
● *Short Communication*

ASSESSMENT OF THE PORE GEOMETRY OF STEREOLITHOGRAPHIC MODELS BY HIGH RESOLUTION MRI

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It is becoming increasingly evident that material strength and other mechanical properties depend not only on the density but also on the internal architecture of the structure in question. The internal structures of five different stereolithographic samples were examined noninvasively using high resolution magnetic resonance imaging (MRI). The image analysis techniques of segmentation applied to the acquired images allowed the quantification of the structural parameters mean pore size and pore separation. These parameters were quantified along many angular orientations with a spatial resolution of 0.12 mm, and their distributions clearly revealed the structural anisotropy of the samples. © 1998 Elsevier Science Inc.

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INTRODUCTION

The nuclear magnetic resonance (NMR) behaviour of liquids confined in pores has been used to infer information about the structure and mechanical properties of porous material such as porous rocks¹ and bones.² The interaction between liquid molecules and pore surfaces, and motion restriction due to pore geometry, are often quantified using nuclear magnetic resonance through the spatial measurement of spin density and relaxation times. The aim of this work is to use magnetic resonance imaging (MRI) to study pore geometry (both shape and size) through the quantification of pore size and separation and the transverse relaxation time. In this work we simplified the structure under investigation by preparing stereolithographic samples with controlled structural elements such as pore size and separation. Correlation between these MRI measurements and parameters describing mechanical strength, such as Young's modulus, are planned for a variety of samples including rocks and bones.

MATERIALS AND METHODS

MRI and Data Processing

All images were acquired using a 1.5-Tesla GE Signa clinical scanner (Milwaukee, WI, USA). Both gradient-

echo and spin-echo images were acquired in the axial plane with matrix sizes of 256×256 and 512×512 , respectively, covering a field of view of 6 cm. A gradient-echo pulse sequence was used with 10 equally spaced echo times ranging from 7–70 ms and a repetition time of 500 ms to generate T_2^* -weighted images. Images were then segmented using spin density histograms,³ which exhibited two well resolved peaks. The number of pixels occupied by water or sample material was then counted along 19 orientations with a 10° separation and expressed as pore size and pore separation, respectively. The terms pore separation and wall thickness are used interchangeably in this work.

Samples

Five cubic samples (side = 3 cm) were made using the process of stereolithographic (SL) modelling, which uses a photosensitive resin (Ciba Giegy, Nottingham, UK; XB 5154) polymerised using a scanning laser. The laser spot polymerises the resin according to three-dimensional structural information stored in a series of computer-generated slice files. For the purpose of this preliminary study a structure similar in its structural complexity to cancellous bone was created. Limited by the lateral resolution of the SL system (governed by the laser spot size), a basic SL sample of 70% porosity with

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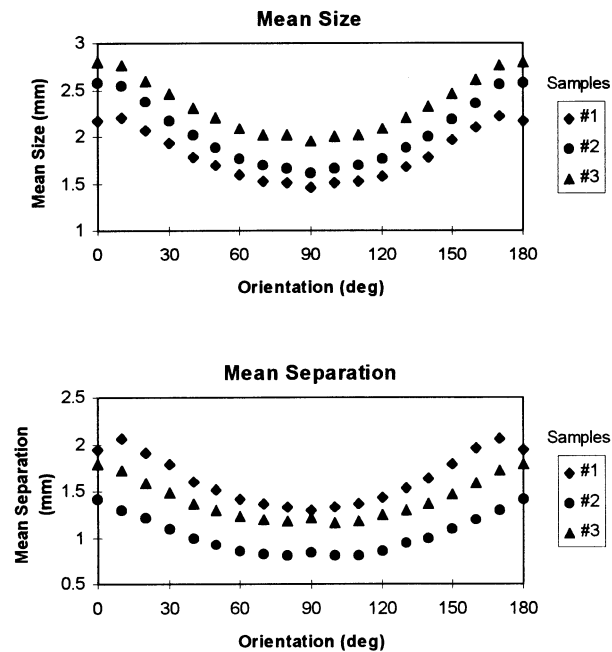


Fig. 1. The mean pore size and separation plotted for three samples in Set 1.

a wall thickness of 300 μm was initially made. Two sets of samples were then prepared by either dilatation or perforating of the wall elements. The first set contained three samples with gradually increasing pore size, but with the overall pore shape preserved. The second set contained two samples with significant wall dilatation in one of them, resulting in pore size and shape anisotropy.

RESULTS AND DISCUSSION

Set 1

The mean pore size and separation (wall thickness) were measured along 19 angular orientations (0–180°).

Table 1. Measured parameters describing the three samples in Set 1

Sample	1	2	3
Pore size (mm)	1.812	2.050	2.337
Pore separation (mm)	1.646	1.034	1.403
% Porosity (design)	50	70	70
% Porosity (MRI)	52	65	63
T_2^* (ms)	261	153	182

Figure 1a shows a plot of the mean pore size against orientation, confirming structural symmetry in the three samples with gradually increasing pore spacing. The variation of mean pore separation with orientation is demonstrated in Fig. 1b. It is interesting to note that the order of increasing pore separation is not the exact reverse of pore size. This is because although Sample 3 possesses thicker individual wall elements resulting from the dilatation of walls in Sample 2, it has fewer elements. These two factors combine to produce larger, but fewer, pores in Sample 3, but with equal porosity.

T_2^* maps for these samples were produced by fitting individual pixels from T_2^* -weighted images to a single mono-exponential decay function. Further work is being carried out to quantify T_2 . Mean T_2^* values, averaged over a large region of interest, are shown in Table 1, along with the mean pore size and separation averaged over all orientations. Sample porosity, as measured by the SL manufacturer and by MRI, are also shown. These results show a corresponding reduction in T_2^* with decreasing pore separation.

Set 2

Figure 2 shows an example of high resolution (0.120 mm) spin-echo images of the two samples studied in Set 2. Due to the extent of the dilatation process, pore shape

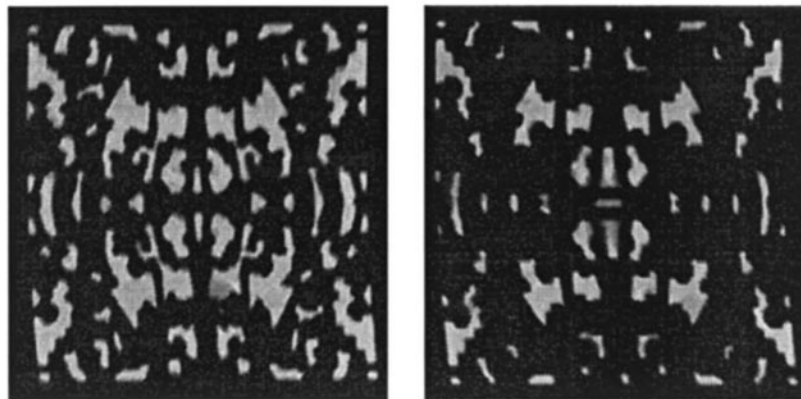


Fig. 2. High-resolution spin-echo images for samples in Set 2.

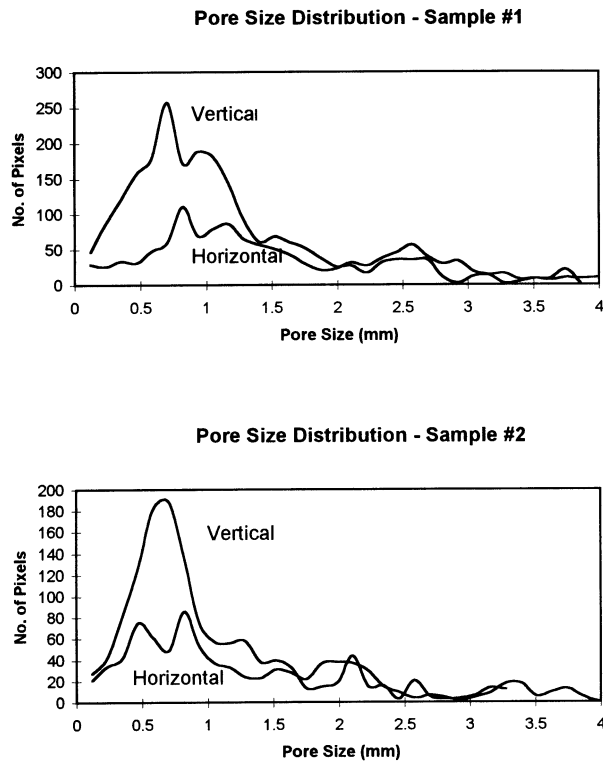


Fig. 3. The pore-size distributions along the horizontal and vertical orientations are plotted for the two samples in Set 2.

anisotropy is evident in Sample 2. To quantify this feature, the distributions of pore size along the horizontal and vertical directions were examined. For Sample 1 (Fig. 3a), the shapes of the distributions are very similar, apart from a scaling factor, with two peaks just resolved and with mean values for pore size of 1.136 and 1.838 mm. The results for Sample 2 (Fig. 3b), however, reveal the collapse of pore sizes along the vertical direction into

one dominant peak and a larger separation of the peaks along the horizontal direction. The extreme dilatation has resulted in the appearance of a group of small pores, but in significant numbers to form a single peak. The mean values for pore size are reduced to 1.008 and 1.467 mm in Sample 2 along the horizontal and vertical directions, respectively.

CONCLUSIONS

Careful examination is needed to understand the effect of pore-size distribution on the measured parameters. For example, although small pores may have a negligible contribution to T_2^* values due to the large surface to volume ratios, they contribute to the strength of the material because of greater wall thickness. In addition to the size of the pores, their spatial distribution is important to material strength, as may be addressed by connectivity measures. By studying the spatial distribution and relaxation times of water confined in porous material, information about the internal structure can be obtained. Control over the design of synthetic materials allows separation of the effects of different structural elements on the measured nuclear magnetic resonance parameters and thereafter on their mechanical properties.

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