The Future of Carbon-Based Scaffolds in Foot and Ankle Surgery

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KEYWORDS

• Biomaterials • Carbon • Scaffolds • Reconstruction • Tissue • Cell growth • Biomechanics • Biologics

KEY POINTS

- Carbon-based materials offer enhanced biological response and tunability.
- Carbon-based scaffolds offer tensile properties comparable with those of current synthetic tissue scaffolds.
- Cellular behavior on carbon-based scaffolds is enhanced by varying material orientation, porosity, and crystallinity.

INTRODUCTION

Autologous grafts have been the gold standard in tissue replacement and the most accurate means of recapitulating both the biological and mechanical properties of tissue. However, autologous grafts have had complications and drawbacks. Skin grafting, a prime example of an autologous tissue graft, has been limited by the size of graft, availability, and secondary donor site morbidity.[1] Use of cadaveric tissues circumvents several limitations of autologous grafts; however, sterilization processes used to reduce the risk of disease transmission potentially weaken tissues and eliminate living cells and some growth factors from scaffolds, making them suboptimal tissue

Disclosure Statement: There are no commercial relationships to products of companies mentioned in the article. The funding for this article was provided by University of Dayton and Center for Tissue Regeneration and Engineering at Dayton (TREND). The authors do not have any corporate appointments related to the products or companies mentioned in this article. The authors do not have any financial relationships to products mentioned in this article.

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Clin Podiatr Med Surg 32 (2015) 73–91

http://dx.doi.org/10.1016/j.cpm.2014.09.001 podiatric.theclinics.com

replacements.[2,3] Chemical cross-linkage of tissue scaffolds has been used in some circumstances to strengthen weak tissues, but can result in a prolonged inflammatory response and limit graft integration in vivo.[4–9] Partial enzymatic digestion of cadaveric tissues has also been used to improve graft porosity, which potentially assists with graft neovascularization, although this procedure has not been overwhelmingly successful.[8] Proprietary methods of chemically and physically stripping tissues of cellular materials have been commercially developed to minimize graft rejection and loss of essential biological factors; however, these methods cannot be universally applied to all tissues.[6,10] GraftJacket Matrix (GJ) (Wright Medical, Arlington, TN, USA),[4] an acellular human dermis–derived graft, is an example of a commercially available graft that is commonly used in surgery for soft-tissue augmentation and repair.[4,10–13] The elastic properties of skin-derived scaffolds make GJ an inferior replacement for stiffer tissues such as tendon. Hence, current limitations in tissue processing have spawned interest in emerging technologies that enable precise engineering and manufacturing of scaffold materials on a nanoscale that recapitulate the unique mechanical needs of a variety of tissues while promoting tissue repair that also occurs on a nanoscale.

To date, biomedical scaffold materials have included synthetic, semisynthetic, and tissue-derived matrices with or without biological activity from growth factors or living cells incorporated within the scaffolds.[10,14–19] Various extracellular matrix molecules such as collagen and resorbable synthetic materials commonly utilized in suture and medical implants have all been used as scaffolds in the past.[16,18,20,21] The most advanced generations of commercially available scaffolds attempt to provide some level of structural function with biological activity, such as Trinity (Orthofix, Lewisville, TX, USA),[22] which combines mesenchymal stem cells with a cancellous bone allograft and is used for bone healing; Infuse (Medtronic, Minneapolis, MN, USA),[23] which incorporates recombinant bone morphogenic protein 2 with a resorbable collagen scaffold sponge and is used in spine fusion; Apligraf (Organogenesis, Canton, MA, USA),[24] which integrates human keratinocytes and dermal fibroblasts with bovine type I collagen as a graft for the treatment of skin ulcerations; and GraftJacket Matrix,[4] an acellular human dermis–derived scaffold with retained growth factors and extracellular matrix molecules.

Carbon-based materials are novel subsets of synthetic materials that have been incorporated into medical scaffolds, implants, and nanoartifact drug-delivery vehicles because of their strength, flexibility, durability, and biocompatibility, but have been examined less extensively as a combined vehicle for cell delivery and biomechanical construct for soft-tissue repair and regeneration.[25–30] Potential advantages of an engineered carbon scaffold may include the following: (1) tunable geometric and surface characteristics to fit biological demands of a healing tissue; (2) reproducible mechanical properties to meet specific functional requirements; (3) lack of donor site morbidity; (4) no communicable disease transmission; and (5) unlimited availability.

This article examines the mechanical behavior of 2 fibrous carbon-based scaffolds and evaluates their potential as a vehicle for cell and biologics delivery that promotes tissue repair. The structure, tensile properties, and human fibroblast adhesion and proliferation on carbon scaffold substrates were analyzed and compared with a control scaffold, GJ, which is commonly used in surgery for soft-tissue augmentation and repair.[4,6,10,11,13,31,32]

MATERIALS AND METHODS

Materials

A spool of commercially available PAN-based carbon fibers from Cytec Industries Inc. (Woodland Park, NJ, USA) was used to create carbon scaffold substrates. Before