

Title	Evaluation of a novel collagen-gelatin scaffold for achieving the sustained release of basic fibroblast growth factor in a diabetic mouse model.
Author(s)	Kanda, Norikazu; Morimoto, Naoki; Ayvazyan, Artem A; Takemoto, Satoru; Kawai, Katsuya; Nakamura, Yoko; Sakamoto, Yuki; Taira, Tsuguyoshi; Suzuki, Shigehiko
Citation	Journal of tissue engineering and regenerative medicine (2012), 8(1): 29-40
Issue Date	2012-05-24
URL	<a href="http://hdl.handle.net/2433/196766">http://hdl.handle.net/2433/196766</a>
Right	© 2012 John Wiley & Sons, Ltd. This is the peer reviewed version of the following article: Kanda, N., Morimoto, N., Ayvazyan, A. A., Takemoto, S., Kawai, K., Nakamura, Y., Sakamoto, Y., Taira, T. and Suzuki, S. (2014), Evaluation of a novel collagen–gelatin scaffold for achieving the sustained release of basic fibroblast growth factor in a diabetic mouse model. J Tissue Eng Regen Med, 8: 29–40. , which has been published in final form at <a href="http://dx.doi.org/10.1002/term.1492">http://dx.doi.org/10.1002/term.1492</a>
Type	Journal Article
Textversion	author

**Title Page**

**Full title: Evaluation of a novel collagen/gelatin scaffold for achieving the sustained release of basic fibroblast growth factor in a diabetic mouse model**

Short title: “Sustained release of bFGF from CGS accelerated tissue regeneration in diabetic mice.”

Authors’ names and affiliations:

Norikazu Kanda, MD<sup>1</sup>; Naoki Morimoto, MD, PhD<sup>1</sup>; Artem A. Ayvazyan, MD<sup>1</sup>; Satoru Takemoto, MD, Ph.D<sup>2</sup>; Katsuya Kawai, MD, PhD<sup>1</sup>; Yoko Nakamura, MD<sup>1</sup>; Yuki Sakamoto<sup>3</sup>; Tsuguyoshi Taira, MAg<sup>3</sup>; Shigehiko Suzuki, MD, Ph.D<sup>1</sup>

<sup>1</sup>Department of Plastic and Reconstructive Surgery, Graduate School of Medicine, Kyoto University, 54 Kawahara-cho Shogoin, Sakyo-ku, Kyoto, Japan.

<sup>2</sup>Department of Plastic and Reconstructive Surgery, Matsue-city hospital, 32-1 noshira-cho, Matsue-shi, Shimane, Japan.

<sup>3</sup>Gunze Research and Development Center, 1 Ishiburo Inokurashin-machi, Ayabe, Kyoto, Japan.

The senior author:

Norikazu Kanda

1  
2  
3  
4 606-8507 Japan Kyoto-shi, Sakyo-ku, Shogoin Kawahara-cho 54  
5  
6

7 Graduate School of Medicine, Department of Plastic and Reconstructive Surgery.  
8

9 Tel: +81-75-751-3613; Fax: +81-75-751-4340.  
10

11 E-mail address: nkanda@kuhp.kyoto-u.ac.jp  
12  
13

14  
15  
16 This work was supported by a grant from the Japan Science and Technology Agency.  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

For Peer Review

**ABSTRACT**

The objective of this study was to evaluate the ability of a scaffold, collagen/gelatin sponge (CGS), to release basic fibroblast growth factor (bFGF) in a sustained manner using a pressure-induced decubitus ulcer model involving genetically diabetic mice. We confirmed that the CGS **impregnated with** a bFGF concentration of up to  $50\mu\text{g}/\text{cm}^2$  **were able to sustained the release of bFGF** throughout their biodegradation. We prepared decubitus ulcers on diabetic mice. After debriding the ulcers, we implanted CGS (diameter: 8mm) impregnated with normal saline solution (NSS) or bFGF solution (7, 14, 28, or  $50\mu\text{g}/\text{cm}^2$ ). At one and two weeks after implantation, the mice were sacrificed, and tissue specimens were obtained. The wound area, neoepithelium length, and numbers and total area of newly formed capillaries were evaluated. The CGS impregnated with NSS became infected and degraded, whereas the CGS impregnated with 7 or  $14\mu\text{g}/\text{cm}^2$  of bFGF displayed accelerated dermis-like tissue formation, and the CGS impregnated with  $14\mu\text{g}/\text{cm}^2$  of bFGF produced significant improvements in the remaining wound area, neoepithelium length, and **numbers and total area** of newly formed capillaries compared with the NSS group. No significant difference was observed between the NSS and  $50\mu\text{g}/\text{cm}^2$  bFGF groups. CGS impregnated with  $7\mu\text{g}/\text{cm}^2$  to  $14\mu\text{g}/\text{cm}^2$  bFGF accelerated wound healing, and an excess amount of bFGF did not increase the wound-healing efficacy of the CGS. Our CGS is a scaffold that can release positively charged growth factors such as bFGF in a sustained manner and shows promise as a scaffold for skin regeneration.

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

Keywords: bFGF, artificial skin, collagen/gelatin sponge, scaffold, sustained release, wound healing, diabetic mice

For Peer Review

## 1. INTRODUCTION

We were involved in the development of a bilayered acellular artificial dermis (AD, Pelnac®, Gunze Co. Ltd, Kyoto, Japan) as a biodegradable scaffold containing an upper layer composed of a silicone sheet and a lower layer made of collagen sponge by modifying the artificial dermis proposed by Yannas and Burke (Yannas et al., 1980; Suzuki et al., 1990a). After the AD has been grafted onto a full-thickness skin defect, the collagen sponge is biodegraded and gradually replaced with regenerated dermis-like tissue within 2 to 3 weeks (Suzuki et al., 1990b). Basic FGF was released during the biodegradation of the CGS.

Artificial dermises have been used in clinical practice for the treatment of full-thickness skin defects caused by severe burns and tumor excision for more than 10 years. However, some problems remain to be solved. Before capillaries have infiltrated the collagen sponge, the artificial dermis is not resistant to infection (Matsuda et al., 1992). Therefore, it is difficult to apply artificial dermises to chronic ulcers such as decubitus, diabetic, and leg ulcers, because of the high probability of infection (Matsuda et al., 1988).

Basic fibroblast growth factor (bFGF), which was identified in 1974 (Gospodarowicz et al., 1974), promotes the proliferation of fibroblasts and capillary formation and accelerates tissue regeneration (Uchi et al., 2009). In Japan, human recombinant bFGF (FIBRAST SPRAY® Kaken Pharmaceutical, Tokyo, Japan) has been used clinically for the treatment of chronic skin ulcers since 2001, and its clinical effectiveness has been demonstrated (Kawai et al., 2000). Recently, combination therapy involving bFGF and artificial dermis has been reported to accelerate dermis-like tissue formation (Muneuchi et al., 2005;

1  
2  
3  
4 Ito et al., 2005; Akita et al., 2008). In spite of its effectiveness, this combination therapy  
5  
6 has not become a standard treatment because bFGF must be applied every day as it rapidly  
7  
8 diffuses away from the site of administration and is also inactivated quickly after its  
9  
10 administration (Kawai et al., 2000).  
11  
12

13  
14 To overcome these problems, we have developed a novel scaffold, collagen/gelatin  
15  
16 sponge (CGS), containing a 10wt% concentration of acidic gelatin that is capable of  
17  
18 releasing positively charged growth factors such as bFGF for more than 10 days in vivo via  
19  
20 the formation of ion complexes between bFGF and gelatin (Takemoto et al., 2008).  
21  
22 Human bFGF, which has an isoelectric point (IEP) of 9.6 (Kanda et al., 2011; Artem et al.,  
23  
24 2011; Takemoto et al., 2008; Kawai et al., 2005; Kawai et al., 2000; Tabata Y et al., 1999 ;  
25  
26 Muniruzzaman et al., 1998), is ionically complexed with acidic gelatin, which has an IEP  
27  
28 of 5.0 (Muniruzzaman et al., 1998). CGS acts in the same manner as a scaffold such as AD,  
29  
30 and the bFGF impregnated into the CGS is released during its biodegradation (Takemoto et  
31  
32 al., 2008). In our previous study involving normal mouse skin defects, CGS impregnated  
33  
34 with  $7\mu\text{g}/\text{cm}^2$  bFGF accelerated dermis-like tissue formation 2 or 3 fold compared with AD  
35  
36 (Kanda et al., 2011). In another study in which we created full-thickness palatal mucosa  
37  
38 defects in beagles, CGS impregnated with  $7\mu\text{g}/\text{cm}^2$  bFGF accelerated the regeneration of  
39  
40 the palatal mucosa, induced good levels of neovascularization, and produced less wound  
41  
42 contracture (Artem et al., 2011). We expect that CGS impregnated with bFGF will prove to  
43  
44 be an effective treatment for full thickness skin defects including chronic ulcers such as  
45  
46 diabetic foot ulcers and decubitus ulcers. In this study, we examined the optimal bFGF  
47  
48 dosage with which to impregnate CGS and the release profile of bFGF from CGS after  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 impregnation. Then, we investigated the effectiveness of CGS impregnated with bFGF and  
5  
6 the optimal bFGF dosage in an impaired wound healing model involving genetically  
7  
8 diabetic mice with pressure-induced decubitus ulcers.  
9  
10

## 11 12 13 14 **2. MATERIALS AND METHODS**

### 15 16 17 18 **2.1. Animals and operations**

19  
20 The animals were maintained at the Institute of Laboratory Animals, Graduate School of  
21  
22 Medicine, Kyoto University. The number of animals used in this study was kept to a  
23  
24 minimum, and all possible efforts were made to reduce suffering in compliance with the  
25  
26 protocols established by the Animal Research Committee of Kyoto University.  
27  
28  
29  
30  
31

### 32 33 **2.2. Preparation of CGS**

34  
35 We used gelatin isolated from pig dermis with an isoelectric point (IEP) of 5.0 and a  
36  
37 molecular weight of 99,000 (Nippi, Inc., Tokyo, Japan) and atelocollagen isolated from pig  
38  
39 tendons with an IEP of 8.5 and a molecular weight of 300,000 (Nitta Gelatin, Inc., Osaka,  
40  
41 Japan). CGS was produced according to production procedure has described in  
42  
43 Takemoto's paper (Takemoto et al., 2008). CGS with a gelatin concentration of 10wt% of  
44  
45 the total solute was prepared by mixing 3wt% gelatin solution with 0.3wt% collagen  
46  
47 solution. We then spread a thin layer of silicone paste onto a polyester mesh. Before the  
48  
49 silicone paste had dried, the top of the CGS was attached to the silicone paste covered  
50  
51 polyester mesh. As the silicone paste dried, it formed a sheet that adhered to the CGS.  
52  
53  
54  
55  
56  
57  
58  
59  
60



### 2.3. *In vitro* bFGF release study and degradation rate of CGS

We prepared CGS of 10mm×20mm in size and 3.0mm in thickness. We weighed all of the CGS (n=10) and then placed them into 15ml test tubes (Thermo Fisher Scientific Inc. Osaka, Japan). We prepared distilled water (DW, Otsuka Pharmaceutical, Tokyo, Japan) and distilled water solution containing bFGF (FIBRAST SPRAY® Kaken Pharmaceutical, Tokyo, Japan) at concentrations of 0.07, 0.14, 0.28, and 0.5µg/µl and applied 200 µl of each bFGF solution to CGS. Thus, we prepared four bFGF groups, in which CGS was impregnated with 7, 14, 28, or 50µg/cm<sup>2</sup> bFGF and incubated overnight at 4°C.

We prepared Tris-HCl buffer solution (pH7.4) containing 4 units/ml collagenase (Collagenase Type A, Sigma-Aldrich Corporation Japan, Tokyo, Japan) and poured 5ml of collagenase solution into the test tubes to dissolve the CGS at 37°C. At 1, 2, 4, and 6 hours after the degradation, we collected 1 ml of the solution from the test tubes and used it to estimate the bFGF concentrations in the four bFGF groups. After collecting the solutions, collagenase was completely removed from the test tubes, and the CGS inside the test tubes were immediately washed with distilled water to stop the enzyme reaction. The CGS were removed from the test tubes and freeze-dried for 12 hours to remove any water using a freeze dryer (BRZ350WA, ADVANTEC Toyo Kaisha, Ltd., Tokyo, Japan). The CGS were then weighed in order to calculate the degradation rate of the CGS impregnated with bFGF at each time point.

The analysis was performed using ELISA (Enzyme-Linked Immunosorbent Assay) kits (Human FGF basic immunoassay kit: R&D Systems, Inc, Minneapolis, USA). To estimate

1  
2  
3  
4 the concentrations of the bFGF solutions, solutions and standards were assayed in  
5  
6 duplicate according to the manufacturer's instructions. The test wavelength of each well  
7  
8 was set at 490 nm using a microplate reader (MTP-450 CORONA ELECTRIC Co., Ltd.,  
9  
10 Ibaragi, Japan) and compared to a reference wavelength of 650 nm. The bFGF  
11  
12 concentrations were determined by plotting their values on a standard curve. The amount  
13  
14 of bFGF released from the CGS was calculated at each time point.  
15  
16  
17  
18  
19  
20

#### 21 ***2.4. Pressure-induced ulcer model in diabetic mice***

22  
23 We prepared 40 genetically diabetic mice (Nine-week-old BKS.Cg-+ Leprdb/+  
24  
25 Leprdb/Jcl, CLEA Japan Inc, Osaka, Japan). All mice had their backs and abdomens  
26  
27 shaved and depilated under anesthesia with diethyl ether (Wako Pure Chemical Industries,  
28  
29 Osaka, Japan) and then were positioned on experimental tables. In our previous study, we  
30  
31 developed a pressure induced ulcer model using diabetic mice and a pneumatic compressor  
32  
33 (Kawai et al., 2005). In this study, 4 hours prolonged pressure (2h×2 pressure sessions;  
34  
35 2h interval between pressure sessions; 500 g/cm<sup>2</sup>) was loaded onto the area above the  
36  
37 femoral trochanters of the mice using a pneumatically driven compressor for two  
38  
39 consecutive days (EARTH MAN AC-20 OL, TAKAGI Co., Ltd. Japan, Niigata, Japan).  
40  
41 The air pressure was regulated with a precision regulator providing a constant pressure  
42  
43 level. Five days after the completion of the pressure loading, the area of necrosis was  
44  
45 clearly demarcated (Fig. 3A).  
46  
47  
48  
49  
50  
51  
52  
53  
54

#### 55 ***2.5. Impregnation of bFGF into CGS and the implantation of the CGS***

1  
2  
3  
4 We used CGS of 8mm in diameter and 3mm in thickness. As for the dosage of bFGF,  
5  
6 the recommended therapeutic dose of bFGF for chronic ulcers is  $1\mu\text{g}/\text{cm}^2$  per day (Uchi et  
7  
8 al., 2009). In a diabetic mouse study, the daily application of bFGF produced a similar  
9  
10 bell-shaped dose-response pattern with a peak at  $1\mu\text{g}/\text{cm}^2$  per day (Okumura et al., 1996).  
11  
12 This shows that the effective dosage of bFGF is not very different between humans and  
13  
14 diabetic mice. According to the daily bFGF dosage recommendations and a CGS release  
15  
16 period of about 10 days, we hypothesized that the optimal bFGF dosage for impregnating  
17  
18 the CGS ranged from  $7\mu\text{g}/\text{cm}^2$  to  $14\mu\text{g}/\text{cm}^2$  for 7 or 14 days. In this experiment, we  
19  
20 prepared CGS containing NSS or one of four different doses of bFGF (7, 14, 28, or  
21  
22  $50\mu\text{g}/\text{cm}^2$ ) as in the in vitro study and then incubated them overnight at  $4^\circ\text{C}$ .  
23  
24  
25  
26  
27

28 The mice were anesthetized via the intraperitoneal injection of 25mg/kg pentobarbital  
29  
30 (Abbott Laboratories, North Chicago, IL, USA) and the inhalation of diethyl ether (Wako  
31  
32 Pure Chemical Industries, LTD., Osaka, Japan). Five days after the completion of the  
33  
34 pressure loading, the necrotic tissues were resected, and skin defects of 8mm in diameter  
35  
36 were created using a 8mm-diameter skin punch biopsy tool (Kai industries, Gifu, Japan)  
37  
38 and scissors (Fig. 3B). CGS impregnated with NSS or bFGF solution were implanted into  
39  
40 the defects and sutured into the marginal skin wounds with 5-0 nylon sutures (Johnson &  
41  
42 Johnson K.K., Tokyo, Japan) (Fig. 3C). All wounds were covered with gauze and fixed in  
43  
44 place with adhesive tape (ALCARE<sup>®</sup>, ALCARE Co., LTD. Tokyo, Japan).  
45  
46  
47  
48  
49  
50  
51

## 52 ***2.6. Assessment of the wound area and histological assessment of neoeithelization***

53

54 One and two weeks after implantation, the mice were sacrificed via the inhalation of  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 carbon dioxide. After the removal of the silicone sheets, the wounds were photographed,  
5  
6 and the wound area was measured using the imaging analyzer ImageJ software (version  
7  
8 1.38, National Institutes of Health, USA). The wound area is expressed as a percentage of  
9  
10 the original wound area.  
11

12  
13  
14 The implanted CGS and dermis-like tissue were harvested using scalpels and scissors  
15  
16 and sectioned axially. Specimens were then fixed with 20% formalin fluid,  
17  
18 paraffin-embedded, and sliced into 4 $\mu$ m thick sections, before the sections were stained  
19  
20 with hematoxylin and eosin. Using a light microscope and NIS Elements (Nikon  
21  
22 Instruments Company, Tokyo, Japan), the neopithelium length of each specimen was  
23  
24 measured from the innermost hair root of the marginal skin to the end of the neopithelium  
25  
26 on each side of each cross-section at a magnification of x 100.  
27  
28  
29  
30  
31  
32

### 33 ***2.7. Immunohistological staining and evaluation of the area and number of newly*** 34 ***formed capillaries*** 35

36  
37 Using 4 $\mu$ m thick paraffin-embedded sections, immunohistological staining with von  
38  
39 Willebrand factor was performed to detect newly formed capillaries in the CGS. After the  
40  
41 sections had been dewaxed and rehydrated, they were incubated in PBS with 0.1% trypsin  
42  
43 (Vector Laboratories Inc., Burlingame, CA) for 15 minutes at 37°C for antigen retrieval.  
44  
45 Anti-Von Willebrand factor rabbit polyclonal antibody (DAKO Japan, Tokyo, Japan) was  
46  
47 used as the primary antibody (1: 500 dilutions), and EnVision+Rabbit/HRP (DAKO Japan,  
48  
49 Tokyo, Japan) was used as the secondary antibody. These sections were exposed to DAB  
50  
51 (3,3'-diaminobenzidine-4HCl) (DAKO Japan, Tokyo, Japan) for 2 minutes at room  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4  
5 temperature. Counterstaining was performed with hematoxylin.  
6

7 Digital light micrographs of the sections of the CGS and dermis-like tissue beyond the  
8 muscle layers were taken at a magnification of x 100. In each section, two square areas of  
9 500 $\mu$ m in width and height were chosen from the dermis-like tissues beneath the marginal  
10 skin. The area and number of newly formed capillaries in two squares in each section were  
11 measured twice. Using a microscope, we measured the epithelium length directly using  
12 NIS Elements. An assessment of neoepithelization and newly formed capillaries was also  
13 performed using NIS Elements.  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25

## 26 **2.8. Statistical analysis**

27 All data were analyzed using Fisher's protected least significant difference test (Fisher's  
28 PLSD) and expressed as the mean+standard error. A value of  $p < 0.05$  was accepted as  
29 significant.  
30  
31  
32  
33  
34  
35  
36  
37

## 38 **3. RESULTS**

### 39 **3.1. The degradation of CGS and basic FGF release in vitro**

40 The degradation rates of the CGS are shown as percentages compared to their original  
41 weight or their collagenase treated weight (Fig.1). The CGS were digested by collagenase  
42 throughout the degradation period. There were significant differences in the degradation  
43 rate at 1, 2, and 4 hours after the start of the degradation between the CGS impregnated  
44 with 50 $\mu$ g/cm<sup>2</sup> of bFGF and those containing 7 or 14 $\mu$ g/cm<sup>2</sup> of bFGF, but no significant  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 differences were seen at 6 hours after the start of the degradation. The time course of bFGF  
5 release from the CGS is shown in Fig.2. No initial burst of bFGF release from CGS was  
6  
7 observed; rather, the bFGF was continuously released throughout the degradation of the  
8  
9 CGS (Fig.2).  
10  
11  
12  
13  
14  
15

### 16 **3.2. Wound area**

17  
18 The gross appearance of the wounds at one and two weeks after implantation is shown in  
19 Fig. 4 and Fig.5. One week after implantation, the CGS in the NSS group were infected,  
20 whereas dermis-like tissue had begun to form in the wounds treated with the bFGF  
21 impregnated CGS (Fig. 4). Two weeks after the implantation, the CGS in the NSS group  
22 displayed implantation failure. In contrast, the wound areas covered with CGS containing 7  
23 or  $14\mu\text{g}/\text{cm}^2$  of bFGF had markedly reduced and were infection-free, and the wounds  
24 treated with  $14\mu\text{g}/\text{cm}^2$  of bFGF were almost completely epithelized (Fig. 5). In the wounds  
25 treated with CGS containing 28 or  $50\mu\text{g}/\text{cm}^2$  bFGF, dermis-like tissue had formed but  
26 epithelization had not proceeded as quickly as that seen in the wounds treated with CGS  
27 containing 7 or  $14\mu\text{g}/\text{cm}^2$  bFGF.  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41

42 The time course of the remaining wound area is shown in Fig. 6. One week after  
43 implantation, the wound area in the  $14\mu\text{g}/\text{cm}^2$  bFGF group was significantly smaller than  
44 that in the control group. Two weeks after implantation, the wound areas in the 7 and  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

### 3.3. *Histological assessment of neopithelium length*

Light microphotographs of the histological sections are shown in Fig. 7 and Fig.8. The low magnification image (x 40) shows the neopithelium, CGS, and marginal skin. The high magnification image (x 100) shows neopithelium formation. The neopithelium formation was especially marked in the 7 and 14 $\mu\text{g}/\text{cm}^2$  bFGF groups.

The time course of neopithelium length is shown in Fig. 9. One week after implantation, the neopithelial lengths in the 7 and 14 $\mu\text{g}/\text{cm}^2$  bFGF groups were significantly longer than those in the control group. Two weeks after implantation, the neopithelium length in the 14 $\mu\text{g}/\text{cm}^2$  bFGF group was significantly longer than those in the control and 50 $\mu\text{g}/\text{cm}^2$  bFGF groups.

### 3.4. *Evaluation of newly formed capillaries in the wounds*

Light microphotographs of newly formed capillaries stained with von Willebrand Factor are shown in Fig.10. The number of capillaries in the bFGF impregnated group was significantly larger than that in the NSS group, although no significant difference was observed among the bFGF impregnated groups (Fig. 11) . The capillary areas in the bFGF impregnated groups treated with 7, 14, or 28 $\mu\text{g}/\text{cm}^2$  bFGF were significantly larger than those in the control (almost 20 times larger) and 50 $\mu\text{g}/\text{cm}^2$  bFGF groups (almost 8 times larger). No significant difference was observed between the control and 50 $\mu\text{g}/\text{cm}^2$  bFGF groups (Fig. 12).

## 4. DISCUSSION

1  
2  
3  
4  
5  
6  
7 Chronic skin ulcers can result from diabetic neuropathy, pressure sores, venous  
8  
9 insufficiency, peripheral vascular disease, infectious disease, or acute surgical wounds in  
10  
11 cases in which the healing process is disturbed. Chronic skin ulcers have a significant  
12  
13 impact on public health through increased disability, morbidity, and mortality, all of which  
14  
15 increase the cost of healthcare (Ho et al., 2005). In patients suffering from these conditions,  
16  
17 diabetic foot ulcers are a leading cause of hospitalization and amputation. Many advanced  
18  
19 technologies, such as wound dressings, topical ointments, enzymatic debridement  
20  
21 compounds, and hyperbaric oxygen therapy, have been developed to improve the treatment  
22  
23 of chronic skin ulcers (Heyneman et al., 2008; Dunn et al., 2008; McCallon et al., 2008;  
24  
25 Collier et al., 2009; Baroni et al., 1987; Oriani et al., 1990; Kessler L et al., 2003, Ong M.  
26  
27 2008). Recently, due to advances in tissue engineering and cell culture techniques,  
28  
29 cultured skin substitutes have been used in the treatment of diabetic ulcers, pressure ulcers,  
30  
31 and venous leg ulcers (Karr et al., 2008; Ohara et al., 2010; Cervelli et al., 2010). Negative  
32  
33 pressure wound therapy such as Vacuum Assisted Closure (VAC) Therapy (KCI, Texas,  
34  
35 U.S.A.) involves the delivery of intermittent or continuous subatmospheric pressure,  
36  
37 thereby providing an occlusive environment in which wound healing can proceed under  
38  
39 moist, clean, and sterile conditions (Labanaris et al., 2009; Nather et al., 2010). In addition,  
40  
41 various growth factors such as basic FGF (Fu et al., 2002; Kurokawa et al., 2003),  
42  
43 PDGF-BB (platelet-derived growth factor (Bhansali et al., 2009), EGF (epidermal growth  
44  
45 factor) (Kim et al., 2010), and PRP (platelet-rich plasma) (Cervelli et al., 2009; Kathleen et  
46  
47 al., 2010) have been used for the clinical treatment of chronic wounds.  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60



1  
2  
3  
4  
5 A major clinical problem with the use of AD is their low resistance to infection when  
6 applied to chronic ulcers. We have attempted to experimentally impregnate AD with  
7 antibiotics or sulfadiazine silver to prevent infection; however, the clinical application of  
8 these techniques has not been actualized because there is a danger of the emergence of  
9 antibiotic-resistant bacteria or silver toxicity (Matsuda et al., 1991; Kawai et al., 2001).  
10  
11 Recently, the combination of AD and the daily application of bFGF was reported to  
12 accelerate granulation tissue formation during the treatment of uninfected chronic ulcers  
13 (Muneuchi et al., 2005; Ito et al., 2005; Akita et al., 2008). We previously reported that AD  
14 containing bFGF-impregnated gelatin microspheres (MS) sustained the release of  
15 biologically active bFGF, accelerated angiogenesis, and promoted dermis-like tissue  
16 formation (Tabata et al., 1999; Kawai et al., 2000; Kawai et al., 2005). This therapy did not  
17 require the daily application of bFGF; however, the injection of MS into AD is complicated  
18 and time consuming. Our CGS is a scaffold that can sustain the release of positively  
19 charged growth factors such as bFGF, PDGF-BB, and TGF- $\beta$  (transforming growth factor)  
20 (Takemoto et al., 2008). As for the optimal dosage of bFGF to impregnate into CGS, it is  
21 reported that bFGF forms a polyion complex with acidic gelatin at a bFGF/ gelatin molar  
22 ratio of 1/1 (Muniruzzaman et al., 1998). Therefore, our CGS was able to sustain a bFGF  
23 concentration of more than  $60\mu\text{g}/\text{cm}^2$  depending on the gelatin content of the CGS. In our  
24 previous study, we achieved the sustained release of bFGF from CGS impregnated with  $20$   
25  $\mu\text{g}/\text{cm}^2$  bFGF. In this study, we confirmed that CGS is able to sustain bFGF at  
26 concentrations ranging from  $7\mu\text{g}/\text{cm}^2$  to  $50\mu\text{g}/\text{cm}^2$  during its biodegradation (Fig.2).  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53

54 It has been reported that the dose-effect relationship of bFGF is bell-shaped (Okumura et  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 al., 1996; Motomura et al., 2008; Uchi et al., 2009). In a clinical study of diabetic foot  
5  
6 ulcers, Uchi reported that the bFGF showed a bell-shaped dose-response pattern with a  
7  
8 peak at  $1\mu\text{g}/\text{cm}^2$  bFGF per day (Uchi et al., 2009). In our previous studies, we compared the  
9  
10 wound healing processes induced by various bFGF concentrations. In our previous study in  
11  
12 which we created skin defects in C57BL mice, CGS impregnated with  $7\mu\text{g}/\text{cm}^2$  of bFGF  
13  
14 accelerated dermis-like tissue formation the most, and CGS impregnated with  $14\mu\text{g}/\text{cm}^2$  of  
15  
16 bFGF had the second strongest effect. However, the application of CGS impregnated with  
17  
18  $50\mu\text{g}/\text{cm}^2$  bFGF did not accelerate wound healing (Kanda et al., 2011 Jul 5. [Epub ahead of  
19  
20 print]). In another study in which palatal mucosal defects were created in beagles, CGS  
21  
22 impregnated with  $7\mu\text{g}/\text{cm}^2$  of bFGF also accelerated the tissue regeneration the most, and  
23  
24  $14\mu\text{g}/\text{cm}^2$  of bFGF had the second strongest effect (Artem et al., 2011 Jul 23. [Epub ahead  
25  
26 of print]). According to these results, we considered that a bFGF concentration of between  
27  
28  $7\mu\text{g}/\text{cm}^2$  and  $14\mu\text{g}/\text{cm}^2$  would be optimal for accelerating wound healing.  
29  
30  
31  
32  
33  
34

35  
36 In this study, as expected, CGS impregnated with 7 or  $14\mu\text{g}/\text{cm}^2$  of bFGF accelerated  
37  
38 dermis-like tissue formation, and CGS containing  $14\mu\text{g}/\text{cm}^2$  of bFGF produced a  
39  
40 significant reduction in the remaining wound area compared with CGS impregnated with  
41  
42  $7\mu\text{g}/\text{cm}^2$  bFGF. The remaining wound area, neoeepithelium length, and area of newly  
43  
44 formed capillaries in the wounds treated with CGS containing  $50\mu\text{g}/\text{cm}^2$  bFGF were  
45  
46 significantly inferior to those of the wounds treated with CGS containing 7 or  $14\mu\text{g}/\text{cm}^2$   
47  
48 bFGF. It has been reported that treatment with an excess amount of bFGF prolonged  
49  
50 wound closure in diabetic mice and prevented keratinocyte proliferation in vitro (Okumura  
51  
52 et al., 1996; Motomura et al., 2008). CGS impregnated with  $50\mu\text{g}/\text{cm}^2$  of bFGF released a  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 persistently high dose of bFGF throughout their biodegradation, which might have  
5 inhibited the formation of the neoeepithelium and capillaries. Our results regarding the  
6 degradation rate of CGS suggest that  $50\mu\text{g}/\text{cm}^2$  bFGF inhibits the activity of collagenase.  
7 This inhibition might prolong the biodegradation of CGS and hence bFGF release in vivo  
8 and so have an adverse effect on wound healing.  
9  
10  
11  
12  
13  
14  
15

16 Our CGS containing bFGF showed resistance to infection. Some combination therapies  
17 have been reported to solve the problem of the lower resistance of AD to infection.  
18 Combination therapy involving AD (Integra<sup>®</sup>, Integra LifeSciences Corp., Plainsboro, NJ,  
19 USA) and the VAC Therapy System has been reported to be effective at increasing  
20 granulation tissue formation (Molnar et al., 2004; Pollard et al., 2008). This therapy does  
21 not require daily treatment, but does need a specialized pump to maintain a constant  
22 negative pressure, and the patient's movements are restricted by the device. As another  
23 combination therapy, AD seeded with autologous or allogeneic cultured fibroblasts has  
24 been reported to be effective at accelerating granulation tissue formation. The fibroblasts  
25 contained in the AD release various growth factors and extracellular matrix molecules and  
26 accelerate wound healing (Ohara et al., 2010). Kuroyanagi reported that spongy collagen  
27 containing allogeneic fibroblasts was an effective therapy for patients with intractable skin  
28 ulcers including burns, venous ulcers, and autoimmune disease (Kuroyanagi et al., 2001).  
29 Although tissue-engineered substitutes are attractive, some problems remain, such as the  
30 possibility of disease transmission, unfavorable immune and local inflammatory reactions  
31 and their high cost, the latter of which is very important from a clinical perspective.  
32 Tissue-engineered skin substitutes, such as Dermagraft<sup>®</sup> (Advanced Tissue Sciences, Inc,  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

1  
2  
3  
4 USA.), Transcyte® (Advanced Tissue Sciences, USA.), and Aprigraf® (Organogenesis,  
5  
6 Inc., Canton, MA, USA and Novartis Pharmaceuticals Corp, USA.) are expensive, and  
7  
8 access to these treatments is limited in many parts of the world (Eran et al., 2006). CGS is  
9  
10 cheap compared with AD, and bFGF is cheaper than treatment with the VAC Therapy  
11  
12 System or living cells. The procedure for our novel combination therapy involving CGS  
13  
14 and bFGF is simple; i.e., bFGF is sprayed onto the CGS just before their application.  
15  
16

17  
18 Basic FGF has not been authorized for use in most countries. The acidic gelatin  
19  
20 contained in CGS can sustain the release of not only bFGF but also other positively  
21  
22 charged growth factors such as PDGF-BB and TGF- $\beta$  (transforming growth factor- $\beta$ )  
23  
24 found in PRP (Hong et al., 2000; Kanematsu et al., 2004). PRP can be prepared from a  
25  
26 patient's blood and PL (platelet lysate) produced from donated platelets (Mirabet et al.,  
27  
28 2008). When bFGF can not be used, combination therapy involving CGS and autologous  
29  
30 or allogeneic PRP is an alternative.  
31  
32  
33

34  
35 Recently, tissue engineering has been recognized as a newly emerging biomedical  
36  
37 technology for regenerating and repairing body defects using various combinations of cells,  
38  
39 scaffolds, and growth factors (Tsuji-Saso et al., 2007). Collagen sponge scaffolds are one  
40  
41 of the most common scaffolds, and it has been reported that collagen scaffolds treated with  
42  
43 growth factors are effective at regenerating various kinds of tissues such as the dermis,  
44  
45 epidermis, fat, bone, and cartilage (Langer et al., 2007; Kimura et al., 2010; Nishizawa et  
46  
47 al., 2010). Our CGS, which is capable of the sustained release of positively charged growth  
48  
49 factors, is useful as a scaffold for tissue engineering.  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

## CONCLUSIONS

CGS impregnated with bFGF at concentrations ranging from  $7\mu\text{g}/\text{cm}^2$  to  $14\mu\text{g}/\text{cm}^2$  accelerated wound healing in decubitus ulcer models involving diabetic mice, and an excess amount of bFGF did not increase their wound-healing efficacy. Our CGS is a novel scaffold that can sustain the release of positively charged growth factors such as bFGF. Combination therapy involving CGS and bFGF or PRP is a promising strategy for the treatment of chronic skin ulcers.

## ACKNOWLEDGMENT

This work was supported by a grant from the Japan Science and Technology Agency.

## REFERENCES

- Artem A, Naoki M, Norikazu K , et al. 2011; Collagen-gelatin scaffold impregnated with bFGF accelerates palatal wound healing of palatal mucosa in dogs. *Journal of Surgical Research J Surg Res*. Jul 23. [Epub ahead of print].
- Akita S, Akino K, Tanaka K , et al. 2008; A basic fibroblast growth factor improves lower extremity wound healing with a porcine-derived skin substitute. *J Trauma* **64**(3): 809-815.
- Bhansali A, Venkatesh S, Dutta P, et al. 2009; Which is the better option: recombinant human PDGF-BB 0.01% gel or standard wound care, in diabetic neuropathic large

1  
2  
3  
4  
5  
6  
7  
8  
9  
10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60

plantar ulcers off-loaded by a customized contact cast? *Diabetes Res Clin Pract* **83**(1): e13-16.

Baroni G, Porro T, Faglia E, et al. 1987; Hyperbaric oxygen in diabetic gangrene treatment. *Diabetes Care* **10**(1): 81-86.

Cervelli V, Gentile P, Scioli MG, et al. 2009; Application of platelet-rich plasma in plastic surgery: clinical and in vitro evaluation. *Tissue Eng Part C Methods* **15**(4): 625-634.

Cervelli V, Lucarini L, Cerretani C, et al. 2010; The use of Matriderm and autologous skin grafting in the treatment of diabetic ulcers: a case report. *Int Wound J* **7**(4): 291-296.

Collier M. 2009; Silver dressings: more evidence is needed to support their widespread clinical use. *J Wound Care* **18**(2): 77-78.

Dunn R, Dolianitis C. 2008; Prolidase deficiency: the use of topical proline for treatment of leg ulcers. *Australas J Dermatol* **49**(4): 237-238.

Eran B, David M, Eyal W. 2006; SKINSUBSTITUTES. *IMAJ* **8**: 188-191.

Fu X, Shen Z, Guo Z, et al. 2002; Healing of chronic cutaneous wounds by topical treatment with basic fibroblast growth factor. *Chin Med J (Engl)* **115**(3): 331-335.

Gospodarowicz D. 1974; Localization of a fibroblast growth factor and its effect alone and with hydrocortisone on 3T3 cell growth. *Nature* **249**(453): 123-127.

Heyneman A, Beele H, Vanderwee K, et al. 2008; A systematic review of the use of hydrocolloids in the treatment of pressure ulcers. *J Clin Nurs* **17**(9): 1164-1173.

Ho C, Tran K, Hux M, et al. 2005; Artificial skin grafts in chronic wound care: A meta-analysis of clinical efficacy and a review of cost-effectiveness. In *Technology Report*, **52**.

- 1  
2  
3  
4 Hong L, Tabata Y, Miyamoto S, et al. 2000; Bone regeneration at rabbit skull defects  
5 treated with transforming growth factor-beta1 incorporated into hydrogels with different  
6 levels of biodegradability. *J Neurosurg* **92**(2): 315-325.  
7  
8  
9  
10  
11 Ito K, Ito S, Sekine M , et al. 2005; Reconstruction of the soft tissue of a deep diabetic foot  
12 wound with artificial dermis and recombinant basic fibroblast growth factor. *Plast*  
13 *Reconstr Surg* **115**(2): 567-572.  
14  
15  
16  
17  
18 Kanematsu A, Yamamoto S, Ozeki M, et al. 2004; Collagenous matrices as release  
19 carriers of exogenous growth factors. *Biomaterials* **25**(18): 4513-4520.  
20  
21  
22  
23  
24 Karr J. 2008; Utilization of living bilayered cell therapy (Apligraf) for heel ulcers. *Adv*  
25 *Skin Wound Care* **21**(6): 270-274.  
26  
27  
28  
29 Kathleen M, Lacci, M, PA-C, et al. 2010; Platelet-Rich Plasma: Support for Its Use in  
30 Wound Healing. *Yale J Biol Med* **83**(1): 1-9.  
31  
32  
33  
34 Kawai K, Suzuki S, Tabata Y , et al. 2000; Accelerated tissue regeneration through  
35 incorporation of basic fibroblast growth factor-impregnated gelatin microspheres into  
36 artificial skin, *Biomaterials* **21**(5); 489-499.  
37  
38  
39  
40  
41 Kawai K, Suzuki S, Tabata Y, et al. 2001; Development of an artificial dermis preparation  
42 capable of silver sulfadiazine release. *J Biomed Mater Res* **57**(3): 346-356.  
43  
44  
45  
46  
47 Kawai K, Suzuki S, Tabata Y, et al. 2005; Accelerated wound healing through the  
48 incorporation of basic fibroblast growth factor-impregnated gelatin microspheres into  
49 artificial dermis using a pressure-induced decubitus ulcer model in genetically diabetic  
50 mice. *Br J Plast Surg* **58**(8): 1115-1123.  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60 Kanda N, Morimoto N, Takemoto S, et al. 2011; Efficacy of Novel Collagen/Gelatin

1  
2  
3  
4 Scaffold With Sustained Release of Basic Fibroblast Growth Factor for Dermis-like  
5  
6 Tissue Regeneration. *Ann Plast Surg.* Jul 5. [Epub ahead of print].  
7  
8

9  
10 Kessler L, Bilbault P, Ortéga F, et al. 2003; Hyperbaric oxygenation accelerates the healing  
11  
12 rate of nonischemic chronic diabetic foot ulcers. *Diabetes Care* **26**(8): 2378-2382.  
13

14  
15 Kim YS, Lew DH, Tark KC, et al. 2010; Effect of recombinant human epidermal growth  
16  
17 factor against cutaneous scar formation in murine full-thickness wound healing. *J*  
18  
19 *Korean Med Sci* **25**(4): 589-596.  
20

21  
22 Kimura Y, Tsuji W, Yamashiro H, et al. 2010; In situ adipogenesis in fat tissue augmented  
23  
24 by collagen scaffold with gelatin microspheres containing basic fibroblast growth factor.  
25  
26 *J Tissue Eng Regen Med* **4**(1): 55-61.  
27

28  
29 Kurokawa I, Hayami J, Kita Y. 2003; A therapy-resistant chronic leg ulcer treated  
30  
31 successfully with topical basic fibroblast growth factor. *J Int Med Res* **31**(2): 149-151.  
32

33  
34 Kuroyanagi Y, Yamada N, Yamashita R, et al. 2001; Tissue-engineered product:  
35  
36 allogeneic cultured dermal substitute composed of spongy collagen with fibroblasts.  
37  
38 *Artif Organs* **25**(3): 180-186.  
39

40  
41 Labanaris AP, Polykandriotis E, Horch RE. 2009; The effect of vacuum-assisted closure  
42  
43 on lymph vessels in chronic wounds. *J Plast Reconstr Aesthet Surg* **62**(8): 1068-1075.  
44

45  
46 Langer R. 2007; Tissue engineering: Perspectives, challenges, and future directions. *Tissue*  
47  
48 *Eng* **13**(1): 1-2.  
49

50  
51 **Matsuda K, Suzuki S, Isshiki N. 1992; Evaluation of a bilayer artificial skin capable of**  
52  
53 **sustained release of an antibiotic. *Biomaterials* **13**(2): 119-122**  
54

55  
56 Matsuda K, Suzuki S, Isshiki N, et al. 1991; A bilayer "artificial skin" capable of sustained  
57  
58  
59  
60



1  
2  
3  
4  
5 release of an antibiotic. *Br J Plast Surg* **44**(2): 142-146.

6  
7 **Matsuda K, Suzuki S, Ihiki N. 1988; Experiments on sustained release of an antibiotic**  
8  
9 **from bilayer artificial skin. *Japanese Journal of Burn Injuries* **14**: 202.**

10  
11  
12  
13  
14  
15  
16  
17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
McCallon SK, Hurlow J. 2009; Clinical applications for the use of enzymatic debriding ointment and broad-spectrum bacteriostatic foam dressing. *J Wound Ostomy Contenance Nurs* **36**(6 Suppl): S17-24.

Mirabet V, Solves P, Miñana MD, et al. 2008; Human platelet lysate enhances the proliferative activity of cultured human fibroblast-like cells from different tissues. *Cell Tissue Bank* **9**(1): 1-10.

Molnar JA, DeFranzo AJ, Hadaegh A , et al. 2004; Acceleration of Integra incorporation in complex tissue defects with subatmospheric pressure. *Plast Reconstr Surg* **113**(5): 1339-1346.

Motomura K, Hagiwara A, Komi-Kuramochi A , et al. 2008; An FGF1:FGF2 chimeric growth factor exhibits universal FGF receptor specificity, enhanced stability and augmented activity useful for epithelial proliferation and radioprotection. *Biochim Biophys Acta* **1780**(12): 1432-1440.

Muneuchi G, Suzuki S, Moriue T , et al. 2005; Combined treatment using artificial dermis and basic fibroblast growth factor (bFGF) for intractable fingertip ulcers caused by atypical burn injuries. *Burns* **31**(4): 514-517.

Muniruzzaman, Tabata Y, Ikada Y. 1998; Complexation of basic fibroblast growth factor with gelatin. *J Biomater Sci Polym Ed* **9**(5): 459-473.

Nather A, Chionh SB, Han AY, et al. 2010 , et al. Effectiveness of vacuum-assisted closure

(VAC) therapy in the healing of chronic diabetic foot ulcers. *Ann Acad Med Singapore* **39**(5): 353-358.

Nishizawa K, Imai S, Mimura T, et al. 2010; In-advance trans-medullary stimulation of bone marrow enhances spontaneous repair of full-thickness articular cartilage defects in rabbits. *Cell Tissue Res* **341**(3): 371-379.

Ohara N, Mihara S, Nihara H, et al. 2010; A case of lower-extremity deep burn wounds with periosteal necrosis successfully treated by use of allogenic cultured dermal substitute. *J Artif Organs* **13**(2): 101-105.

Okumura M, Okuda T, Nakamura T, et al. 1996; Acceleration of wound healing in diabetic mice by basic fibroblast growth factor. *Biol Pharm Bull* **19**(4): 530-535.

Ong M. 2008; Hyperbaric oxygen therapy in the management of diabetic lower limb wounds. *Singapore Med J* **49**(2): 105-109.

Oriani G, Meazza D, Favales F, et al. 1990; Hyperbaric oxygen therapy in diabetic gangrene. *J Hyperb Med* **5**(3): 171-175.

Pollard RL, Kennedy PJ, Maitz PK. 2008; The use of artificial dermis (Integra) and topical negative pressure to achieve limb salvage following soft-tissue loss caused by meningococcal septicaemia. *J Plast Reconstr Aesthet Surg* **61**(3): 319-322.

Suzuki S, Matsuda K, Isshiki N, et al. 1990a; Clinical evaluation of a new bilayer 'artificial skin' composed of collagen sponge and silicone layer. *Br J Plast Surg* **43**(1): 47-54.

Suzuki S, Matsuda K, Isshiki N, et al. 1990b; Experimental study of a newly developed bilayer artificial skin. *Biomaterials* **11**(5): 356-360.

Tabata Y, Nagano A, Ikada Y. 1999; Biodegradation of hydrogel carrier incorporating

1  
2  
3  
4 fibroblast growth factor. *Tissue Eng* **5**(2): 127-138.

5  
6  
7 Takemoto S, Morimoto N, Kimura Y , et al. 2008; Preparation of collagen/gelatin sponge  
8  
9 scaffold for sustained release of bFGF. *Tissue Eng* **14**(10): 1629-1638.

10  
11  
12 Tsuji-Saso Y, Kawazoe T, Morimoto N, et al. 2007; Incorporation of basic fibroblast  
13  
14 growth factor into preconfluent cultured skin substitute to accelerate neovascularisation  
15  
16 and skin reconstruction after transplantation. *Scand J Plast Reconstr Surg Hand Surg*  
17  
18 **41**(5): 228-35.

19  
20  
21 Uchi H, Igarashi A, Urabe K, et al. 2009; Clinical efficacy of basic fibroblast growth factor  
22  
23 (bFGF) for diabetic ulcer. *Eur J Dermatol* **19**(5): 461-468.

24  
25  
26 Yannas IV, Burke JF, Gordon PL, et al. 1980; Design of an artificial skin. II. Control of  
27  
28 chemical composition. *Biomed Mater Res* **14**(2): 107-132.

Degradation rate of CGS

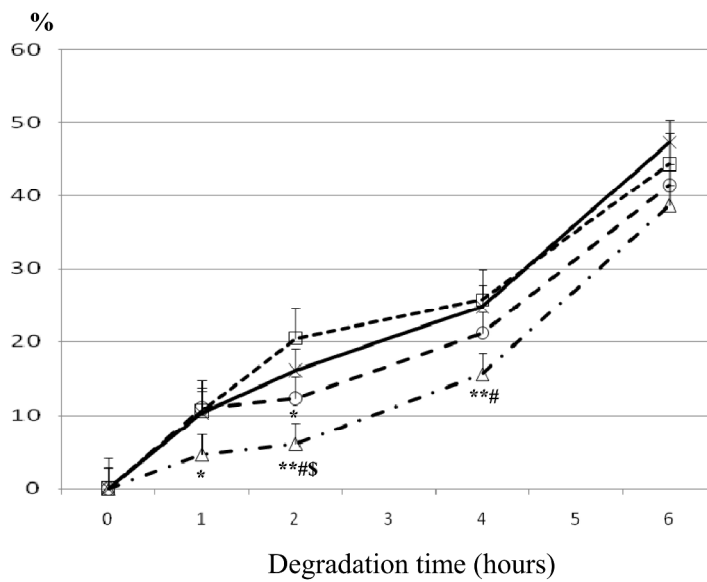


Fig.1. Time course of the degradation of CGS by collagenase. CGS were impregnated with 7 $\mu\text{g}/\text{cm}^2$  (□), 14 $\mu\text{g}/\text{cm}^2$  (×) 28 $\mu\text{g}/\text{cm}^2$  (○), or 50  $\mu\text{g}/\text{cm}^2$  of bFGF (Δ). \* $p < 0.05$ , \*\* $p < 0.01$  versus 7 $\mu\text{g}/\text{cm}^2$  of bFGF; # $p < 0.01$  versus 14 $\mu\text{g}/\text{cm}^2$  of bFGF. \$ $p < 0.05$  versus 28 $\mu\text{g}/\text{cm}^2$  of bFGF.  
297x420mm (300 x 300 DPI)

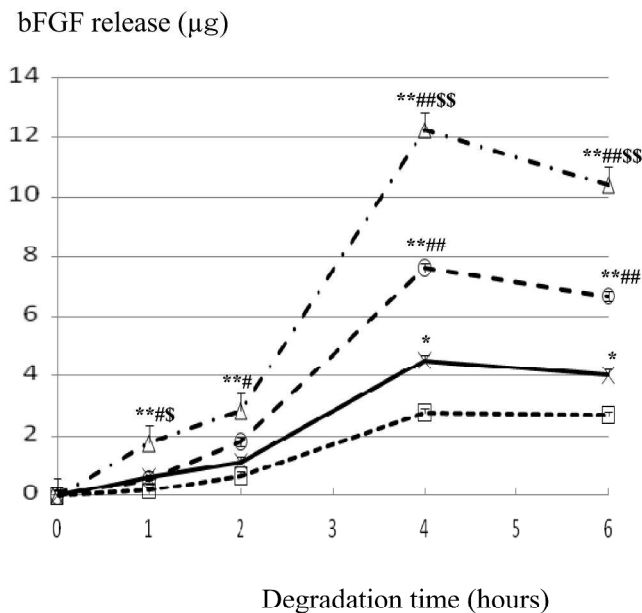


Fig. 2. Time course of bFGF release from CGS. CGS were impregnated with 7 µg/cm<sup>2</sup> (□), 14 µg/cm<sup>2</sup> (×), 28 µg/cm<sup>2</sup> (○), or 50 µg/cm<sup>2</sup> of bFGF (Δ). \*p<0.05, \*\*p<0.01 versus 7 µg/cm<sup>2</sup> of bFGF; #p<0.05, ##p<0.01 versus 14 µg/cm<sup>2</sup> of bFGF. \$p<0.05, \$\$p<0.01 versus 28 µg/cm<sup>2</sup> of bFGF.  
297x420mm (300 x 300 DPI)

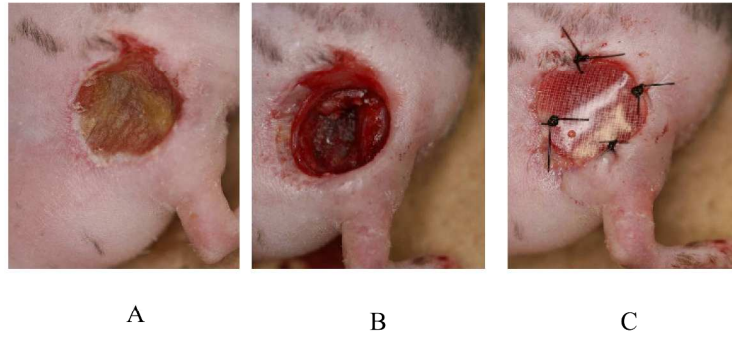
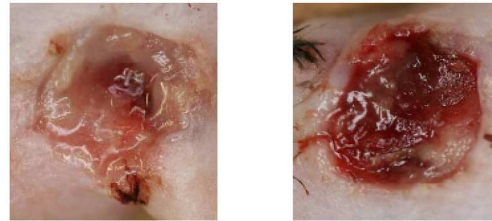


Fig. 3. (A) The gross appearance of the decubitus ulcers at 5 days after the completion of the pressure loading.

(B) The necrotic tissue was resected.

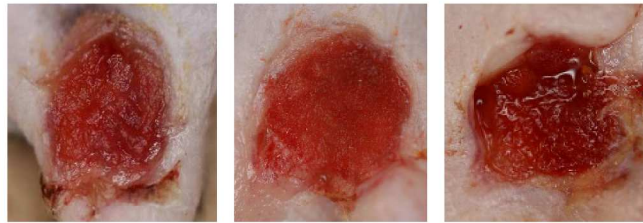
(C) The CGS were implanted into the defect and sutured in place.

297x420mm (300 x 300 DPI)



A

B



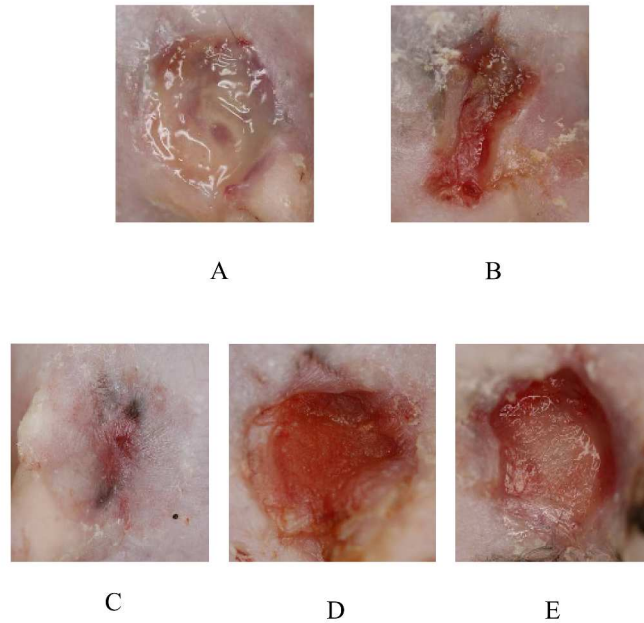
C

D

E

Fig. 4. Gross appearance of the wounds at one week after CGS implantation. The wounds were treated with CGS impregnated with NSS (A) or  $7\mu\text{g}/\text{cm}^2$  (B),  $14\mu\text{g}/\text{cm}^2$  (C),  $28\mu\text{g}/\text{cm}^2$  (D), or  $50\mu\text{g}/\text{cm}^2$  of bFGF (E). One week after implantation, the CGS impregnated with NSS were infected, whereas dermis-like tissue had begun to form in the wounds treated with the bFGF impregnated CGS.

297x420mm (300 x 300 DPI)



---

Fig. 5. Gross appearance of the wounds at two weeks after CGS implantation. The wounds were treated with CGS impregnated with NSS (A) or  $7\mu\text{g}/\text{cm}^2$  (B),  $14\mu\text{g}/\text{cm}^2$  (C),  $28\mu\text{g}/\text{cm}^2$  (D), or  $50\mu\text{g}/\text{cm}^2$  of bFGF (E). Two weeks after implantation, the CGS impregnated with NSS had become infected and degraded. In contrast, the wound areas covered with CGS containing 7 or  $14\mu\text{g}/\text{cm}^2$  of bFGF had markedly reduced without infection. The wounds treated with  $14\mu\text{g}/\text{cm}^2$  of bFGF had become almost completely epithelized. 297x420mm (300 x 300 DPI)



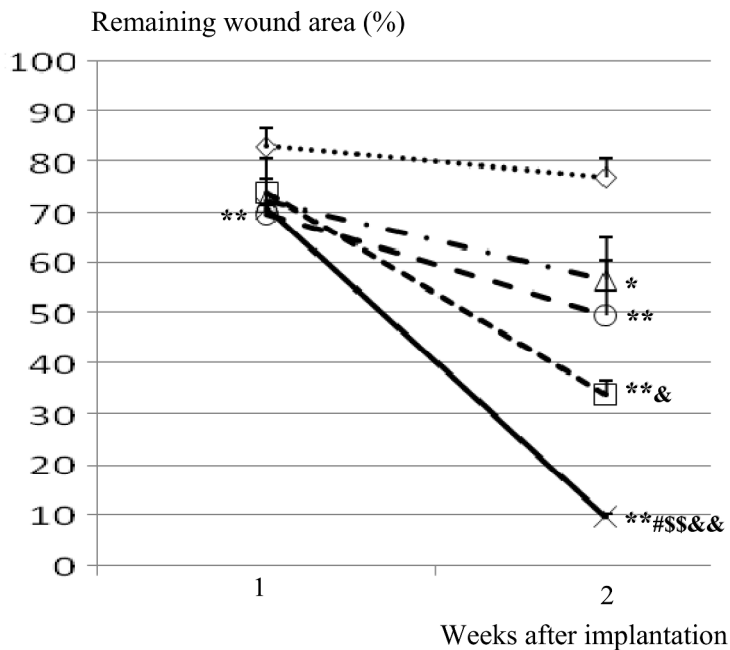


Fig. 6. Time course of the remaining wound area. Wounds treated with CGS impregnated with NSS (□) or 7µg/cm<sup>2</sup> (□), 14µg/cm<sup>2</sup> (×), 28µg/cm<sup>2</sup> (○), or 50µg/cm<sup>2</sup> of bFGF (△). \*p<0.05, \*\*p<0.01 versus NSS; #p<0.05, ##p<0.01 versus 7µg/cm<sup>2</sup> of bFGF. \$p<0.05, \$\$p<0.01 versus 28µg/cm<sup>2</sup> of bFGF. &p<0.05, &&p<0.01 versus 50µg/cm<sup>2</sup> of bFGF.

One week after implantation, the wound area in the group treated with CGS containing 14µg/cm<sup>2</sup> bFGF was significantly smaller than that in the control group. Two weeks after implantation, the wound areas in the groups treated with CGS impregnated with 7 or 14µg/cm<sup>2</sup> bFGF were significantly smaller than those in the control and CGS with 50µg/cm<sup>2</sup> of bFGF groups.

297x420mm (300 x 300 DPI)

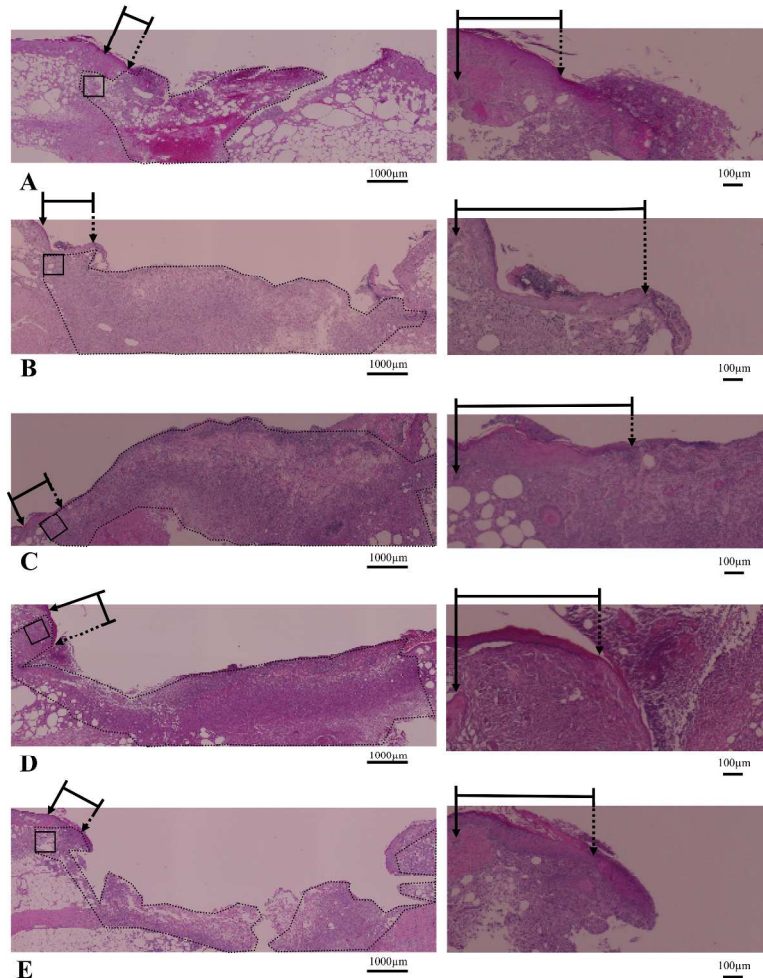


Fig. 7. Hematoxylin and eosin stained sections of wounds at one week after implantation. The wounds were treated with CGS impregnated with NSS (A) or  $7\mu\text{g}/\text{cm}^2$  (B),  $14\mu\text{g}/\text{cm}^2$  (C),  $28\mu\text{g}/\text{cm}^2$  (D), or  $50\mu\text{g}/\text{cm}^2$  of bFGF (E). The low magnification image (original magnification  $\times 40$ , left side) shows a whole image of the implanted CGS. The area of remaining CGS is indicated by a broken line. The square bounded by solid lines shows the area used for the immunohistological staining of newly formed capillaries. The high magnification image (original magnification  $\times 100$ , right side) shows the newly formed epithelium on the left side. The black arrow with the solid line indicates the hair root. The black arrow with the broken line indicates the end of the neoepithelium. The neoepithelium is shown in the upper section as a black line that is closed at both ends.

297x420mm (300 x 300 DPI)

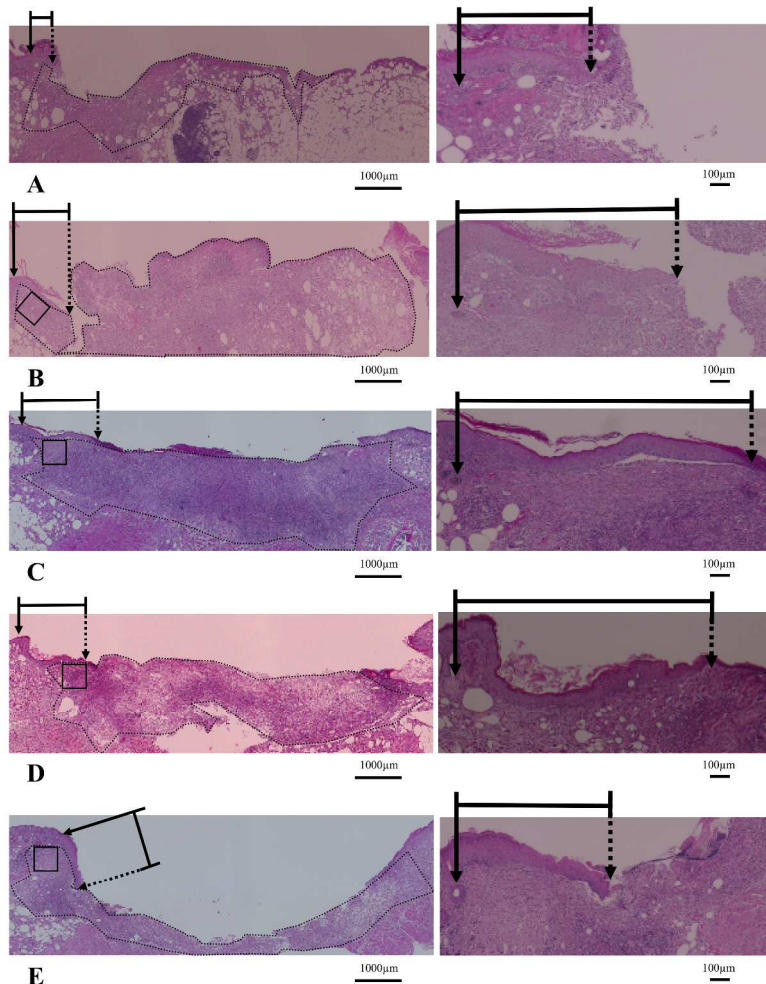


Fig.8. Hematoxylin and eosin stained wound sections at two weeks after implantation. The wounds were treated with CGS impregnated with NSS (A) or  $7\mu\text{g}/\text{cm}^2$  (B),  $14\mu\text{g}/\text{cm}^2$  (C),  $28\mu\text{g}/\text{cm}^2$  (D), or  $50\mu\text{g}/\text{cm}^2$  of bFGF (E). The low magnification image (original magnification  $\times 40$ , left side) shows a whole image of the implanted CGS. The two black solid squares ( $500\mu\text{m}$  in width and height) show the area of the CGS in which the area and number of newly formed capillaries were investigated. The area of remaining CGS is surrounded by a broken line. The square bounded by solid lines shows the area used for the immunohistological staining of newly formed capillaries. The high magnification image (original magnification  $\times 100$ , right side) shows the newly formed epithelium on the left side. The black arrow with the solid line indicates the hair root. The black arrow with the broken line indicates the edge of the epithelium. The neopithelium is shown in the upper section as a black line that is closed at both ends.

297x420mm (300 x 300 DPI)

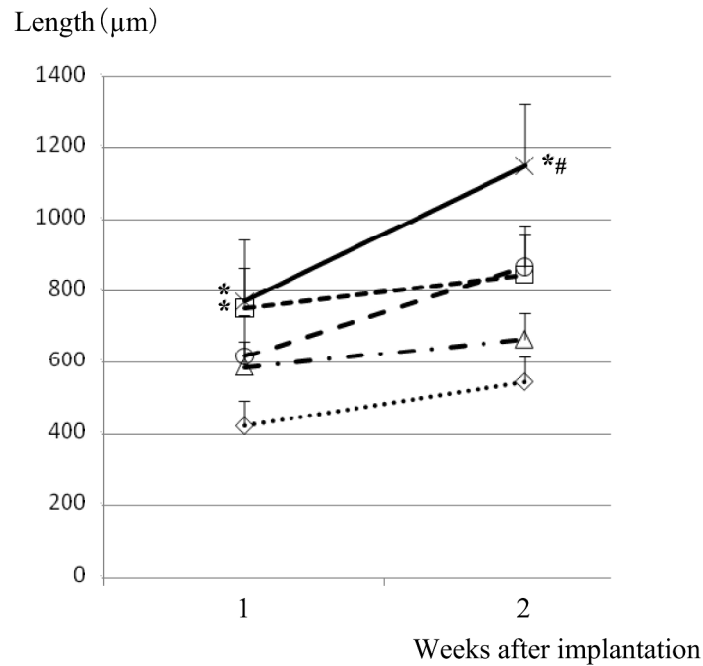


Fig. 9. Time course of neopithelium length. Wounds treated with CGS impregnated with NSS (◇) or 7 μg/cm<sup>2</sup> (□), 14 μg/cm<sup>2</sup> (×), 28 μg/cm<sup>2</sup> (○), or 50 μg/cm<sup>2</sup> of bFGF (△). \*p<0.01 versus NSS, #p<0.01 versus 50 μg/cm<sup>2</sup> of bFGF. One week after implantation, the neopithelial lengths in the wounds treated with 7 μg/cm<sup>2</sup> or 14 μg/cm<sup>2</sup> of bFGF were significantly longer than that of the control group. Two weeks after implantation, the neopithelium length of the wounds treated with 14 μg/cm<sup>2</sup> of bFGF was significantly longer than those of the control group and the group treated with 50 μg/cm<sup>2</sup> of bFGF.

297x420mm (300 x 300 DPI)

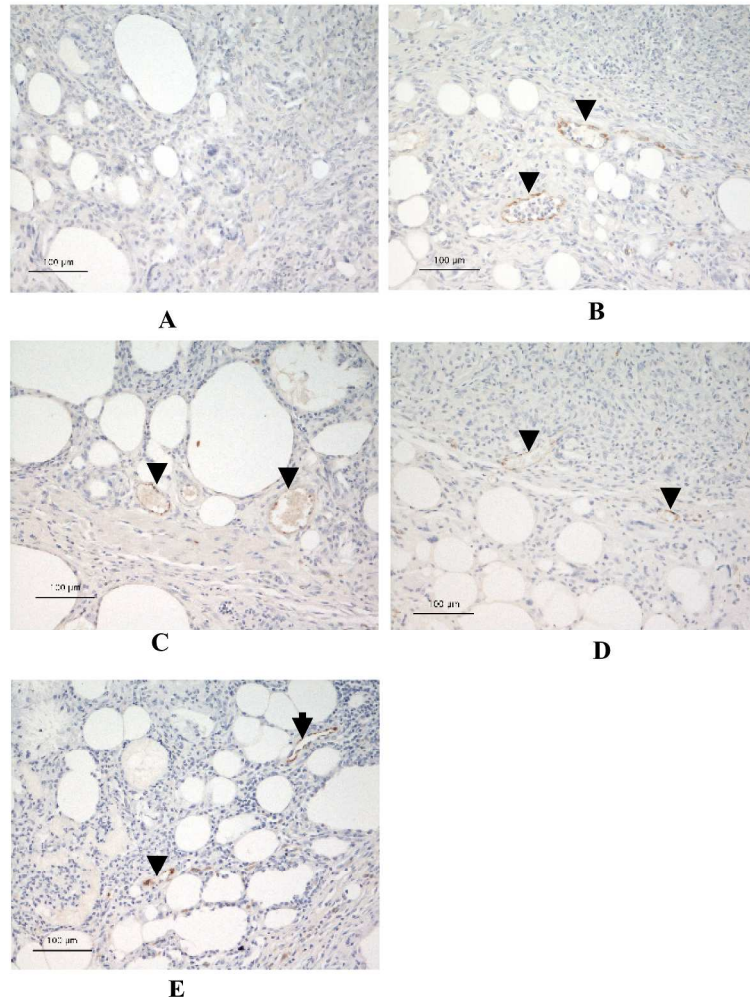
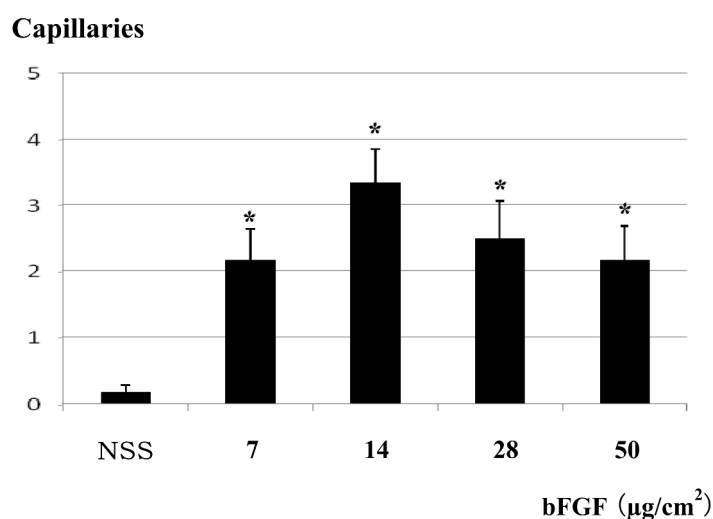


Fig. 10. Immunohistological staining of CGS two weeks after implantation. The newly formed capillaries were immunostained with Von Willebrand Factor (original magnification  $\times 200$ ). CGS with NSS (A),  $7\mu\text{g}/\text{cm}^2$  of bFGF (B),  $14\mu\text{g}/\text{cm}^2$  of bFGF (C),  $28\mu\text{g}/\text{cm}^2$  of bFGF (D), and  $50\mu\text{g}/\text{cm}^2$  of bFGF (E). The black arrowheads indicate capillaries.  
297x420mm (300 x 300 DPI)



46 Fig.11. The area of newly formed capillaries immunostained with Von Willebrand Factor (two weeks after  
47 implantation).

48 CGS treated with NSS or  $7\mu\text{g}/\text{cm}^2$ ,  $14\mu\text{g}/\text{cm}^2$ ,  $28\mu\text{g}/\text{cm}^2$ , or  $50\mu\text{g}/\text{cm}^2$  of bFGF. \* $p < 0.01$  versus NSS ;  
49 # $p < 0.01$  versus  $50\mu\text{g}/\text{cm}^2$  bFGF.

50 The area of newly formed capillaries in the group treated with CGS impregnated with  $7\mu\text{g}/\text{cm}^2$  bFGF was  
51 significantly larger than those in the control group and the group treated with CGS impregnated with  
52  $50\mu\text{g}/\text{cm}^2$  of bFGF. The areas of newly formed capillaries in the groups treated with CGS impregnated with  
53  $14\mu\text{g}/\text{cm}^2$  or  $28\mu\text{g}/\text{cm}^2$  bFGF were significantly larger than that in the control group.

54  
55 297x420mm (300 x 300 DPI)