Stabilization, Rolling, and Addition of Other Extracellular Matrix Proteins to Collagen Hydrogels Improve Regeneration in Chitosan Guides for Long Peripheral Nerve Gaps in Rats

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BACKGROUND: Autograft is still the gold standard technique for the repair of long peripheral nerve injuries. The addition of biologically active scaffolds into the lumen of conduits to mimic the endoneurium of peripheral nerves may increase the final outcome of artificial nerve devices. Furthermore, the control of the orientation of the collagen fibers may provide some longitudinal guidance architecture providing a higher level of mesoscale tissue structure.

OBJECTIVE: To evaluate the regenerative capabilities of chitosan conduits enriched with extracellular matrix-based scaffolds to bridge a critical gap of 15 mm in the rat sciatic nerve.

METHODS: The right sciatic nerve of female Wistar Hannover rats was repaired with chitosan tubes functionalized with extracellular matrix-based scaffolds fully hydrated or stabilized and rolled to bridge a 15 mm nerve gap. Recovery was evaluated by means of electrophysiology and algesimetry tests and histological analysis 4 months after injury.

RESULTS: Stabilized constructs enhanced the success of regeneration compared with fully hydrated scaffolds. Moreover, fibronectin-enriched scaffolds increased muscle reinnervation and number of myelinated fibers compared with laminin-enriched constructs.

CONCLUSION: A mixed combination of collagen and fibronectin may be a promising internal filler for neural conduits for the repair of peripheral nerve injuries, and their stabilization may increase the quality of regeneration over long gaps.

KEY WORDS: Chitosan, Extracellular matrix, Fibronectin, Laminin, Peripheral nerve, Regeneration

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The use of artificial nerve conduits has emerged as an alternative to the classical autologous graft repair to bridge gaps in continuity of peripheral nerves after severe injuries.[1-3] Nerve conduits avoid some of the main problems associated with autograft repair, such as the additional surgical intervention to obtain the graft material, the mismatch between the injured nerve and the graft, and the limited source of donor nerves. Regeneration of peripheral nerves through artificial nerve guides is highly limited by the length of the gap, being poor for gaps longer than a critical length. Such a critical gap length is dependent on the size of the nerve and the species.[4] Thus, when using standard silicone or plastic tubes, nerve regeneration occurs in the rat sciatic nerve if the gap is 10 mm or less but fails in most cases with 15 mm gaps,[5,6] whereas in the mouse sciatic nerve regeneration occurs in all cases with a 4 mm gap but fails with gaps 6 mm or longer.[7-9]

Current advances in the use of artificial nerve conduits to repair severe peripheral nerve lesions aim to create an internal milieu that mimics the natural microstructure found in a normal nerve.[1] An explored direction is the addition of biologically active scaffolds to the inner lumen that mimics the endoneurium of peripheral nerve tissue. The extracellular matrix (ECM) plays an important role in the proliferation and migration of Schwann cells, which guide the regenerating axons and their myelination after nerve damage.[10,11] Among other ECM components, laminin and fibronectin have a fundamental role in guiding the regrowth of damaged axons. Both laminin and fibronectin have been implicated in the regeneration of peripheral neurons in Vitro[12,13] and in Vivo.[14-18]

However, the incorporation of ECM-based scaffolds into nerve conduits should take into account the matrix composition, density, and the orientation of the fibrils, all factors that may influence the final outcome of the regeneration.[16,19] Cell and ECM alignment is a common feature of biological tissues, with anisotropy being critical to function in many instances.[20] The control of the orientation and direction of collagen fibers has been demonstrated to increase the invasion of neurites and Schwann cells from dorsal root ganglia cultured on the gel surface compared with unaligned collagen gels in Vitro.[21] The range of approaches to achieve anisotropic engineered tissues includes the use of aligned fibers, patterned surfaces, electrical and magnetic fields, mechanical gradient loadings, or physical and chemical cues. Aligned cellular collagen-based hydrogels have been recently used to bridge peripheral nerve defects[20] reporting regeneration of peripheral nerves in a critical gap model of 15 mm in rats. In the experiments described here, we have compared the capability to support regeneration across a nonpermissive 15 mm long defect of the sciatic nerve in the adult rat of chitosan conduits prefilled with collagen I-based matrices enriched with either laminin or fibronectin, and delivered as simple fully hydrated hydrogels or stabilized by plastic compression and rolled to provide some longitudinal guidance architecture. Regardless of the cell and fibril level architecture, the meso-level anisotropy of the substrate may improve regeneration, since the matrix will serve to distribute the collagen fibers in a 3-D space, and the anisotropic fibers will provide a 2-D surface for regenerating axons.[22] By means of functional and morphological methods, we assessed the effects of stabilized and rolled collagen-based matrices enriched with laminin or fibronectin to sustain nerve regeneration, migration of Schwann cells, and axonal growth.

METHODS

Animals

Adult female Wistar Hannover rats (Janvier), weighing 220 to 250 g, were housed in plastic cages under standard conditions ad libitum. All the experimental procedures were approved by the Ethical Committee of our institution and followed the rules of the European Communities Council Directive.

Preparation of Conduits Prefilled with ECM

A solution of 800 μL of rat tail type I collagen (BD Biosciences, San Jose, California) at a concentration of 3 to 4 mg/mL was mixed with 50 μL of 10× Eagle's medium (Gibco; ThermoFisher Scientific, Waltham, Massachusetts) and 2 μL of 7.5% sodium bicarbonate. For enriched matrices, 200 μL (20% final volume) of human fibronectin (BD Biosciences) at 1 mg/mL and laminin type I (Sigma-Aldrich, Inc., St. Louis, Missouri) at 1 mg/mL (concentration of the solution) were added separately to the collagen type I mixed solution. The collagen concentration was then corrected to 2 mg/mL with extra phosphate-buffered saline (PBS).

The manufacturing and characteristics of chitosan tubes were reported in a previous study.[23] For the preparation of fully hydrated gels, the chitosan tubes were carefully filled with the matrix preparations and kept in the incubator at 37°C for at least 30 min to allow matrix gel formation prior to implantation.

For the preparation of stabilized rolled hydrogels, the same matrix solutions were used to fill rectangular ABS molds following the method described previously for cellular gels.[24] One milliliter of the mixture was added to each mold and integrated with tethering mesh at opposite ends. Tethered gels were covered with PBS and the molds kept in the incubator at 37°C for 24 h, and then gels were separated from the tethering mesh and rapidly stabilized using drying-compression with an absorbent pad. The resulting sheets were rolled (approximately 15 mm length) and placed into a longitudinally opened chitosan tube, which was closed with glue prior to implantation (Figure 1).

Experimental Design and Surgical Procedure

For the study of regeneration over a critical sciatic nerve gap (15 mm), 37 rats were used. The animals were randomly assigned to one of 5 experimental groups in which the chitosan conduits contained: collagen I matrix (n = 7, COL), laminin-enriched matrix (n = 7, LM), fibronectin-enriched matrix (n = 8, FN), laminin-stabilized matrix (n = 7, LM-St), and fibronectin-stabilized matrix (n = 8; FN-St).

All surgical procedures were performed by the same researcher under aseptic conditions. Rats were anesthetized by intraperitoneal injection of ketamine/xylazine (90/10 mg/kg). Right sciatic nerves were exposed and cut, and a 6 mm nerve segment was resected at a distance of 6 mm distal from the exit of the gluteal nerve. Then, nerve stumps were sutured with 2 epineural 10-0 sutures to 18 mm length chitosan devices with an internal diameter of 2 mm and leaving a 15 mm gap. The muscle plane and the skin were sutured with resorbablele silk sutures and metallic clips, and the wound was disinfected. Animals were treated with amitriptyline to prevent autotomy.[25]

For the study of Schwann cell migration, 20 female Wistar Hannover rats were randomly distributed in the same experimental conditions (n = 4 per group). We used a short sciatic nerve gap of 6 mm repaired with chitosan tubes of 9 mm in length. The operations were performed as described above.

Electrophysiological Tests

Functional reinnervation of target muscles was assessed for the long gap study monthly up to 120 days. Animals were anesthetized and placed in a warm plate. Percutaneous electrodes were used to stimulate the sciatic nerve at the sciatic notch and register the compound muscle action potentials (CMAPs) and latencies of the M waves of distal muscles (tibialis anterior, gastrocnemius, and plantar muscles).[23]

Functional Evaluation of Sensory Recovery

The threshold for nociceptive responses to mechanical and thermal stimuli was evaluated on both hindpaws by means of algesimetry tests monthly up to 122 dpo. For both tests, nociceptive responses were evaluated in the lateral part of the paw, which is the territory of the plantar surface innervated by the sural branch of the sciatic nerve. The contralateral paw was used as control to overcome possible variations between testing conditions. To discard confounding effects due to collateral reinnervation of the saphenous nerve,[26] this nerve was resected after 120 dpo tests and they were repeated at 122 dpo.

Mechanical algesimetry measurements obtained in grams were obtained by an electronic Von Frey algesimeter (Bioseb, Chaville, France), whereas thermal algesimetry values measured in seconds were

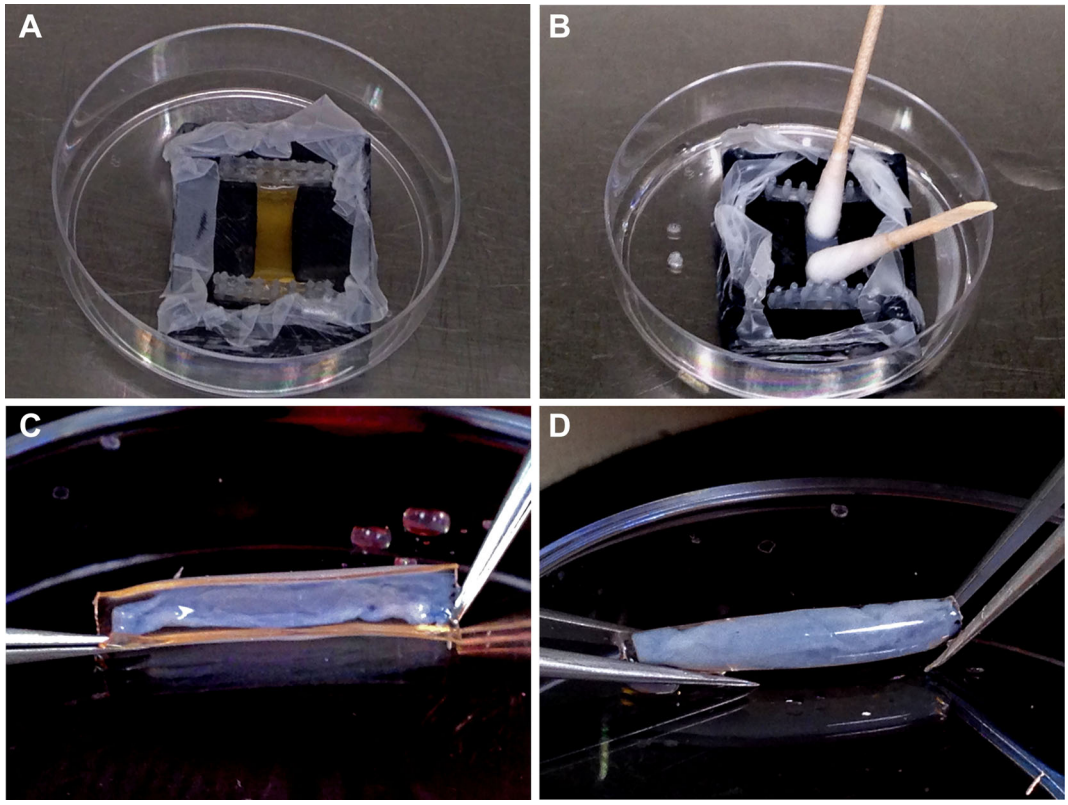

FIGURE 1. *Representative images of the stabilization and rolling technique. ABS molds were filled with a collagen solution and let to gelify and stabilize for 24 h in the incubator at 37° C* **A**. *The excess of liquid was removed using absorbent pads for 15 min* **B**. *The gel was carefully removed from the mold and inserted in a longitudinally cut chitosan guide* **C** *and sealed prior to implantation* **D**.

studied using a plantar algesimeter (Ugo Basile, Comerio, Italy). For both, a cutoff point was settled at 40 g or 20 s, respectively. All values are presented as the mean of 3 repetitive measures and as the percentage of response between the injured and noninjured paw expressed in percentage.[23]

Histology and Morphometry

Four months after the injury, animals were deeply anesthetized and perfused with 4% paraformaldehyde in PBS solution (0.1 M, pH = 7.4) and postfixed in 3% paraformaldehyde–3% glutaraldehyde phosphate-buffered solution. The nerves were postfixed in osmium tetroxide (2%, 2 h, 4°C), dehydrated through ascending series of ethanol, and embedded in Epon resin. Semithin sections (0.5 μm) of the regenerated nerves were obtained by an ultramicrotome (Leica, Wetzlar, Germany) stained with toluidine blue and examined by light microscopy. Representative images of the whole regenerated nerve were acquired at ×10 magnification, whereas higher magnification images at ×100 were obtained to count the number of myelinated fibers with a digital camera (Olympus DP50; Olympus Corporation, Tokyo, Japan) attached to a microscope (Olympus BX51; Olympus Corporation). At least a 30% of the nerve area was acquired at the highest magnification to estimate the number of regenerated myelinated axons. Images were obtained at midpoint of the tube and 3 mm distal. Measurements of both the nerve area and the number of estimated myelinated fibers were carried out using ImageJ software (National Institute of Health, Bethesda, Maryland).[23] In cases where matrix remnants were present inside the regenerated nerve at the tube level, the area occupied by them was excluded for the measurements.

Assessment of Schwann Cell Migration

For the study of Schwann cell migration, 12 days after nerve section and tube repair leaving a 6 mm gap, animals were deeply anesthetized and perfused transcardiacally as above. The tubes were harvested and postfixed in 4% paraformaldehyde. Thirty-micrometer-thick longitudinal sections of the regenerating cable were cut with a cryostat (Leica). Samples were incubated for 48 h with rabbit antibody against S100 (1:100; Immunostar, Hudson, Wisconsin) to label Schwann cells and anti-NF-200 (1:1000; EMD Millipore, Billerica, Massachusetts) to label regenerating axons. After washes, the sections were incubated for 2 h with biotinylated IgG (1:200; Life Bioscience, Oakleigh, Australia) and incubated overnight with secondary antibodies goat anti-rabbit conjugated with Alexa 488 and Alexa 594 (1:200; Life BioScience). To analyze Schwann cell migration, microphotographs of the regenerative front and Schwann cells were taken at ×4 magnification with a digital camera, acquired in Adobe Photoshop CS and photomerged (Adobe, San Jose, California). Using ImageJ software (NIH), resolution parameters were fixed and Schwann cells were followed from the proximal to the distal

part of the implanted tube. The distance of the regenerated axonal front and the percentage of area occupied by migrating Schwann cells was calculated and compared.

Statistical Analysis

Statistical comparison between groups and intervals in this study was analyzed by 2-way analysis of variance (ANOVA) for repeated measurements followed by Bonferroni post hoc tests. When analyzing histological results and the migration of Schwann cells in the short gap, results were analyzed by 1-way ANOVA followed by Bonferroni posttest. Results were expressed as mean ± SEM and differences were considered significant when $P < .05$.

RESULTS

Muscle Reinnervation

Initial evidence of reinnervation of the tibialis anterior and gastrocnemius muscles was found at 60 dpo in some animals of each group, with CMAPs of small amplitude. The CMAPs progressively increased in amplitude and were recorded in more animals over time, with a similar pattern for both muscles (Figures 2A and 2B). At the end of the follow-up (120 dpo), reinnervation of the tibialis anterior and the gastrocnemius muscles was observed in 3 of 7 animals in the COL group, 2 of 7 in the LM group, 5 of 8 in the FN group, 4 of 7 in LM-St group, and 6 of 8 in the FN-St group. Significant differences ($P < .05$) were observed at the final time point between the FN-St group and the COL and LM groups. Both FN and LM-St groups performed better than the LM group ($P < .01$; Figures 2A and 2B).

At the more distal plantar interosseous muscles, onset of reinnervation was also found at 60 dpo. In this case, the CMAPs were of very small amplitude (less than 0.05 mV). At the end of the follow-up (120 dpo), evoked CMAPs of the plantar muscle were observed in 3 of 7 animals in the COL group (CMAP amplitude 0.22 ± 0.16 mV), 2 of 7 in the LM group

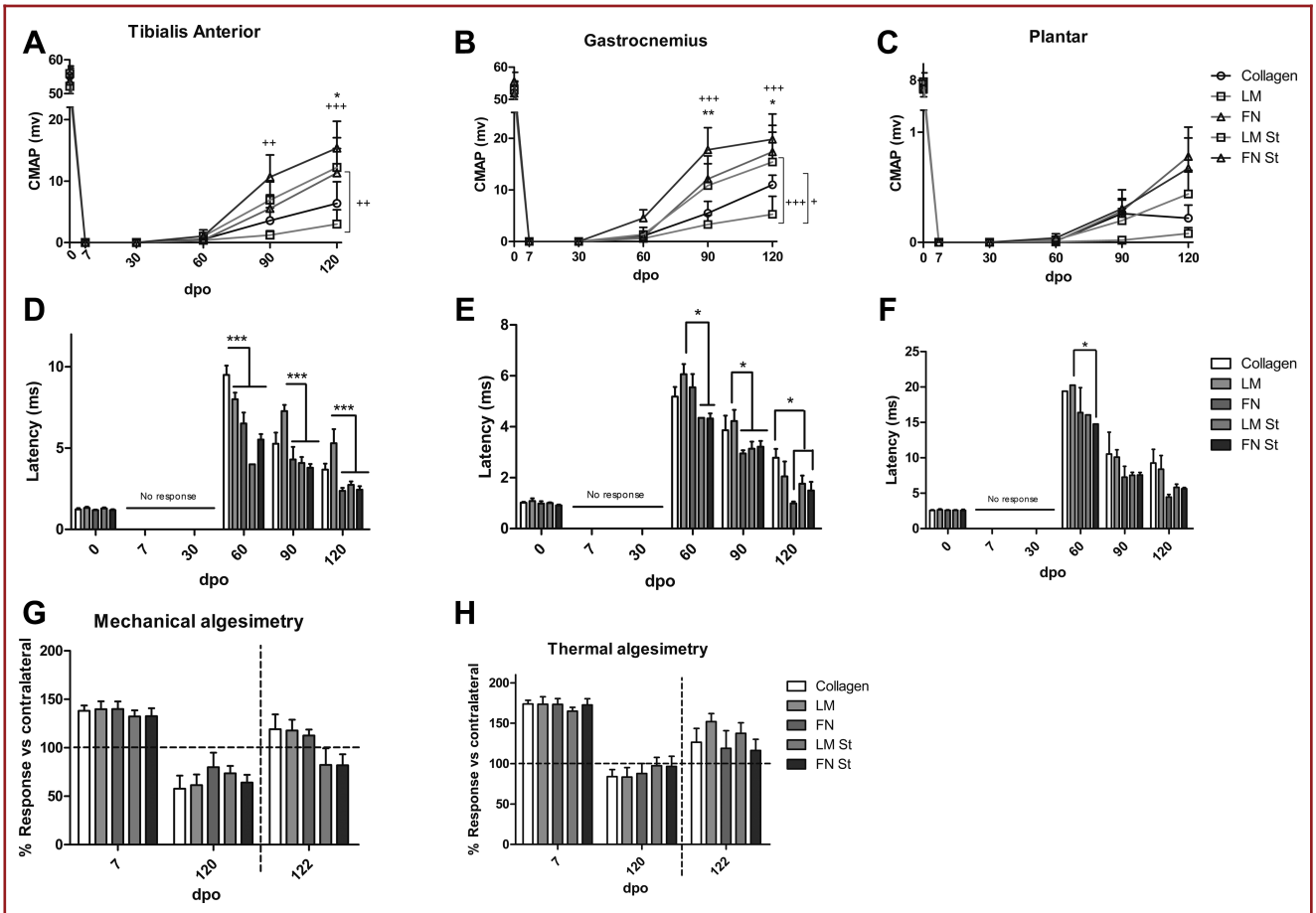

FIGURE 2. *Mean amplitude of the CMAP of tibialis anterior* **A**, *gastrocnemius* **B**, *and plantar muscles* **C** *of the injured hindlimb of the rats during 4 months after sciatic nerve lesion and repair.* $^{*}P < .05$ *fibronectin vs laminin-enriched groups;* $^{+}P < .05$ *fibronectin vs collagen group. Mean latencies of the tibialis anterior* **D**, *gastrocnemius* **E**, *and plantar* **F** *CMAPs recorded in the regenerated rats during the 4 months follow-up.* $^{*}P < 0.05$. *Mechanical* **G** *and thermal* **H** *algesimetry test results. Values are expressed as percentage of withdrawal threshold to mechanical and thermal stimuli applied to the lateral side of the injured paw vs the contralateral uninjured paw. Horizontal dotted lines represent the normalized baseline values. Vertical dotted lines indicate when the saphenous nerve was cut.*

(0.08 ± 0.08 mV), 5 of 8 in the FN group (0.78 ± 0.37 mV), 4 of 7 in the LM-St group (0.44 ± 0.28 mV), and 5 of 8 in the FN-St group (0.67 ± 0.37 mV), but no significant differences were observed between groups (Figure 2C).

The latencies of the registered CMAPs were shortened in time toward normal values. At the end of the follow-up, the latencies of the waves recorded on tibialis anterior and gastrocnemius muscles were significantly shorter in the FN, FN-St, and LM-St groups than in the LM and COL groups (Figures 2D and 2E).

The plantar CMAP latency averaged 9.25 ± 2.51 ms in the COL group, 8.37 ± 2.52 ms in the LM group, 4.45 ± 0.59 ms in the FN group, 5.83 ± 0.60 ms in the LM-St group and 5.64 ± 0.21 ms in the FN-St group at the end of the follow-up, without significant differences between groups (Figure 2F).

Recovery of Nociceptive Sensibility

Withdrawal responses to mechanical stimuli, evaluated with the Von Frey test, demonstrated absence of responses during the first 30 dpo, and therefore they were penalized with a cutoff value of 40 g. From 60 to 120 dpo, most of the rats showed withdrawal responses in the injured paw at lower stimulus intensity than in the contralateral side, indicating some degree of hyperalgesia. After elimination of the saphenous nerve at 120 dpo, withdrawal responses to mechanical stimuli in rats of the COL group (119.01 ± 20.48 g), the LM group (117.69 ± 15.91 g), and the FN group (112.53 ± 8.87 g) were slightly higher but not significantly different ($P > .05$) than in the contralateral side, whereas both LM-St (82.17 ± 21.17 g) and FN-St (81.96 ± 13.84 g) groups were slightly lower but not significantly different compared with the contralateral paw, suggesting increased skin reinnervation in these 2 groups (Figure 2G).

Withdrawal responses to thermal stimulation in the plantar test showed similar evolution than those observed for the Von Frey test. Animals had no response to heat stimuli on the denervated paw during the first 30 dpo. From 60 to 120 dpo, most rats showed withdrawal responses at lower stimulus intensity than in the contralateral side. When the saphenous nerve was cut, the withdrawal time of the injured paw at 122 dpo in rats of the COL group (126.37 ± 22.72 s), LM group (151.93 ± 14.15 s), FN group (118.97 ± 30.97 s), LM-St group (137.49 ± 16.07 s), and FN-St group (116.29 ± 16.97 s) were higher, although not significantly different to the contralateral intact side (Figure 2H).

Histological Results

Macroscopic examination of the injured nerves after the 4-month follow-up showed that 3 of 7 animals in the COL group, 2 of 7 in the LM group, 5 of 8 in the FN group, 4 of 7 in the LM-St group, and 6 of 8 in the FN-St group presented a regenerated cable inside the chitosan tube. Transverse sections of the regenerated nerves taken at the midpoint of the tube and at the distal segment were analyzed under light microscopy (Figure 3). The mean number of myelinated fibers at the midpoint of the tube was higher in the FN group (5673 ± 2501) followed by FN-St (4999 ± 1922), LM-St (3882 ± 1985), COL (1909 ± 1521), and LM (614 ± 838) groups, without significant differences between groups due to high variability (Figure 4A). The same pattern was observed in sections taken 3 mm distal to the end of the tube, where the number of myelinated fibers was higher in the FN group (3098 ± 1813) followed by FN-St (2894 ± 1218), LM-St (2860 ± 1990), COL (857 ± 904), and LM (568 ± 774) groups, without significant differences (Figure 4B).

When analyzing the cross-sectional area of the regenerated nerve in the tube, the FN-St group had the largest area (0.26 ± 0.09 μm^2), followed by LM-St group (0.15± 0.09 μm^2), FN group (0.13± 0.06 μm^2), COL group (0.08± 0.05 μm^2), and LM group (0.03 ± 0.02 μm^2), with significant differences between the FN-St and LM group ($P < .05$). Distally, the same order was found for the size of the nerve, but without significant differences between groups (Figures 4C and 4D).

When analyzing the residual matrices that were not degraded at the midlevel of the tube, the groups repaired with stabilized gels showed larger remnants (FN-St 0.12 ± 0.06 μm^2, and LM-St 0.07 ± 0.04 μm^2) than groups with hydrated gels (FN 0.02 ± 0.02 μm^2, COL 0.01 ± 0.003 μm^2, and LM 0.005 ± 0.003 μm^2), but without significant differences between groups.

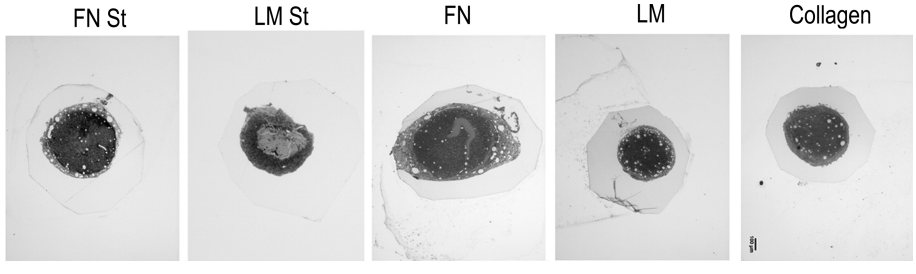

FIGURE 3. *Micrographs of semithin sections of the regenerated nerve taken at the midpoint of the tube 4 months after sciatic nerve resection and repair from a representative animal of collagen group, laminin group, fibronectin group, laminin-stabilized group, and fibronectin-stabilized group. The whole regenerated nerve is shown in the left panels; scale bar = 500 μm.*

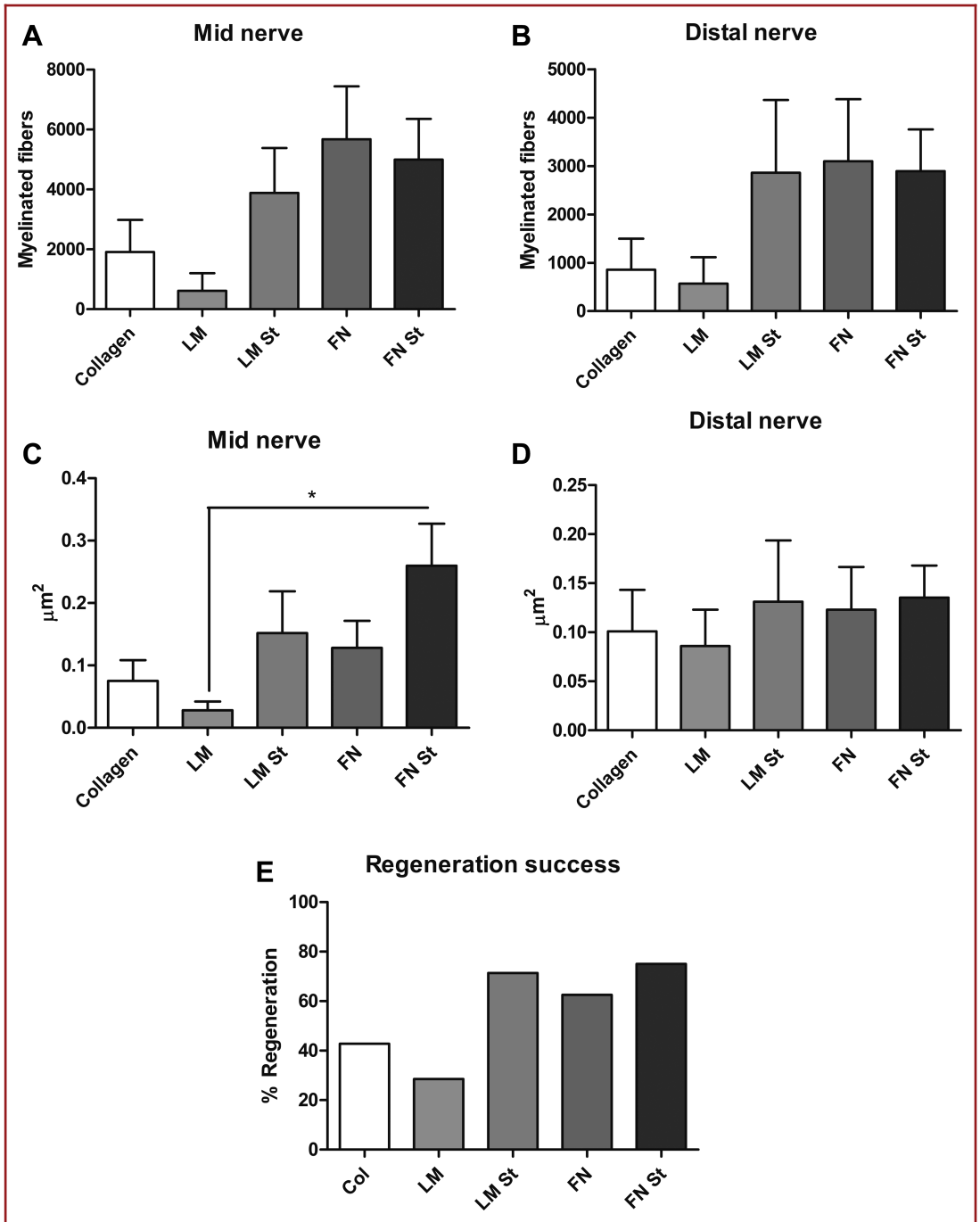

FIGURE 4. *Estimated number of regenerated myelinated fibers in the regenerated nerve at the midtube* **A** *and 3 mm distal* **B** *to the tube 4 months after sciatic nerve resection and repair. Cross-sectional area of the nerve at midtube* **C** *and 3 mm distal* **D** *levels. Animals with no regenerated nerve were also included (with null values) in the calculation.* $^{*}P < .05$. *Plot representing the percentage of regenerated nerves found at 120 dpo* **E**.

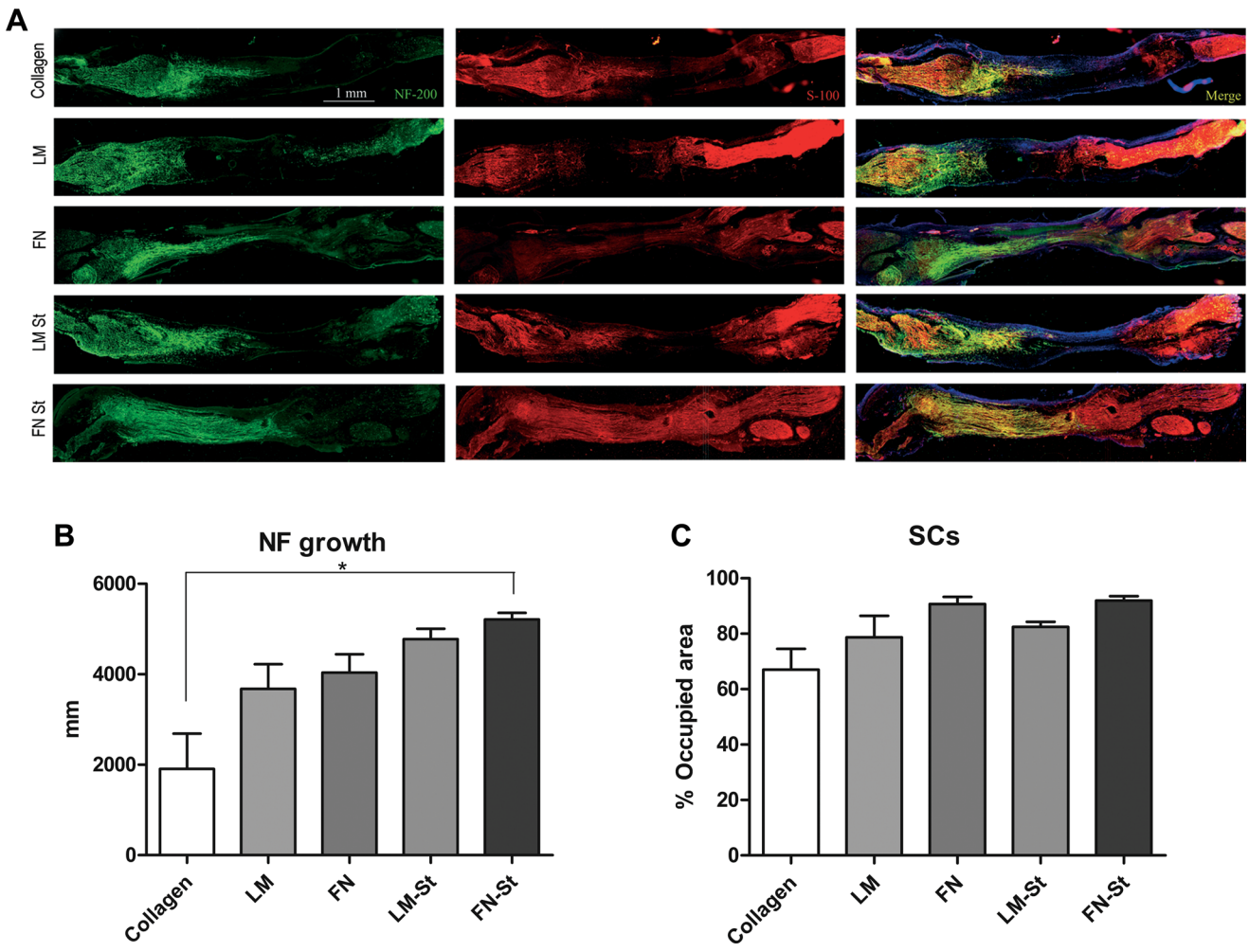

FIGURE 5. *Representative images of longitudinal sections of sciatic nerves from rats injured and repaired with a chitosan conduit leaving a 6 mm gap in the collagen, laminin, fibronectin, laminin-stabilized. and fibronectin-stabilized groups. Twelve days after the surgery, regenerated axons were labeled with NF-200 (left panels), Schwann cells were labeled with S-100 (central panels), and the images were photomerged (right panels) with DAPI (blue). Scale bar = 1 mm* **A**. *Length of the front of axonal growth from the proximal end of the tube* **B** *and percentage of the nerve cable area occupied by migrating Schwann cells* **C**. **P < .05.*

The percentage of regenerated animals with the presence of distal axons and positive reinnervation of target muscles was also represented (Figure 4E).

Schwann Cell Migration

Immunohistochemical labeling of the regenerating cable formed inside the tube at 12 dpo (Figure 5A) revealed that the distance covered by the regenerating front, labeled against neurofilament heavy chain, was longest in the FN-St (5214 ± 124 μm) and LM-St groups (4778 ± 198 μm), followed by the FN (4037 ± 495 μm) and LM (3675 ± 668 μm) horizontally polymerized groups, and finally the COL group (1906 ± 954 μm), with significant differences between the FN-St and the COL group ($P < .05$; Figure 5B). Similarly, the area occupied by Schwann cells, labeled for S-100, was largest in the FN-St group (91.98 ± 1.37%), followed by the FN (90.66 ± 3.34%), LM-St (82.48 ± 1.61%), LM (78.68 ± 9.87%), and COL groups (67.03 ± 9.23%), without significant differences between them (Figure 5C).

DISCUSSION

In this study, we have compared the effect of the addition of laminin or fibronectin in a collagen type I-based matrix, both incorporated either as fully hydrated hydrogel fillers or stabilized and organized into longitudinally oriented scaffolds, within chitosan conduits to sustain axonal regeneration across a critical model of 15 mm gap resection of the sciatic nerve in rats. Our

results show that addition of fibronectin in the collagen matrix enhanced nerve regeneration, and that stabilization and organization of the hydrogels into longitudinally oriented structures further increased the cases in which regeneration occurred over the 15 mm long gap. Furthermore, we investigated the effect of those matrices at short term, and found that the stabilization and organization of the initial matrix increased Schwann cell migration and axonal growth.

Here we have used a chitosan tube that was already proven to be more effective than the standard silicone tube for supporting axonal regeneration across limiting gaps in rats.[23] However, the percentage of success in this model is still far from the 100% success of an autograft, the gold standard repair technique to bridge long peripheral nerve gaps. Therefore, there is a need to further improve the regenerative capability of these guides. Regeneration in tubular guides is dependent on the formation of an initial fibrin matrix which has to bridge the gap formed between the stumps. This fibrin cable provides a guidance surface to fibroblasts, blood vessels, and Schwann cells to migrate from proximal and distal nerve stumps to populate the cable and sustain the advance of the regenerating axons.[6] Therefore, prefilling the tube with scaffolds can favor Schwann cell migration and facilitate regeneration across the conduits when the formation of the fibrin cable is limited.

In this work, we have used a collagen type I hydrogel matrix as a base that has previously been shown to allow axonal growth in 3-D in Vitro assays.[27] It is easy to manipulate and can be enriched with different ECM molecules, such as fibronectin or laminin, in a mixture that is permissive for regeneration both in Vitro and in Vivo.[28] Previous works have already shown that prefilling a nerve conduit with ECM components supports axonal growth,[14,15,16,18] although the regeneration promoting capacity remains inferior compared with an autograft.[29] This limitation may be due to the composition, the density of the matrices, and the lack of alignment of their components[18,30] that may interfere with the migration of Schwann cells and the directed growth of axons along the conduit lumen. The longitudinal alignment of an ECM gel within a nerve conduit attempts to mimic the natural geometry of the endoneurial tubes in nerve grafts. Many efforts during the last years have focused on the development of novel tissue engineering techniques and biomaterials that can confer orientation upon cells and ECM, including the use of gradients, electrical and magnetic fields, and cellular self-alignment in response to tension in tethered collagen gels.[19,21,31] In addition to regeneration support and guidance resulting from microscale and nanoscale alignment of cells and collagen fibrils in the latter studies,[20,32] rolling sheets of stabilized collagen hydrogel inside a conduit provides an additional level of mesoscale tissue structure than obtained from simply filling the conduit lumen with a fully hydrated hydrogel. Here we have isolated this variable, and directly compared the extent of nerve regeneration that results from using simple hydrogel fillers with the same materials stabilized and rolled to provide some tissue architecture. The results indicate that the more organized matrix structure is beneficial in promoting regeneration even in the absence of self-aligned therapeutic cells and the accompanying nanofibrillar anisotropy of the collagen matrix.

Interestingly, we found that addition of fibronectin to the intratubular matrix increased the proportion of animals that regenerated, and enhanced motor reinnervation and number of myelinated axons more than the addition of laminin or the collagen matrix alone. Furthermore, when stabilized rolled gels were incorporated in the tube, the regeneration was further improved; in the FN-St group, the proportion of animals that presented a regenerative cable after 4 months increased to 75% of the rats, whereas in the LM-St group it was 57% (Table). Both laminin and fibronectin have been used to promote nerve regeneration and provide support in long nerve gaps using various different approaches. A previous study compared the addition of laminin and/or fibronectin in tubular devices with repair long nerve gaps.[14] The authors filled silicone tubes with saline solution containing these ECM proteins and found that the incidence of

TABLE. Comparison of Results of Muscle Reinnervation and Nerve Regeneration From This Study In Which a 15 mm Gap of the Sciatic Nerve Was Repaired With a Chitosan Conduit Prefilled With ECM Matrices with Results Obtained After Repair With a Hollow Chitosan Conduit and an Autograft In a Previous Study[23]

	% Recovery TA m	Statistics	% Recovery Pl m	Statistics	Regenerated cable	Muscle reinnervation
AG	60 ± 5%	$P < .05$ vs all groups	33 ± 8%	$P < .05$ vs all groups	7/7	7/7
Hollow Chitosan	18 ± 9%	$P < .05$ vs LM	8 ± 9%	–	5/10	4/10
COL	12 ± 7%	$P < .05$ vs LM	3 ± 1%	–	3/7	3/7
LM	5 ± 4%	–	1 ± 1%	–	2/7	2/7
FN	21 ± 7%	$P < .05$ vs LM	10 ± 4%	–	5/7	5/7
LM-St	22 ± 8%	$P < .05$ vs LM	6 ± 3%	–	4/7	4/7
FN-St	29 ± 8%	$P < .05$ vs COL and LM	9 ± 3%	–	6/8	6/8

Abbreviations: AG, autograft; COL, collagen; FN, fibronectin; FN-St, fibronectin stabilized; LM, laminin; Pl m, plantar muscle; TA m, tibialis anterior muscle.

cable formation that bridged the gap was similar in all groups, although combination of both molecules increased the number of regenerating axons.[14] In contrast, we have found that the addition of fibronectin within a collagen-based matrix increased the percentage of regeneration across a critical gap compared with the laminin-containing matrix. These differences could be due to the composition and topographical conformation of the fibrils constituting the matrix used to fill the tube, which are important factors determining the rate of axonal regeneration.[18,30,33,34] The interaction between collagen type I and laminin or fibronectin is not well characterized. It is possible that the addition of laminin to collagen matrices increases the thickness and density of the strands, whereas the combination of fibronectin and collagen might result in a better organization.

Microscopic examination of the regenerated nerves revealed the presence of residual matrices at the tube level. Although larger remnants were found in the animals repaired with stabilized hydrogels, significant differences were not observed between groups. The appearance of these residual matrices may be attributed to the compact conformation of the stabilized gels, as previously reported,[31] in which enzymatic degradation by collagenase and other proteases was probably slower. However, as noted in the quantification of the number of myelinated fibers, such ECM remnants did not compromise axonal regeneration.

Since aligned type I collagen facilitates migration of Schwann cells in Vitro compared with unaligned collagen gel,[21] and fibronectin plays an important role in migration of Schwann cells in Vitro and into neural guides,[35] we wanted to evaluate migration of Schwann cells from the proximal and the distal stump. For that experiment, we used a shorter gap, to guarantee the formation of the fibrin cable in all the animals. We observed that the regenerating axon front extended to longer distances in fibronectin- and laminin-stabilized rolled hydrogel groups compared with fully hydrated hydrogel matrices. Schwann cell migration was not significantly different between groups at 12 days using this gap length. However, the trend observed in the short gap between fibronectin and laminin groups may become a relevant difference in the long gap model, and thus, the slight enhancement of Schwann cell migration into the tube may be decisive to sustain regeneration in a critical gap. Indeed, fibronectin-aligned fibers were shown to provide an orientating cue for migrating fibroblasts and Schwann cells, and for neurite elongation.[36] Besides its effects on Schwann cell migration, the beneficial effects of fibronectin in nerve conduits can also be due to its supportive effect on viable Schwann cells.[35]

CONCLUSION

This study shows the importance of the conformation and organization of hydrogel matrix components on promoting regeneration after severe peripheral nerve injuries. Stabilization and rolling of collagen-based matrices and enrichment with other ECM proteins improved the quality and quantity of the nerve repair process. The fibronectin- and collagen-stabilized rolled construct seems a promising candidate to be used as internal filler of tubular nerve conduits, allowing regeneration across a critical long gap in a significant number of cases, by facilitating formation of the fibrin cable, Schwann cell migration, and growth of regenerating axons through the neural conduit.

Disclosures

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COMMENT

This is a well-done study that looks at the effect on nerve regeneration and Schwann cell migration of anatomically and functionally bridging a critical 15-mm gap in the rat using fabricated Chitosan tubes supplemented with extracellular matrix molecules known to promote axon regeneration such as laminin and fibronectin. In some cases, the geometry of the tubes was also manipulated to provide a 3-dimensional microenvironment that mimics more closely that of the Bands of Bungner found in degenerating and regenerating nerves with and without nerve grafts. The results are believable and contribute to an already large literature on tubes and factors that promote nerve regeneration.

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