 1–10.
128. Nalwa, H.S. *Encyclopedia of Nanoscience and Nanotechnology*; American Scientific Publishers: Los Angeles, CA, USA, 2011; Volumes 11–25.
129. Cho, Y.W.; Cho, Y.N.; Chung, S.H.; Yoo, G.; Ko, S.W. Water-soluble chitin as a wound healing accelerator. *Biomaterials* **1999**, *20*, 2139–2145.
130. Loke, W.K.; Lau, S.K.; Yong, L.L.; Khor, E.; Sum, C.K. Wound dressing with sustained anti-microbial capability. *J. Biomed. Mater. Res. Appl. Biomater.* **2000**, *53*, 8–17.
131. Han, S.S. Topical formulations of water-soluble chitin as a wound healing assistant-evaluation on open wounds using a rabbit ear model. *Fibers Polym.* **2005**, *6*, 219–223.
132. Pietramaggiore, G.; Yang, H.J.; Scherer, S.S.; Kaipainen, A.; Chan, R.K.; Alperovich, M.; Newalder, J.; Demcheva, M.; Vournakis, J.N.; Valeri, C.R.; Hechtman, H.B.; Orgill, D.P. Effects of poly-N-acetyl glucosamine (pGlcNAc) patch on wound healing in db/db mouse. *J. Trauma.* **2008**, *64*, 803–808.
133. Nagahama, H.; Rani, V.V.; Shalumon, K.T.; Jayakumar, R.; Nair, S.V.; Koiwa, S.; Furuike, T.; Tamura, H. Preparation, characterization, bioactive and cell attachment studies of alpha-chitin/gelatin composite membranes. *Int. J. Biol. Macromol.* **2009**, *44*, 333–337.
134. Tamura, H.; Nagahama, H.; Tokura, S. Preparation of chitin hydrogel under mild conditions. *Cellulose* **2006**, *13*, 357–364.
135. Lee, D.W.; Lim, H.; Chong, H.N.; Shim, W.S. Advances in chitosan material and its hybrid derivatives: a review. *Open Biomater. J.* **2009**, *1*, 10–20.
136. Ishihara, M.; Ono, K.; Sato, M.; Nakanishi, K.; Saito, Y.; Yura, H.; Matsui, T.; Hattori, H.; Fujita, M.; Kikuchi, M.; Kurita, A. Acceleration of wound contraction and healing with a photocrosslinkable chitosan hydrogel. *Wound Repair Regen.* **2001**, *9*, 513–521.

137. Ishihara, M.; Nakanishi, K.; Ono, K.; Sato, M.; Kikuchi, M.; Saito, Y.; Yura, H.; Matsui, T.; Hattori, H.; Uenoyama, M.; Kurita, A. Photocrosslinkable chitosan as a dressing for wound occlusion and accelerator in healing process. *Biomaterials* **2002**, *23*, 833–840.
138. Kweon, D.K.; Song, S.B.; Park, Y.Y. Preparation of water-soluble chitosan/heparin complex and its application as wound healing accelerator. *Biomaterials* **2003**, *24*, 1595–1601.
139. Murakami, K.; Aoki, H.; Nakamura, S.; Nakamura, S.; Takikawa, M.; Hanzawa, M.; Kishimoto, S.; Hattori, H.; Tanaka, Y.; Kiyosawa, T.; Sato, Y.; Ishihara, M. Hydrogel blends of chitin/chitosan, fucoidan and alginate as healing-impaired wound dressings. *Biomaterials* **2010**, *31*, 83–90.
140. Yang, X.; Yang, K.; Wu, S.; Chen, X.; Yu, F.; Li, J.; Ma, M.; Zhu, Z. Cytotoxicity and wound healing properties of PVA/ws-chitosan/glycerol hydrogels made by irradiation followed by freeze-thawing. *Radiat. Phys. Chem.* **2010**, *79*, 606–611.
141. Sung, J.H.; Hwang, M.R.; Kim, J.O.; Lee, J.H.; Kim, Y.I.; Kim, J.H.; Chang, S.W.; Jin, S.G.; Kim, J.A.; Lyoo, W.S.; *et al.* Gel characterisation and *in vivo* evaluation of minocycline-loaded wound dressing with enhanced wound healing using polyvinyl alcohol and chitosan. *Int. J. Pharm.* **2010**, *392*, 232–240.
142. Liu, R.; Xu, X.; Zhuang, X.; Cheng, B. Solution blowing of chitosan/PVA hydrogel nanofiber mats. *Carbohydr. Polym.* **2014**, *101*, 1116–1121.
143. Aoyagi, S.; Onishi, H.; Machida, Y. Novel chitosan wound dressing loaded with minocycline for the treatment of severe burn wounds. *Int. J. Pharm.* **2007**, *330*, 138–145.
144. Xu, H.; Ma, L.; Shi, H.; Gao, G.; Han, C. Chitosan-hyaluronic acid hybrid film as a novel wound dressing: *in vitro* and *in vivo* studies. *Polym. Adv. Technol.* **2007**, *18*, 869–875.
145. Dong, Y.; Liu, H.Z.; Xu, L.; Li, G.; Ma, Z.N.; Han, F.; Yao, H.M.; Sun, Y.H.; Li, S.M. A novel CHS/ALG bi-layer composite membrane with sustained antimicrobial efficacy used as wound dressing. *Chin. Chem. Lett.* **2010**, *21*, 1011–1014.
146. Kofuji, K.; Huang, Y.; Tsubaki, K.; Kokido, F.; Nishikawa, K.; Isobe, T.; Murata, Y. Preparation and evaluation of a novel wound dressing sheet comprised of  $\beta$ -glucan-chitosan complex. *React. Funct. Polym.* **2010**, *70*, 784–789.
147. Rai, M.; Yadav, A.; Gade, A. Silver nanoparticles as a new generation of antimicrobials. *Biotechnol. Adv.* **2009**, *27*, 76–83.
148. Luo, C.; Zhang, Y.; Zeng, X.; Zeng, Y.; Wang, Y. The role of poly(ethylene glycol) in the formation of silver nanoparticles. *J. Colloid Interface Sci.* **2005**, *288*, 444–448.
149. Jing, A.; Xiaoyan, Y.; Qingzhi, L.; Desong, W. Preparation of chitosan-graft-(methyl methacrylate)/Ag nanocomposite with antimicrobial activity. *Polym. Int.* **2010**, *59*, 62–70.
150. Lu, S.Y.; Gao, W.J.; Gu, H.Y. Construction, application and biosafety of silver nanocrystalline chitosan wound dressing. *Burns* **2008**, *34*, 623–628.
151. Cohen, M.I. The theory of real materials. *Ann. Rev. Mater. Sci.* **2000**, *30*, 1–26.
152. Wang, Z.L. Zinc oxide nanostructures: growth, properties and applications. *J. Phys. Condens. Matter.* **2004**, *16*, R829–R858.
153. Sharma, A.; Rao, P.; Mathur, R.P.; Ameta, S.C. Photocatalytic reactions of xylydine ponceau on semiconducting zinc oxide powder. *J. Photochem. Photobiol. A* **1995**, *86*, 197–200.
154. Li, L.H.; Deng, J.C.; Deng, H.R.; Liu, Z.L.; Li, X.L. Preparation, characterization and antimicrobial activities of chitosan/Ag/ZnO blend films. *Chem. Eng. J.* **2010**, *16*, 378–382.

155. Vicentini, D.S.; Smania, A., Jr.; Laranjeira, M.C.M. Chitosan/poly (vinyl alcohol) films containing ZnO nanoparticles and plasticizers. *Mater. Sci. Eng.* **2010**, *C30*, 503–508.
156. Anisha, B.S.; Biswas, R.; Chennazhi, K.P.; Jayakumar, R. Chitosan-hyaluronic acid/nano silver composite sponges for drug resistant bacteria infected diabetic wounds. *Int. J. Biol. Macromol.* **2013**, *62*, 310–320.
157. 1Kumar, P.T.; Lakshmanan, V.K.; Anilkumar, T.V.; Ramya, C.; Reshmi, P.; Unnikrishnan, A.G.; Nair, S.V.; Jayakumar, R. Flexible and microporous chitosan hydrogel/nano ZnO composite bandages for wound dressing: *in vitro* and *in vivo* evaluation. *ACS Appl. Mater. Interfaces* **2012**, *4*, 2618–2629.
158. Jaikumar, D.; Sajesh, K.M.; Soumya, S.; Nimal, T.R.; Chennazhi, K.P.; Nair, S.V.; Jayakumar, R. Injectable alginate-O-carboxymethyl chitosan/nano fibrin composite hydrogels for adipose tissue engineering. *Int. J. Biol. Macromol.* **2015**, *74*, 318–326.
159. Sudheesh Kumar, P.T.; Raj, M.; Govinth, P.; Nair, S.V.; Chennazhi, K.P.; Jayakumar, R. *In vitro* and *In vivo* Evaluation of Micro-Porous Chitosan Hydrogel/Nano Fibrin Composite Bandage for Skin Tissue Regeneration. *Tissue Eng. Part A* **2013**, *19*, 380–392.
160. Mehdizadeh, M.; Yang, J. Design strategies and applications of tissue bioadhesives. *Macromol. Biosci.* **2013**, *13*, 271–288.
161. Wheat, J.C.; Wolf, J.S. Advances in bioadhesives, tissue sealants, and hemostatic agents. *Urol. Clin. North Am.* **2009**, *36*, 265–275.
162. Spotnitz, W.D.; Burks, S. Hemostats, sealants, and adhesives: components of the surgical toolbox. *Transfusion* **2008**, *48*, 1502–1516.
163. Valbonesi, M. Fibrin glues of human origin. *Best Pract. Res. Clin. Haematol.* **2006**, *19*, 191–203.
164. Spotnitz, W.D.; Prabhu, R. Fibrin sealant tissue adhesive-review and update. *J. Long Term Eff. Med. Implants* **2005**, *15*, 245–270.
165. Braunwald, N.S.; Gay, W.; Tatooles, C.J. Evaluation of crosslinked gelatin as a tissue adhesive and hemostatic agent: An experimental study. *Surgery* **1966**, *59*, 1024–1030.
166. Elvin, C.M.; Vuocolo, T.; Brownlee, A.G.; Sando, L.; Huson, M.G.; Liyou, N.E.; Stockwell, P.R.; Lyons, R.E.; Kim, M.; Edwards, G.A.; *et al.* A highly elastic tissue sealant based on photopolymerised gelatin. *Biomaterials* **2010**, *31*, 8323–8331.
167. Ryan, B.M.; Stockbrugger, R.W.; Ryan, J.M. A pathophysiologic, gastroenterologic, and radiologic approach to the management of gastric varices. *Gastroenterology* **2004**, *126*, 1175–1189.
168. Radosevich, M.; Goubran, H.I.; Burnouf, T. Fibrin sealant: Scientific rationale, production methods, properties, and current clinical use. *Vox Sang.* **1997**, *72*, 133–143.
169. Leggat, P.A.; Kedjarune, U.; Smith, D.R. Toxicity of cyanoacrylate adhesives and their occupational impacts for dental staff. *Industrial Health* **2004**, *42*, 207–211.
170. Smith, T.W.; DeGirolami, U.; Crowell, R.M. Neuropathological changes related to the transorbital application of ethyl 2-cyanoacrylate adhesive to the basal cerebral arteries of cats. *J. Neurosurg.* **1985**, *62*, 108–114.
171. Ono, K.; Saito, Y.; Yura, H.; Ishikawa, K.; Kurita, A.; Akaike, T.; Ishihara, M. Photocrosslinkable chitosan as a biological adhesive. *J. Biomed. Mater. Res.* **2000**, *49*, 289–295.

172. Renbutsu, E.; Hirose, M.; Omura, Y.; Nakatsubo, F.; Okamura, Y.; Okamoto, Y.; Saimoto, H.; Shigemasa, Y.; Minami, S. Preparation and biocompatibility of novel UV-curable chitosan derivatives. *Biomacromolecules* **2005**, *6*, 2385–2388.
173. Nie, W.; Yuan, X.; Zhao, J.; Zhou, Y.; Bao, H. Rapidly *in situ* forming chitosan/ε-polylysine hydrogels for adhesive sealants and hemostatic materials. *Carbohydr. Polym.* **2013**, *96*, 342–348.
174. Lih, E.; Lee, J.S.; Park, K.M.; Park, K.D. Rapidly curable chitosan-PEG hydrogels as tissue adhesives for hemostasis and wound healing. *Acta Biomater.* **2012**, *8*, 3261–3269.
175. Barton, M.J.; Morley, J.W.; Stoodley, M.A.; Shaikh, S.; Mahns, D.A.; Lauto, A. Long term recovery of median nerve repair using laser-activated chitosan adhesive films. *J. Biophotonics.* **2015**, *8*, 196–207.
176. Barton, M.J.; Morley, J.W.; Mahns, D.A.; Mawad, D.; Wuhler, R.; Fania, D.; Frost, S.J.; Loebbe, C.; Lauto, A. Tissue repair strength using chitosan adhesives with different physical-chemical characteristics. *J. Biophotonics.* **2014**, *7*, 948–955.
177. Azuma, K.; Nishihara, M.; Shimizu, H.; Itou, Y.; Takashima, O.; Osaki, T.; Itoh, N.; Imagawa, T.; Murahata, Y.; Tsuka, T.; *et al.* Biological adhesive based on carboxymethyl chitin derivatives and chitin nanofibers. *Biomaterials* **2015**, *42*, 20–29.

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