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ScienceDirect

Ceramics International 40 (2014) 9583–9589

CERAMICS INTERNATIONAL

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Effect of capillary action on bone regeneration in micro-channeled ceramic scaffolds

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Received 7 January 2014; received in revised form 8 February 2014; accepted 9 February 2014
Available online 24 February 2014

Abstract

A new scaffold design was introduced with macro-pores and micro-channels, which greatly assisted in the initial bone marrow absorption and uniform cell distribution. Unfortunately, the underlying scientific reasons for the new scaffold's efficiency are currently unknown. Hence, we approached using a mathematical and experimental method to elucidate the new scaffold's efficiency. The mathematical formula describe rising fluid height in a narrow cylindrical vessel due to capillary action. Through the mathematical simulation, the maximum fluid heights at equilibrium for scaffold tubes of diameters 50, 150, 350, and 750 μm were 156.6, 52.7, 22.6, and 10.5 mm, respectively. The fluid would theoretically reach 90% of the maximum height at 900, 30, 3, and 0.3 s, respectively. In the experiment, the fluid heights were observed from 30 to 600 s. All the scaffolds had 50 μm micro-channels with different macro-pore sizes of 150, 350, and 750 μm. The media rose through macro-pores of the three scaffolds until 40, 15, and 10 mm, respectively. The fluid heights were observed at about 2 s and 0.5 s after being immersed for the 350 μm and 750 μm macro-pore scaffolds. In the case of the 150 μm sample, the fluid height was 30 mm at about 30 s and 40 mm at about 75 s. Since all samples had 50 μm micro-channels, the fluid reached to the top of the scaffolds, eventually. The results showed that capillary action was highly dependent on the size of the tubes within the scaffold. They also confirmed the simulated data in both equilibrium height and the time trajectory. The data from both the experiment and the mathematical simulation proved our hypothesis that capillary action was the cause for the improvement in cell immigration in the new scaffold since the data matched each other in both equilibrium height and the time trajectory.

Keywords: Absorption; Bone regeneration; Capillary action; Distribution; Micro-channel

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1. Introduction

Bones are important vital components of the skeletal system. They serve numerous functions such as protecting important organs including brain and heart, body support, moving muscles and joints, storing minerals and fat, acid–base balance, and synthesizing blood cells [1]. Bone defects could occur due to trauma caused by accidents, sports injuries, tumors, osteoporotic fractures, or other diseases and infections [2]. Despite the progress made in bone regeneration in recent years, it still has many clinical obstacles that prevent doctors to comfortably use regenerative techniques on patients. One such advancement is the scaffold, which is an artificial structure capable of supporting three-dimensional bone regeneration. However, treatment of large bone defects is still currently a major clinical dilemma [3]. Therefore, there must be an effective method of bone regeneration so that bone defects and injuries can be successfully treated by orthopedic surgery.

Tissue engineering is the use of a combination of cells, engineering, special materials, and suitable biochemical and

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http://dx.doi.org/10.1016/j.ceramint.2014.02.033

physio-chemical factors. The goal of using engineered tissue is to replace or restore native tissue functions. Scaffolds are artificial structures capable of supporting three-dimensional tissue formation [4–7]. In order to work correctly, these scaffolds must mimic natural bone characteristics such as pore size, porosity, interconnectivity of the pores, and permeability. If these scaffolds can mimic bone structure accurately, then proper cell attachment, proliferation, differentiation, nutrient flow and cell communication, which are all crucial for proper bone healing, can be achieved [8–11]. Unfortunately, current scaffold structures limit active initial cell infiltration and cell colonization use as they decrease the rate of the diffusion of oxygen and nutrients [12,13]. In order to overcome these limitations, the initial host bone marrow absorption and the quality of nutrient flow into and out of the graft must be improved through a more efficient scaffold design [14].

Recently, a novel hydroxyapatite (HA) ceramic scaffold design with macro-pores and micro-channels was introduced to enhance fluid absorption and retention [14]. This HA-scaffold has a synthetic construction that actively initiates bone marrow absorption and uniform distribution of bone marrow. On the cellular level, this HA-scaffold induced exceptional cell attachment, proliferation, and differentiation on a uniform scale throughout the scaffold. This scaffold also provided several advantages such as histo-morphometry parameters similar to those of the human lumbar vertebrae bone, high surface-area/porosity ratio, successful bone marrow absorption and retention capability, and excellent preliminary mobilization and habitation of cells in in-vitro experiments. However, the underlined scientific principles of the advantages of the micro-channeled scaffold design are not well known.

We hypothesize that hollow channels with micron-scale diameters within the scaffold exhibit highly efficient fluid absorption due to natural phenomenon called “capillary action.” More specifically, we hypothesize that capillary action would exert a fluidic force on attached cells through scaffold's micro-channels, mechanically inducing cell proliferation or differentiation. This study has two purposes. The first purpose is to estimate the maximum height the fluid would reach in samples of scaffolds with different micro-channel diameters by formulating a mathematical model describing capillary action, fluid height, and time. The second purpose is to validate the mathematical model for capillary action by conducting experiments with samples of the actual scaffolds that were matched with the mathematical model's scale.

2. Materials and methods

2.1. Physics of capillary action with real-world examples

Capillary action is the ability of a fluid to flow into narrow spaces (the micro-channels in this experiment) against external forces, such as the pull of gravity, due to cohesive forces between the fluid's molecules and adhesive forces between the fluid's molecules and the molecules of the fluid's container [15,16]. If the diameter of the tube is sufficiently small, then this combination of cohesive and adhesive forces between the liquid and container acts to lift the liquid [16]. There are several examples of the capillary action in the natural world. For example, when the bottom of a piece of paper is dipped in water, the water will actually flow higher than the surface of the water in its container. This happens because there exist very small gaps between the paper fibers into which the water can enter. The polar water molecules are attracted to the paper molecules (there is an adhesive force between them) and as a result of this, the water rises and as the water molecules rise they ‘pull up’ more water molecules with them due to the cohesive forces between the molecules. This process continues until the combination of cohesive and adhesive forces equals the downward pull of gravity. A dry paper towel absorbs liquid by drawing it into the narrow openings between the fibers [17]. The transport of fluids within plants is also an example of capillary action in nature. As the plant releases water from its leaves, water is drawn upward from the roots to replace it. In the human circulatory system, blood movement in microscopic capillaries from arterioles to venules is achieved by capillary action against the blood flowing downward due to gravity [18].

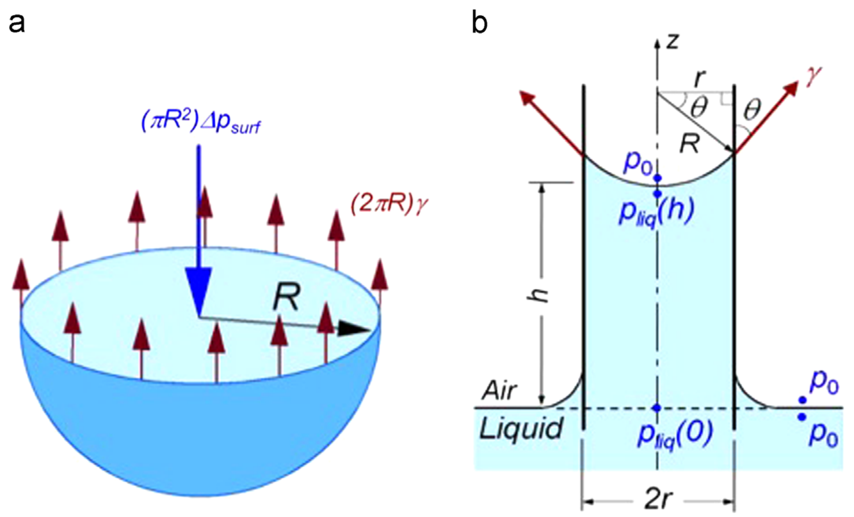

Fig. 1. (a) The free body diagram of half a droplet [19]. (b) The capillary rise in a narrow cylindrical tube [20].