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Enhanced wound healing associated with Sharpey's fiber-like tissue formation around FGF-2-apatite composite layers on percutaneous titanium screws in rabbits

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Abstract

Background Pin-tract infections are the most common complications of external fixation. To solve the problem, we developed a fibroblast growth factor-2 (FGF-2)-apatite composite layer for coating titanium screws. The purpose of this study was to elucidate the mechanism of the improvement in infection resistance associated with FGF-2-apatite composite layers.

Method We analyzed FGF-2 release from the FGF-2-apatite composite layer and the mitogenic activity of the FGF-2-apatite composite layer. We evaluated time-dependent development of macroscopic pin-tract infection around uncoated titanium control screws (n = 10). Screws coated with the apatite layer (n = 16) and FGF-2-apatite composite layer (n = 16) were percutaneously implanted for 4 weeks in the medial proximal tibia in rabbits.

Results A FGF-2-apatite composite layer coated on the screws led to the retention of the mitogenic activity of FGF-2. FGF-2 was released from the FGF-2-apatite composite layer in vitro for at least 4 days, which corresponds to a period when 30% of pin-tract infections develop macroscopically in the percutaneous implantation of uncoated titanium control screws. The macroscopic infection rate increased with time, reaching a plateau of 80–90% within 12 days. This value remained unchanged until 4 weeks after
implantation. The screws coated with an FGF-2-apatite composite layer showed a significantly higher wound healing rate than those coated with an apatite layer (31.25 vs. 6.25%, \( p < 0.05 \)). The interfacial soft tissue that bonded to the FGF-2-apatite composite layer is a Sharpey’s fiber-like tissue, where collagen fibers are inclined at angles from 30 to 40° to the screw surface. The Sharpey’s fiber-like tissue is rich in blood vessels and directly bonds to the FGF-2-apatite composite layer via a thin cell monolayer (0.8–1.7 \( \mu \)m thick).

Conclusion It is suggested that the enhanced wound healing associated with the formation of Sharpey’s fiber-like tissue triggered by FGF-2 released from the FGF-2-apatite composite layer leads to the reduction in the pin-tract inflammation rate.

Keywords

Calcium phosphate coating · External fixation · Fibroblast growth factor-2 · Infection · Sharpey’s fibers
Introduction

Pin-tract infections are the most common complications of external fixation [1-6]. To solve this problem, we developed a fibroblast growth factor-2 (FGF-2)-apatite composite layer for coating anodically oxidized titanium screws using a supersaturated calcium phosphate solution supplemented with FGF-2 [7, 8]. Because FGF-2 enhanced wound healing owing to fibroblast proliferation and vascularization [9-16]. The titanium screws coated with an FGF-2-apatite composite layer demonstrated a marked reduction in the rate of macroscopic pin-tract infection compared with titanium screws without the FGF-2-apatite composite layer on a rabbit percutaneous screw implantation model. The rates of infection associated with macroscopic tissue destruction 4 weeks after the implantation were 43.8% for the screws coated with the FGF-2-apatite composite layer and 93.8% for those without the FGF-2-apatite composite layer [7]. The FGF-2-apatite composite layers consisted of low-crystallinity apatite and approximately 2.3 µg of FGF-2 per screw 4.0 mm diameter and 30 mm length.

Since FGF-2 promotes fibroblast proliferation and wound healing with vascularization [9-16], it is hypothesized that FGF-2 is released from the FGF-2-apatite composite layer, and then this released FGF-2 facilitates fibroblast proliferation and angiogenesis which compete with the spread of infection; finally, the pin-tract infection
is prevented or cured by improved skin wound healing. Moreover, we considered that an anchoring formation between the pin and skin wound is important in order to prevent the pin-tract infection. Sharpey’s fibers are a highly infection-resistant percutaneous structure owing to its periodontal membrane [17]. Sharpey’s fibers in the periodontal membrane bridge the tooth surface and the bone surface. They are aligned perpendicular or inclined to the tooth and bone surfaces with blood vessels and nerves running in the interstices of the fibers. They are embedded in bone on one side and in radicular cementum on the other side. The blood vessels in the interstices of Sharpey’s fibers supply immunological cells that remove bacteria infected through the interface between the tooth surface and the gingival tissue. Therefore, we hypothesized that Sharpey’s fiber-like tissue formation can be related to the marked increase in infection resistance. However, the detailed mechanism of the improved infection resistance remains unclear for the following reasons: Firstly, only limited information is available about the release profile of FGF-2. Secondly, no information is available about how FGF-2-mediated tissue regeneration competes with the development of infection-mediated tissue destruction. Thirdly and most importantly, no information is available about inflammation and soft tissue reactions to FGF-2-apatite composite layers at the histological level. In our previous study, infection resistance was not evaluated in
histological detail but only macroscopically. The purpose of the present study was, therefore, to elucidate the mechanism of the improvement in infection resistance associated with FGF-2-apatite composite layers with particular focus on the above three issues.

Materials and Methods

Formation of FGF-2-apatite composite layer on titanium screws

Titanium cancellous screws with a 142-nm-thick anodic oxide layer (SYNTHES®, USA) (# 407-030, 4.0 mm diameter and 30 mm length) were coated with an apatite layer and an FGF-2-apatite composite layer [7, 8]. Briefly, titanium cancellous screws were immersed for 48 h in a supersaturated calcium phosphate solution (Table 1) with a Ca/P molar ratio of 2.0 at neutral pH at 37 ºC. Each supersaturated calcium phosphate solution (10 ml) was prepared by mixing 5 clinically available infusion fluids in Japan at a certain mixing ratio: Ringer’s solution (8.137 ml, Otsuka Pharmaceutical Co., Ltd., Japan) and Calcium Chloride Corrective Injection 1 mEq/ml (36.85 µl, Otsuka Pharmaceutical Co., Ltd., Japan) as calcium sources, Klinisalz (0.899 ml, I’rom Pharmaceutical Co., Ltd., Japan) and Dipotassium Phosphate Corrective Injection 1 mEq/ml (18.72 µl, Otsuka Pharmaceutical Co., Ltd., Japan) as
phosphorus sources, and Sodium Bicarbonate Substitution Fluid for only BIFIL®
(0.909 ml, AJINOMOTO PHARMACEUTICALS Co., Ltd., Japan) as an alkalinizer.
Therefore, the supersaturated calcium phosphate solution had fixed chemical
composition. The supersaturated calcium phosphate solutions contained FGF-2
(Fiblast®, Kaken Pharmaceutical, Japan) at a concentration of 0 or 4 µg/ml. The screws
immersed in the supersaturated calcium phosphate solutions with FGF-2 concentrations
of 0 and 4 µg/ml were designated as F0 and F4 screws, respectively. F0 and F4 have the
almost same surface morphology and the surface layer on both samples mainly
consisted of low-crystalline apatite [7]. So using these two samples, only the effect of
immobilized FGF-2 in the surface layer should be examined without interference caused
by difference in surface properties. The composition was not actually measured on the
screw surface.

In vitro FGF-2 release from FGF-2-apatite composite layer

The F4 screw was rinsed with 1 ml of physiological saline solution, and then
immersed in 1 ml of fresh physiological saline solution at 37 °C (n = 6). The
physiological saline solution was replaced with a fresh solution every day for 4 days.
The saline solution was analyzed for FGF-2 by fluorometric quantification (excitation
wavelength: 470 nm, emission wavelength: 570 nm) using a NanoOrange® Protein Quantitation Kit (N-6666, Invitrogen, USA) in accordance with the manufacturer’s instructions. The working curve was drawn normally similar to one in the instructions (data not shown).

In vitro assay for mitogenic activity of FGF-2-apatite composite layer

Fibroblastic NIH3T3 cells (NIH3T3-3-4, RIKEN BioResource Center) were cultured on the F0 and F4 screws to evaluate the mitogenic activity of the apatite layer and FGF-2-apatite composite layer. The cells on the screws were cultured in 5 mL of Dulbecco’s modified essential medium supplemented with 0.3 mg/ml l-glutamine, 1.0 mg/ml bovine serum albumin, 5.0 µg/ml insulin and 1.0 µg/ml transferrin (serum-free DMEM) in a humidified atmosphere of 5% CO₂ at 37 ºC. Since serum contains various growth factors and other biologically active substances, serum-free DMEM was used to detect the effect of immobilized FGF-2 on the titanium screw (F4). BSA, insulin and transferrin were added to DMEM as minimum requirement additives for survival of the cells under the condition without serum. The absorbance of serum-free DMEM at 450 nm (n = 6) were measured every day for 6 days using a water-soluble tetrazolium salt (the CCK-8 kit, Dojindo Laboratories, Japan); each screw with cells was incubated in 1
ml of fresh and 10% tetrazolium salt-containing serum-free DMEM to determine the absorbance at 450 nm instead of cell numbers on the screws. After the incubation with CCK-8 reagent, the screws were rinsed and re-immersed in the original 5 ml of serum-free DMEM for cell incubation in a humidified atmosphere of 5% CO₂ at 37 ºC until the next measurement. It is confirmed that the number of the cells is proportional to the measured Abs (450 nm) under this experimental condition in advance (data not shown).

**In vivo study**

The F0 and F4 screws were implanted percutaneously in the medial proximal tibia of sixteen skeletally mature male Japanese white rabbits weighing approximately 3.0 kg. The operation technique was the same as that of our previous works [7, 8]. Briefly, the screws were implanted in both medial proximal tibias of eight rabbits in each group (F0 and F4) after the intravenous injection of barbiturate (40 mg/kg body weight), a small (10 mm) incision in the skin on the medial proximal tibia and a perforation 2.5 mm in diameter in both tibial metaphyses using individual taps. After the implantation, the skin was sutured bilaterally to the screw [7, 8]. Postoperatively, each rabbit was allowed to behave freely in its own cage. The rabbits did not receive
any antibiotics or treatment for their wounds and were sacrificed 4 weeks after the
operation.

Using the same operation techniques, ten uncoated titanium control screws
were implanted percutaneously in both medial proximal tibiae of five skeletally mature
male Japanese white rabbits weighing approximately 3.0 kg to evaluate the natural
development of pin-tract infection using a Kaplan-Meier plot. Pin-tract infection was
macroscopically examined once a day for four weeks. All the animal experiments were
performed in accordance with the guidelines of the Ethical Committee of the University
of Tsukuba, National Institute of Advanced Industrial Science and Technology and the
National Institute of Health guidelines for the care and use of laboratory animals (NIH

Histological evaluation of pin-tract inflammation around F0 and F4 screws

After extracting the F0 and F4 screws, soft tissues at the screw site (F0: n = 16,
F4: n = 16) were fixed in 10% neutral-buffered formalin and embedded in paraffin.
Sections were cut at the center of the screw hole parallel to the screw hole and sliced to
a thickness of 5 μm. The sections were stained with hematoxylin and eosin (H&E) and
by Von Kossa’s method and Masson’s trichrome (MT) method for histological
evaluation by light microscopy (BX-51, Olympus Optical Co., Ltd., Japan). Von Kossa’s and MT methods were used for detecting the FGF-2-apatite composite layer and collagen fibers, respectively.

Pin-tract inflammation was histologically assessed in a blind manner by a single pathologist by classifying it into one of three grades (Grades 0, 1 and 2). Grade 0 corresponds to “no inflammation with good wound healing”. Grade 1 corresponds to “slight inflammation”. Grade 2 corresponds to “severe inflammation”. The alignment of collagenous fibers at the tissue-screw interface in specimens with Grade 0 inflammation was examined by polarized light microscopy (BH-2, Olympus Optical Co., Ltd., Japan).

Evaluation of time-dependent development of macroscopic pin-tract infection around uncoated titanium control screws

The development of pin-tract infection around uncoated titanium control screws was macroscopically evaluated once a day using a modified Checketts and Otterburn classification method, adopting the same criteria as those described elsewhere [7]. Briefly, Grade 0 corresponds to “no redness,” in which no redness, discharge or screw loosening is observed. Grade 1 corresponds to infections only in the soft tissue, characterized by redness and discharge around the screw without screw loosening.
Grade 2 corresponds to infections in both soft and hard tissues, characterized by redness and discharge around the screw associated with screw loosening due to osteomyelitis. Grade 0 survival was determined by the Kaplan-Meier method [18] using Grades 1 and 2 described above as end points. Those experiments were summarized in Table 2.

**Statistical Analyses**

The cell proliferation data of the F0 and F4 screw groups were analyzed using Student’s $t$-test at a $p < 0.05$ significance level. The pin-tract inflammation grades of the F0 and F4 screw groups were compared using Mann-Whitney’s U test at a $p < 0.05$ significance level.

**Results**

*In vitro FGF-2 release from FGF-2-apatite composite layer*

FGF-2 was released from the F4 screw for at least 4 days when the screws were immersed in saline solution. 50 to 85 ng of FGF-2 was released from the F4 screw every day during the 4 day immersion (Fig. 1).
In vitro assay for mitogenic activity of FGF-2-apatite composite layer

It was confirmed that the FGF-2-apatite composite layer retained the mitogenic activity of FGF-2 in vitro (Fig. 2). No significant difference was detected between the initial numbers of NIH3T3 cells adhering to the F0 and F4 screws. Therefore, the apatite layer and FGF-2 apatite composite layer were the same in terms of cell adhesiveness. Nevertheless, after 3 and 4 day incubations, the absorption intensities of metabolized tetrazolium salt in the serum-free DMEM became significantly higher for the F4 screws than that for the F0 screws. This result suggested that the number of cells on the F4 screws became significantly higher than that on the F0 screws.

Development of macroscopic pin-tract infection around uncoated titanium control screw

The macroscopic infection rate for uncoated titanium control screws reached 30% in the initial period between 2 and 4 days after implantation, which was demonstrated by Grade 0 survival in the Kaplan-Meier plot (Fig. 3). The macroscopic infection rate increased with increasing implantation period, reaching a plateau of 80-90% within 12 days. This value remained unchanged until 4 weeks after implantation. The final infection rate was consistent with that in our previous study [7].
Histological evaluation of pin-tract inflammation around F0 and F4 screws

In the F0 screw group, the rates of Grade 0, 1 and 2 inflammation were 1/16 (6.25%), 6/16 (37.5%) and 9/16 (56.25%), whereas in the F4 screw group the rates of Grade 0, 1 and 2 inflammation were 5/16 (31.25%), 7/16 (43.75%) and 4/16 (25.0%), respectively (Fig. 4). The F4 screws demonstrated a significant improvement in wound healing without inflammation compared with the F0 screws, which was demonstrated by the significant difference in the rate of Grade 0 inflammation between the F0 and F4 screw groups (p = 0.018) (Fig. 5).

Sharpey’s fiber-like tissue with blood vessels was found to have formed around two of the five F4 screws in the case of Grade 0 inflammation. In one F4 specimen with Grade 0 inflammation where the screw-skin interface was completely intact (Fig. 6a), an extraordinary interfacial tissue with a thickness of 100 µm was found to have formed on the FGF-2-apatite composite layer. The interfacial tissue consisted of an inner cell monolayer and an outer fibrous tissue layer attached to the inner cell monolayer. The inner cell monolayer consisted of extremely thin and stretched cells (0.8-1.7 µm thick and 16-33 µm long) (Fig. 6b). The inner cell monolayer directly attached to the FGF-2-apatite composite layer (Fig. 7). In the outer fibrous tissue layer,
many blood vessels were formed. Polarized light microscopy demonstrated the interference color (light gray) in the outer fibrous tissue layer with 4-fold color extinction during 360° sample rotation under crossed polar observation (Figs. 6c and d). This meant that collagen fibers ran in one direction. The running direction of the collagen fibers was not parallel to the screw surface but inclined at angles from 30 to 40°, which was demonstrated by the angle between the extinction position and the screw hole direction at the extinction position (Figs. 6c and d). These morphological features of the outer fibrous tissue layer have close similarity to those of Sharpey’s fibers in the periodontal membrane. In the interstices of the slanted collagen fibers, flattened fibroblasts were sparsely present, and aligned parallel to the collagen fibers. The cell sparseness indicated that the intensive formation of an extracellular matrix including collagen occurred. In another F4 specimen with Grade 0 inflammation where the screw-skin interface was incompletely intact, Sharpey’s fiber-like tissue with many blood vessels was again observed. In the other (three) F4 specimens with Grade 0 inflammation, the formation of Sharpey’s fiber-like tissue was not confirmed owing to the rupture of soft tissue on the removal of the screws. On the other hand, the formation of Sharpey’s fiber-like tissue was not confirmed in the only F0 specimen with Grade 0 inflammation (Fig. 8).
Discussion

FGF-2 was released from the F4 screws for at least 4 days *in vitro*. FGF-2 released from the apatite layer retained its bioactivity and triggered the proliferation of NIH3T3 cells for 4 days. On the other hand, most of the pin-tract infections in the case of the uncoated titanium control screws occurred within 12 days, with one-third of them occurring within 4 days (Fig. 3). Wound healing proceeds in the gap between the skin and the uncoated titanium control screws. However, bacteria can easily infect in the gap because the anchoring between the skin and the screws remains loose in the early postoperative period. Therefore, the initial competition of wound healing against the spread of infection is crucial for improving infection resistance. On the basis of these results, it is considered that FGF-2 released in the early postoperative period affected wound healing so that it prevailed over the spread of infection. It was suggested that FGF-2 released from the FGF-2-apatite composite layer facilitated fibroblast proliferation and wound healing in the early postoperative period, and that this initial effect of the FGF-2-apatite composite layer was crucial for preventing pin tract infection up to 4 weeks.

The enhanced wound healing triggered by FGF-2 finally led to the reduction
in the pin-tract inflammation rate. The F4 screws showed a significantly lower
inflammation rate (68.75% vs 93.75%) than the F0 screws in the histological evaluation.
FGF-2 released from the FGF-2-apatite composite layer can promote the regeneration of
skin tissue and blood vessels. Moreover, apatite has a good affinity with soft-tissue [19,
20]. Although the F4 screw reduced pin-tract inflammation rate in the present animal
model without using antibiotics and daily pin care routine, the infection rate was still as
high as 68.75%. To reduce further the inflammation rate, it is necessary to use
antibiotics and daily pin care routine. External fixation pins coated with FGF-2-apatite
composite layers needs to be in combination with antibiotics and daily pin care routine
to prevent inflammation completely.

The induction of Sharpey’s fiber-like tissue is related to the marked increase
in infection resistance. Sharpey’s fibers are present in the periodontal membrane and
bone-tendon junctions, which are subjected to transversal and shear stresses [17, 21-23].
It should be noted that a tooth, which is a natural percutaneous structure, is a highly
infection-resistant percutaneous structure owing to its periodontal membrane. In the
present study, the enhanced wound healing was associated with the formation of an
extraordinary interfacial tissue that contains Sharpey’s fiber-like tissue, where its
collagen fibers are inclined to the screw surface at angles from 30 to 40°. Usually,
collagen fibers align parallel to the surface of a foreign body, forming a fibrous connective tissue. An ordinary fibrous connective tissue that aligns parallel to the surface of a foreign body has no blood vessels or nerves.

Whether one end of the collagen fibers in the present Sharpey’s fiber-like tissue is embedded in the FGF-2-apatite composite layer remains to be clarified. The Sharpey’s fiber-like tissue directly bonded to the cell monolayer. Moreover, no intervening tissues were microscopically observed between the cell monolayer and the FGF-2-apatite composite layer. However, it is unclear whether the Sharpey’s fiber-like tissue penetrates the thin cell monolayer. Further ultrastructural studies are required to clarify this.

FGF-2 administered in alveolar bone defects has been shown to enhance the regeneration of the periodontal membrane with new cementum deposits and new bone formation without epithelial downgrowth 6 to 8 weeks after surgery in a dog model [24, 25]. In addition, the regeneration of the periodontal membrane and tendon-bone attachment with Sharpey’s fiber was reported [26-29]. External fixation screws with the FGF-2-apatite composite layer in skin tissue resemble an FGF-2-administered natural tooth in the periodontal tissue in that both have the surface apatite layer and FGF-2, have one end immersed in bone marrow that can supply mesenchymal stem cells for
tissue induction or regeneration, and are subjected to transversal and shear stresses. Probably owing to these environmental similarities, FGF-2 released from the FGF-2-apatite composite layer promoted wound healing associated with the formation of Sharpey’s fiber-like tissue with blood vessels.

Clinically, the improvement of wound healing of screw-skin interfaces is important in the course of treatment by percutaneous implants such as external fixation. Such implants may also decrease the risk of the inadequate healing of a fractured bone, including nonunion.

In conclusion, titanium screws coated with an FGF-2-apatite composite layer demonstrated the sustained release of FGF-2 for at least 4 days and triggered the enhanced proliferation of fibroblasts in the period. The period was corresponding to the early postoperative phase during which pin-tract infection develops in the percutaneous implantation of uncoated titanium control screws. The skin tissue directly adhered to the FGF-2-apatite composite layer on the screw via a thin cell monolayer. In addition, Sharpey’s fiber-like tissue was induced at the screw-skin interface. The Sharpey’s fiber-like tissue was rich in blood vessels. All these factors contributed to the remarkable infection resistance associated with the FGF-2-apatite composite layer on titanium external fixation screws. Further studies including ultrastructural analysis at the
tissue-apatite composite layer interface, as well as studies entailing long-term implantation and implantation under loaded conditions are required.
References


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Figure 1.

Figure 2.

The change in absorbance of 10% tetrazolium salt-containing serum-free DMEM at 450 nm after 1-hour incubation with NIH3T3 cells that were incubated on F0 and F4 for 0 to 6 days.
Figure 3.

Time-dependent development of macroscopic pin-tract infection around uncoated titanium control screw.
Figure 4.

Typical examples of Grade 0, 1 and 2 inflammation 4 weeks after operation.

Arrows: contact area with screw.

Grade 0: no inflammation with good wound healing (white arrows) (Fig. 4a).

Grade 1: slight inflammation (gray arrows) (Fig. 4b).

Grade 2: severe inflammation (black arrows) (Fig. 4c).
Figure 5.

Histological evaluation of pin-tract inflammation around F0 and F4 screws.

The inflammation around the F4 screw was significantly less prominent than that around the F0 screw (p = 0.018).
Figure 6.

Histological sections of a specimen in F4 screws with Grade 0 inflammation with the screw-skin interface remaining intact 4 weeks after operation, showing the presence of Sharpey’s fiber-like tissue (H&E staining). b), c) and d) Magnified views of the boxed part in a). a) and b) Light microscopic image. c) and d) Polarized light microscopic images under crossed polar observation. d) View of c) after rotation at an angle of 34°.

A cell monolayer (arrow head) on the surface of the screw and many blood vessels (v marks) near the screw are seen (Fig. 6b). Crossed polar observation with the screw hole direction parallel to that of a polar demonstrated the interference color (white) of the aligned collagen fiber (Fig. 6c). Extinction of the interference color after rotation by an angle of 34° from the position in Fig. 6c (Fig. 6d) revealed that the direction of the aligned collagen fiber was 34° to the screw hole direction (black arrows in Figs. 6c and d).
(c) 

(d)
Figure 7.

Histological sections with Von Kossa staining of the specimen shown in Fig. 6.  b) Magnified views of the boxed part in a). The Von Kossa’s method stains a calcium salt brown. The direct adhesion of the thin cell monolayer to the FGF-2-apatite composite layer (brown) is visible.
Figure 8.

Histological sections of a specimen of F0 screws with Grade 0 inflammation with the screw-skin interface remaining intact 4 weeks after operations (H&E staining). b), c) and d) Magnified views of the boxed part in a). a) and b) Light microscopic image. c) and d) Polarized light microscopic images under crossed polar observation. d) View of c) after rotation at an angle of 45°.

A fibrous layer was observed around the screw surface (Fig. 8a and b). The fibrous layer was parallel to the screw (black arrow), which was observed in polarized light microscopy images (Fig. 8c and d). The formation of Sharpey’s fiber-like tissue was not observed.