United States Patent

Laurencin et al.

BIOCOMPATIBLE, BIODEGRADABLE POLYMER-BASED, LIGHTER THAN OR LIGHT AS WATER SCAFFOLDS FOR TISSUE ENGINEERING AND METHODS FOR PREPARATION AND USE THEREOF

Inventors: Cato T. Laurencin, Elkins Park, PA (US); Solomon R. Pollack, North Wales, PA (US); Elliot Levine, Cherry Hill, NJ (US); Edward Botchwey, Philadelphia, PA (US); Helen H. Lu, New York, NY (US); Mohammed Yusuf Khan, Philadelphia, PA (US)

Assignees: Drexel University, Philadelphia, PA (US); The Wistar Institute, Philadelphia, PA (US); The Trustees Of The University of Pennsylvania, Philadelphia, PA (US)

Notice: Subject to any disclaimer, the term of this patent is extended or adjusted under 35 U.S.C. 154(b) by 1155 days.

Related U.S. Application Data

Continuation of application No. 10/052,121, filed on Jan. 9, 2002, now abandoned.

Provisional application No. 60/262,128, filed on Jan. 17, 2001.

International Patent Classification:

C12N 11104

C12N 11108

C12N 5102

C12N 5100

US Patent Classification:

435/182

435/325

Field of Classification Search: None

References Cited

U.S. PATENT DOCUMENTS

4,448,884 A 5/1984 Henderson 435/402
5,066,467 A 4/1991 Kusano et al. 435/180
6,001,643 A 12/1999 Spaulding et al. 435/298
6,210,715 B1 4/2001 Starling et al. 424/489
6,328,990 B1* 12/2001 Ducheyne et al. 424/426

OTHER PUBLICATIONS


Primary Examiner — David Naff

ABSTRACT

Scaffolds for tissue engineering prepared from biocompatible, biodegradable polymer-based, lighter than or light as water microcarriers and designed for cell culturing in vitro in a rotating bioreactor are provided. Methods for preparation and use of these scaffolds as tissue engineering devices are also provided.

19 Claims, No Drawings
OTHER PUBLICATIONS


* cited by examiner
FIELD OF THE INVENTION

The present invention relates to scaffolds for tissue engineering specifically designed for cell culture in vitro in a rotating bioreactor. Scaffolds of the present invention comprise biocompatible, biodegradable polymer-based microcarriers which are lighter than and/or light as water. In a preferred embodiment, the biocompatible, biodegradable, lighter than or light as water microcarriers are bonded into a scaffold which is then cultured with cells in a rotating bioreactor. Methods for preparation and use of these scaffolds as tissue engineering devices are also provided.

BACKGROUND OF THE INVENTION


Using porous polyactic glycolic acid (PLGA) foams with pore sizes ranging from 150 to 710 µm, Ishaug-Riley et al. (Biomaterials 1998 19(15):1405-1412) have observed a limit to osseous tissue ingrowth and mineralization in a static culture environment of about 200 µm. While it is possible that structures with larger pores would facilitate greater diffusion, important cell-cell interactions and scaffold mechanical integrity could be compromised.

Numerous tissue engineering solutions have been proposed to address the need for new bone graft substitutes.


Using porous polyactic glycolic acid (PLGA) foams with pore sizes ranging from 150 to 710 µm, Ishaug-Riley et al. (Biomaterials 1998 19(15):1405-1412) have observed a limit to osseous tissue ingrowth and mineralization in a static culture environment of about 200 µm. While it is possible that structures with larger pores would facilitate greater diffusion, important cell-cell interactions and scaffold mechanical integrity could be compromised.


In the present invention, lighter than or light as water, biocompatible, biodegradable microcarriers and scaffolds
comprising these microcarriers are used in a three-dimensional culturing method for the growth of mineralized tissues in vitro in a rotating bioreactor. The combination of three-dimensionality and fluid flow of the present invention circumvents limitations associated with static three-dimensional culturing methods, eliminates confounding wall collisions, and increases the rate and extent of mineralized tissue formation in the rotating bioreactor. Scaffolds prepared in accordance with the present invention exhibit controllable and quantifiable motion in a bioreactor environment, thereby enhancing fluid transport throughout the scaffold. As demonstrated herein, scaffolds produced in accordance with the present invention support cell attachment, growth, and phenotypic expression over short-term culture ultimately resulting in enhanced synthesis of mineralized bone graft quality tissue.

SUMMARY OF THE INVENTION

An object of the present invention is to provide scaffolds for tissue engineering comprising biocompatible, biodegradable polymer-based, lighter than or light as water microcarriers. In a preferred embodiment, the scaffolds are seeded with cells via culturing in vitro in a rotating bioreactor. Another object of the present invention is to provide a method of producing scaffolds for tissue engineering which comprises preparing biocompatible, biodegradable polymer-based microcarriers which are lighter than or light as water; bonding the biocompatible, biodegradable polymer-based microcarriers into a scaffold and seeding the scaffold with cells via culturing in vitro in a rotating bioreactor. Another object of the present invention is to provide methods for using scaffolds comprising biocompatible, biodegradable polymer-based, lighter than or light as water microcarriers seeded with cells via culturing in vitro in a rotating bioreactor as tissue engineering devices. Scaffolds of the present invention can be seeded with cells including, but not limited to, osteoblast and osteoblast-like cells, endocrine cells, fibroblasts, endothelial cells, genitourinary cells, nerve cells, progenitor cells such as myoblast or stem cells, particularly pluripotent stem cells, and used in the regeneration of tissues derived from such cells.

DETAILED DESCRIPTION OF THE INVENTION

The present invention relates to tissue engineering scaffolds and methods for production of tissue engineering scaffold which promote growth in vitro of mineralized bone tissue in a rotating bioreactor. To produce these scaffolds, polymer microencapsulation methods were adapted for the formation of hollow, lighter than or light as water microcarriers of biocompatible, biodegradable polymers. Scaffolds were then fabricated by sintering together the lighter than or light as water microcarriers into a fully interconnected, three-dimensional network. The microcarriers and scaffolds of the present invention move within the fluid medium of the rotating bioreactor in a near circular trajectory while avoiding collision with the bioreactor wall. Cell culture studies on the scaffolds of the present invention show that cells readily attach to microcarrier scaffolds. In addition, cells cultured in vitro in a rotating bioreactor on these lighter-than-water scaffolds retained their phenotype and showed significant increases in alkaline phosphatase expression and alizarin red staining by day 7 as compared to statically cultured controls.

By “lighter than or light as water microcarriers” it is meant microcarriers with a density equal to or less than water. It has been shown previously that when osteoblast cells are co-inoculated with microcarriers in a rotating bioreactor a random aggregation occurs generated by the adherence of cells to microcarrier beads and the formation of cellular bridges between adjacent microcarriers (Grant et al. Cell Eng. 1998 36(4):513-519; Qiu et al. Tissue Engineering 1998 4(1): 19-34; and Watts et al. Critical Reviews in Therapeutic Drug Carrier Systems 1990 7(3):235-259). However, this random aggregation that occurs in the rotating bioreactor is not conducive to strict quantitative comparison, because the size and shape of cell-head aggregates as well as the degree of aggregation varies greatly. Such a limitation is overcome by the present invention via the sintered pre-assembly of microcarriers into dimensionally reproducible cell scaffolds prior to culture in the bioreactor. Furthermore, the microcarrier sintering method of the present invention is not limited by the adverse effects associated with the particulate leaching and consequently no unwanted degradation of the scaffold occurs during fabrication.

Microcarriers of the present invention which are lighter than or light as water exhibit buoyancy after immersion in deionized water, phosphate buffer solution and tissue culture medium. In a preferred embodiment, microcarriers of the present invention are fabricated to produce lighter than water densities from about 0.6 to about 0.99 g/cc as estimated using a density gradient column (ASTM D-1505). Microcarriers with densities as light as water or 1.0 g/cc can also be used.

Microcarriers of the present invention which are lighter than or light as water are used for scaffold fabrication, as they form structures with an expected pore size range of 113 to 356 µm shown to be suitable for osteoblast adherence and migration (Ishaug-Riley et al. Biomaterials 1998 19(15):1405-1412; Laureen et al. Bone 1996 19(1):S93-S99). PLAGA microcarriers of this size range, when sintered, produce an interconnected network with an average pore size of 187 µm and aggregate density of 0.65 g/cc. While PLAGA has been used as the exemplary microcarrier, as will be understood by those of skill in the art upon this disclosure, other biocompatible, biodegradable polymers can be used in the production of scaffolds of the present invention. Examples of such polymers include, but are not limited to, lactic acid polymers such as poly-(L-lactic acid) (PLLA), poly-(DL-lactic acid) (PLA), and poly-(DL-lactic-co-glycolic acid) (PLGA). Blends of PLLA with PLGA, can also be used for these scaffolds. Other exemplary biodegradable polymers useful in the scaffolds of the present invention include, but are not limited to, polyorthoesters, polyanhydrides, polyphosphazenes, polycaprolactones, polyhydroxybutyrates, degradable polyurethanes, polylactic-deco-imides, polypropylene fumarates, and polydioxanone.

The hollow microcarriers are then fabricated into scaffolds, preferably via sintering in a mold for tissue engineering devices at a temperature which promotes bonding of the microcarriers but is below the melting temperature of the polymer. For example, PLAGA microcarriers were fabricated into 4 mm x 2.5 mm cylindrical scaffolds by sintering at 60°C.
At this temperature, amorphous polymer chains of adjacent microcarriers move past one another and inter-lock forming a mechanical bond. Because this temperature is well below the melting temperature, however, collapse of individual microcarriers is avoided, thereby preserving their hollow, spherical geometry and the lighter-than-water density of the aggregate structure. Porosity is a result of the imperfect packing of spherical microcarriers inside the mold, and thus geometry dictates that there are no isolated spaces (pores) within the structure and that the network of pores in the scaffold is fully interconnected. The effect of sintering on the connectivity of microspheres was evident from SEM linkages showing two or more microspheres fused together at the contact regions. Assuming the spheres approach a close packed configuration in the mold, the diameter of the scaffold pores can be represented as interstitial voids in the structure. Again, geometry dictates that the pore of the structure is given by 0.225R in the case of a tetrahedral site (a void surrounded by 4 spheres in the shape of a regular tetrahedron), or 0.414R in an octahedral site (a void surrounded by 6 spheres in the shape of an octagon), where R is the radius of the surrounding spheres.


The motion of microcarrier scaffolds constructed primarily from 500 to 860 µm lighter than or light as water microcarriers and fashioned into 4x2.5 mm cylindrical discs within the rotating bioreactor was assessed. Particle tracking analysis revealed an instantaneous velocity of 98 mm/second and a trajectory completely absent of wall collisions once equilibrium motion was reached.

Cell attachment to microcarrier scaffolds during rotating culture was estimated from cell concentration profiles taken at times 4, 8, 12, and 24 hours following co-inoculation with lighter than or light as water scaffolds. Cells used in these experiments were osteoblast-like cells. As will be understood by those of skill in the art upon reading this disclosure, however, the scaffolds of the present invention can actually be seeded with any cell type which exhibits attachment and ingrowth and is suitable for the intended purpose of the scaffold. Some exemplary cell types which can be seeded into these scaffolds include, but are not limited to, osteoblast and osteoblast-like cells, endocrine cells, fibroblasts, endothelial cells, genitourinary cells, lymphatic vessel cells, pancreatic islet cells, hematocytes, muscle cells, intestinal cells, kidney cells, blood vessel cells, thyroid cells, parathyroid cells, cells of the adrenal-hypothalamic pituitary axis, bile duct cells, ovarian or testicular cells, salivary secretory cells, renal cells, chondrocytes, epithelial cells, nerve cells and progenitor cells such as myoblast or stem cells, particularly pluripotent stem cells.

In experiments with osteoblast-like cells, cell density in the bioreactor medium decreased about 60%. The decreased concentration of suspended cells during culture is assumed to reflect the attachment of these cells to the scaffolds. By dividing the estimated quantity of attached cells by the total number of scaffolds present in culture, cell seeding was estimated to be approximately 1.4x10^5 cells/scaffold. After 24 hours of dynamic seeding, a sampling of 6 to 10 cell-scaffolds was used to measure directly the number of cells attached to scaffolds using fluorometric DNA analysis. Measurements of attached cell were in excellent agreement with cell concentration estimates with an average value of 1.3x10^6 cells per scaffold and standard deviation of 2.0x10^5 cells. The average surface area per scaffold was calculated to be approximately 6.5x10^4 cells/cm².

Cell proliferation was examined on lighter than or light as water microcarrier scaffolds over a period of 7 days with cell numbers measured immediately following cell seeding and at days 3 and 7. Cells cultured on lighter than or light as water scaffolds in the rotating bioreactor show evidence of a lower rate and extent of proliferation than those cultured on non-rotating controls. Significant differences in cell numbers could be detected by day 7 (p<0.05). The presence of cells within the pores of the scaffold that nearly cover the entire surface of the internal microcarriers was verified by SEM. By progressively focusing the microscope down the pore of the structure, it was estimated that cells had penetrated as deep as 800 µm.

The retention of osteoblastic phenotype was evaluated by ALP histochemical staining and calorimetric analysis. Cells were stained for ALP expression on lighter than or light as water scaffolds in the rotating bioreactor and on the non-rotating three-dimensional controls at days 3 and 7. Positive ALP staining is evident at each time point and for each culture condition. At each time point, more cells per unit area are present on scaffolds cultured under non-rotating three-dimensional conditions than those cultured in the rotating bioreactor, which is consistent with fluorometric DNA analysis described herein. Calorimetric analysis was also performed at 24 hours and at day 7. These results were normalized by the actual number of cells present in each scaffold. It was found that by day 7 the actual amount of ALP expressed per cell is significantly higher for cells cultured in the rotating bioreactor than on non-rotating three-dimensional controls (p<0.05).

The production of calcified matrix was analyzed by alizarin red histochemical staining. Scaffolds cultured in the rotating bioreactor showed substantially greater alizarin positive extracellular matrix material by day 7 as compared to three-dimensional controls (p<0.05). To quantify the amount of early stage calcified matrix formation, alizarin red staining techniques were adapted for calorimetric analysis by solubilizing the red matrix precipitate with cetyl pyridinium chloride to yield a purple solution suitable for optical density measurements at 562 nm. Quantities of ALZ stained matrix were expressed as a molar equivalent CaCl₂ concentration and normalized by the average number of cells per scaffold as determined in companion proliferation studies. Significant increases in the quantity of ALZ stained matrix produced on lighter than or light as water scaffolds under rotating conditions at days 3 and 7 as compared to non-rotating controls were observed.

Thus, as demonstrated herein, lighter than or light as water polymer-based microcapsules are excellent cell microcarriers providing a low shear, non-turbulent flow environment for attached cells that avoids damaging collisions with the biore-
actor wall. These scaffolds adopt a particle trajectory absent of confounding wall collisions, while maintaining a three-dimensional geometry open to mass transport of nutrients and waste products. In particular, the hydrodynamic flow environment produced by the motion of lighter than or light as water scaffolds in the rotating bioreactor enhances \( \text{O}_2 \) and nutrient transport to cells at the near surface (external) of the scaffold and possibly those in the scaffold interior (internal). This may act to advance phenotype development and tissue formation in the system of the present invention. Further, cell seeding of the scaffolds in the rotating bioreactor, as opposed to static seeding methods for these scaffolds, enhances cell migration to the interior of the scaffold and promotes homogeneity of initial cell seeding from one scaffold to another. Accordingly, the scaffolds of the present invention provide a combination of three-dimensionality and fluid transport in the absence of damaging wall collisions that appears to be a closer approximation of the in vivo environment of the cell thereby expanding capacity for in vivo tissue synthesis.

Scaffolds of the present invention are expected to particularly useful in developing bone graft quality tissue. However, as will be understood by one of skill in the art upon reading this disclosure, the method of scaffold fabrication disclosed herein can be used to generate a variety of microcarrier scaffolds of different component size ranges, associated three-dimensional architecture, and density useful in a variety of tissue engineering applications. Scaffolds seeded with cells including, but not limited to, osteoblast and osteoblast-like cells, endocrine cells, fibroblasts, endothelial cells, genitourinary cells, lymphatic vessel cells, pancreatic islet cells, hepatocytes, muscle cells, intestinal cells, kidney cells, blood vessel cells, thyroid cells, parathyroid cells, cells of the adrenal-hypothalamic-pituitary axis, bile duct cells, ovarian or testicular cells, salivary secretory cells, renal cells, chondrocytes, epithelial cells, nerve cells and progenitor cells such as myoblast or stem cells, particularly pluripotent stem cells, are useful in the regeneration of tissues derived from such cells. The following nonlimiting examples are provided to further illustrate the present invention.

**EXAMPLES**

**Example 1**

Buoyant Microcarrier Fabrication

A conventional microsphere fabrication technique was adapted for the formation of hollow, lighter than or light as water microcarriers of bioerodible poly(D,L-lactic-co-glycolide) copolymer. For this technique, a 25% w/v polymer solution of 50:50 PLAGA (molecular weight approximately 30,000) was dissolved in methylene chloride, and poured into a 1000 ml beaker containing 0.1% PVA (Poly-sciences, Lot #413322, molecular weight 25,000). The solution was stirred continuously (Cramco, Model BDCISSO) at 1000 rpm for 4 to 6 hours to allow for solvent evaporation. Buoyant microcarriers were harvested by vacuum filtration (Whatman, 54 µm), washed with deionized water, and lyophilized (Lyph-lock 12, Labconco Corp.) for 24 hours. Size distribution was determined by mechanically sifting the microcarriers using a series of stainless steel sieves with selected mesh sizes. Microcarriers were freeze fractured and analyzed with scanning electron microscopy to confirm that the carriers were indeed hollow. In vitro buoyancy was verified over 7 days by immersion inside a water-tight container maintained at 37° C. in an oscillating (60 rpm) water bath.

**Example 2**

Scaffold Fabrication and Characterization

Microcapsules of a selected size range and weight were poured into a stainless steel mold and heated in an oven (Precision Gravity Convection Incubator) for 1 hour at 60° C., several degrees above the glass transition temperature for the PLAGA 50:50 (\( T_g = 45-50^\circ \text{C} \)). Microcarriers bonded to each other while maintaining their hollow, spherical geometry. Scaffolds used for bioreactor culture were exposed to ultraviolet irradiation for 30 minutes on each side in an effort to minimize bacterial contamination. Microcarrier scaffolds were characterized using a low field emission scanning electron microscope (SEM, JEOL 6300). For SEM, specimens were coated with gold and examined for pore interconnectivity, degree of microcarrier bonding, and deformation of microcarriers. The porosity of the structure was measured by porosimetry using the Micromeritics Autopore HI porosimeter. Specifically, cylindrical polymer scaffolds, 4 mm in diameter and approximately 2.5 mm in length were placed in a 5 cc penetrometer, subjected to a vacuum of 50 µm Hg, and infused with mercury. Porosity is determined by measuring the volume of the mercury infused. In addition to an overall percentage of porosity for the polymer scaffold, porosimetry will also give an approximate distribution of pore sizes within the polymer scaffold, allowing for more accurate characterization of the scaffold geometry.

**Example 3**

Numerical Model Simulation and Particle Motion Analysis

The equations of motion governing microcarrier motion in the rotating bioreactor are as follows. For the particle position \((x, y)\) and velocity \((v_x, v_y)\), microcarrier motion relative to the rotating fluid is governed by equations:

\[
\begin{align*}
\frac{dx}{dt} &= v_x \\
\frac{dy}{dt} &= \frac{1}{\rho_{\text{part}} V_{\text{part}}} \\
\frac{dv_x}{dt} &= \frac{1}{\rho_{\text{part}} V_{\text{part}}} \\
\frac{dv_y}{dt} &= \frac{1}{\rho_{\text{part}} V_{\text{part}}}
\end{align*}
\]

\[
\begin{align*}
\rho_{\text{sphere}} - \rho_{\text{fluid}} &= \frac{\pi \cdot t^2}{100} \\
C_d &= \frac{24}{Re} + \frac{0.4}{1.0 + \sqrt{Re}}
\end{align*}
\]

where \((\rho_{\text{sphere}} - \rho_{\text{fluid}})\) is the difference between the density of the microcapsule and surrounding fluid, \(Re\) is the Reynolds number.
The human SaOS-2 line (ATCC HTB-85), which exhibits homogeneous and reproducible expression of cellular alkaline phosphatase over an infinite life span was used. For all experiments, cells were maintained in M199 (Gibco) culture medium supplemented with 10% fetal bovine serum (Sigma), 2.5 mM L-glutamine and 3 mM b-glycerol phosphate. SaOS-2 cells were grown to confluency and digested in a 1:1 trypsin solution to dissociate cell aggregates and cell numbers were determined using a coulter counter. At 24 hours, the entire cell suspension was removed and the cell number determined.

Example 5

Cell Counting

Immediately following the seeding of the cells for an experiment, a random sampling (n=6 to 10) of selected scaffolds was removed and the initial number of attached cells were determined by means of a fluorometric DNA assay as described by Labarca and Paigen (Anal. Biochem. 1980 102: 344-352). The remaining scaffolds were washed with PBS and divided equally into two experimental groups. Each group of scaffolds was placed, respectively, into two new bioreactor vessels and re-fed with 55 ml of fresh culture medium. To determine the effect of culture vessel rotation on cell function, one vessel was mounted onto a multi-HARV unit and rotated at 25 rpm and the other was cultured statically (no-rotation) as a control. Each vessel was cultured at 37° C. and 5% CO₂ for 7 days. At days 3 and 7, additional scaffolds were removed for DNA quantification. Scaffolds used for DNA analysis were washed 3 times in PBS, combined with 3 ml of additional PBS containing 2 mM EDTA, and pulverized using a tissue homogenizer (PowerGen 35, Fisher) with a 10 mm diameter saw-tooth generator for 1 minute. Cells were ruptured by 2 minutes of further homogenization at 30,000 rpm with a 5 mm diameter flat bottom generator. Homogenates were frozen at −70°C. until the day of analysis. On the day of analysis, 1 ml of scaffold homogenate was combined with 7 μl of a 200 μg/ml solution of bisbenzimide H33258 dye (Calbiochem) and vortexed vigorously. Fluorescence was read using a Tecan Spectrofluor microplate reader with an emission wavelength of 465 nm and an excitation wavelength of 360 nm. Cell standards were used to convert measured fluorescence to cell numbers, and unseeded but cultured scaffolds were analyzed to determine any effect of PLAGA autofluorescence.

Example 6

Alkaline Phosphatase Activity

Alkaline Phosphatase (ALP) activity was measured by using adaptations of standard histochemical (Van Belle, H. Biochimica et Biophysica Acta 1972 289:158-168) and colorimetric (Rattner et al. In Vitro Cellular & Developmental Biology—Animal 1997 33(10):757-762) methods. At days 3 and 7, scaffolds were removed from both the rotating and non-rotating bioreactor vessels and washed twice with PBS. Scaffolds were then incubated for 30 minutes at 37°C. with Naphthol AS-BI (Sigma, N-2250) phosphate salt (0.5 mg/ml; Sigma) and N,N-Dimethyl Formamide (10 μg/ml; Sigma D-8654) in 50 mM Tris buffer (pH 9.0), in the presence of Fast Red (Sigma, F-2768) violet salt (1.0 mg/ml). After 30 minutes, cells were washed two times with PBS and fixed by incubation in 2% paraformaldehyde for 30 minutes at 4°C. ALP staining was viewed by light microscopy. Scaffolds were fractured into halves in order to visualize cells in the interior regions of the 3-dimensional structure.

In addition, ALP expression was quantified in each of the cell-scaffold homogenates used for fluorometric DNA analysis. For this analysis, aliquots of cell homogenates were incubated at 37°C. for 30 minutes in 0.1 M Na₂CO₃ buffer solution (pH 10) containing 2 mM MgCl₂ with disodium...
p-nitrophenyl phosphate (pNP-PO₄) as the substrate. Standard solutions were prepared by serial dilutions of 0.5 mM p-nitrophenol (pNP) in Na₂CO₃ buffer. Enzymatic activity was expressed as total mmoles of pNP produced per minute per total cell number determined by fluorometric DNA analysis. Absorbance was measured at 415 nm using a Tecan Spectrofluor microplate reader.

**Example 7**

**Alizarin Red Calcium Quantification**

The effectiveness of sodium 1,2-dihydroxy anthraquinone-3-sulfonate, commonly known as Alizarin Red (ALZ), as a chelating compound and colorometric reagent for spectrophotometric determination of calcium is well established (Wu, L. and Forsling, W. Acta Chemica Scandinavica 1992 46:418-422). ALZ spectrophotometric methods were adapted for the determination of mineralized matrix production (Stanford et al. J. Biol. Chem. 1995 270:9420-9428) on lighter than or light as water PLAGA by osteoblast-like cells. Scaffolds were removed from the bioreactor, washed in ddH₂O, and incubated in 40 mM Alizarin red solution (pH 4.2) for 10 minutes at room temperature. To remove unreacted ALZ, scaffolds were washed 5-10 times in ddH₂O (until water was clear). Scaffolds were then incubated in 10% cetyl pyridinium chloride for 15 minutes to solubilize reacted ALZ and pulsed using a tissue homogenizer (PowerGen 35, Fisher) with a 10 mm diameter saw-tooth generator. Serial dilutions of 1 N CaCl₂ were used as standards. ALZ concentration per cell was calculated as molar equivalent CaCl₂ divided by the average cell number at each time point as determined by fluorometric DNA analysis. Absorbance was measured at 570 nm using a Tecan Spectrofluor microplate reader.

**Example 8**

**Scanning Electron Microscopy**

Before seeding with cells, microcarriers and microcarrier scaffolds were coated with gold and visualized using a low field emission electron microscope (JEOL 6300) at 2 keV accelerating voltage. To evaluate cell attachment and morphology to lighter-than-water scaffolds cultured in the bioreactor, scaffolds were cultured as described above and removed at day 7 for SEM analysis. Attached cells were fixed to scaffold substrates by washing thoroughly with PBS, then incubation in 1% and 3% glutaraldehyde for 1 hour and 24 hours, respectively. Following fixation, cells were washed with PBS, placed through a series of graded ethanol dehydrations and allowed to air dry. Finally, cell-scaffolds were coated with carbon and analyzed at 2 keV.

**Example 9**

**Statistical Analysis**

Statistical analysis was performed using JMP IN 3.2.1 software. One-way ANOVA was performed to determine any statistically significant relationship between the rotating and non-rotating conditions with respect to the quantity of reacted ALZ, ALP expression, and cell number. Statistical significance was attained at p<0.05. Three scaffolds were analyzed at each time point and for each quantitative assay.

What is claimed is:

1. A scaffold for tissue engineering comprising a 3-dimensional network of microcarriers, said microcarriers comprising at least one biocompatible, biodegradable organic polymer and individually presenting an organic polymer surface to adjacent microcarriers and having densities less than or equal to that of water, wherein adjacent microcarriers are fused to one another at an interface, each interface comprising a region of direct polymer-polymer contact, and wherein the 3-dimensional network of microcarriers further comprises a network of interconnected pores.

2. The scaffold of claim 1 further comprising cells.

3. The scaffold of claim 2 wherein the cells comprise osteoblast cells or cells exhibiting an osteoblastic phenotype, endocrine cells, fibroblasts, endothelial cells, genitourinary cells, lymphatic vessel cells, pancreatic islet cells, hepatocytes, muscle cells, intestinal cells, kidney cells, blood vessel cells, thyroid cells, parathyroid cells, cells of the adrenal-hypothalamic pituitary axis, bile duct cells, ovarian or testicular cells, salivary secretion cells, renal cells, chondrocytes, epithelial cells, nerve cells or progenitor cells.

4. The scaffold of claim 1 wherein the microcarriers are hollow.

5. The scaffold of claim 1 wherein the network of interconnected pores defines a scaffold porosity, and said porosity is 31% of the total volume of the scaffold.

6. The scaffold of claim 1 wherein the network of interconnected pores is characterized by a pore size, and the pore size of the scaffold is in the range of from 113 to 356 microns.

7. The scaffold of claim 1 wherein the biocompatible, biodegradable polymer comprises a polylactic acid, a polylactide, polylactide-co-glycolide, a polyglycolic acid, or a polycaprolactone, a polyhydroxybutyrate, a degradable polyurethane, a polyhydroxycaproate, a polyglycolide, a polyanhydride, or a polylactide-based polymer or mixture thereof.

8. The scaffold of claim 1 wherein the biocompatible, biodegradable polymer is a polylactic acid polymer or a polylactide/polyglycolic acid copolymer or mixture thereof.

9. The scaffold of claim 1 wherein the microcarriers are microspheres and the diameter of the microspheres is in the range of 100 to 860 microns.

10. The scaffold of claim 1 wherein the microcarriers are microspheres and the diameter of the microspheres is in the range of 100 to 500 microns.

11. The scaffold of claim 1 wherein the microcarriers have a density in the range of 0.6 to 0.99 gram per cubic centimeter.

12. The scaffold of claim 1 wherein the microcarriers have a density in the range of 0.6 to 0.99 gram per cubic centimeter.

13. The scaffold of claim 2 wherein the cells are attached to the scaffold by seeding, said seeding being achieved via culturing in vitro in a rotating bioreactor.

14. The scaffold of claim 3 wherein the cells comprise osteoblast cells, cells exhibiting an osteoblastic phenotype, or progenitor cells or mixtures thereof.

15. A method for producing the scaffold of claim 1 comprising:

(a) preparing microcarriers comprising at least one biocompatible, biodegradable organic polymer and individually presenting an organic polymer surface and which have densities less than or equal to that of water;

(b) organizing the microcarriers so that the polymer surfaces of adjacent microcarriers contact one another; and

(c) bonding the biocompatible, biodegradable polymer-based microcarriers into a scaffold, such that the bonding occurs directly between the organic polymer surfaces of adjacent microcarriers.

16. The method of claim 15 wherein the bonding is achieved by a process comprising heating the microcarriers at...
a temperature above the glass transition temperature but below the melting temperature of the biocompatible, biodegradable polymers.

17. A method for regenerating a selected tissue comprising seeding the scaffold of claim 1 with cells which generate the selected tissue and culturing the scaffold and seeded cells in a rotating bioreactor.

18. The method of claim 17 wherein the seed cells comprise seed cells comprise osteoblast and osteoblast-like cells, endocrine cells, fibroblasts, endothelial cells, genitourinary cells, lymphatic vessel cells, pancreatic islet cells, hepatocytes, muscle cells, intestinal cells, kidney cells, blood vessel cells, thyroid cells, parathyroid cells, cells of the adrenal-hypothalamic pituitary axis, bile duct cells, ovarian or testicular cells, salivary secretory cells, renal cells, chondrocytes, epithelial cells, nerve cells or progenitor cells.

19. The method of claim 17 wherein the scaffold in the rotating bioreactor moves within the rotating bioreactor in a near circular particle trajectory.