Improved pore space structure characterization by fusion of relaxation tomography maps

G.C. Borgia [1], V. Bortolotti [1], P. Fantazzini [2], M. Gombia [3], M. Zaniboni [2]

(1) Department of ICMA, University of Bologna, Viale Risorgimento 2, 40136 Bologna, Italy

(2) Department of Physics, University of Bologna, Viale Berti Pichat 6/2, 40127 Bologna, Italy

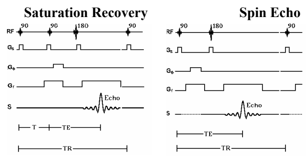
(3) Laboratory of Montecuccolino – Dept. of IENCA, University of Bologna, Via dei Colli 16, 40136 Bologna, Italy

ALMA MATER STUDIORUM
University of Bologna
Physics, ICMA and IENCA Depts
MR&Porous Media Laboratories

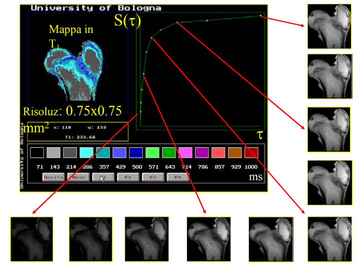
ABSTRACT

Quantitative Relaxation Tomography (QRT) in porous media furnishes maps of internal sections where each pixel represents T_1 or T_2 of water ^1H in the corresponding voxel, so that quantitative information on the pore space structure can be obtained. The porosity can be determined at different length scales by correcting pixel by pixel the signal intensity for T_2 decay. Moreover, on the basis of the distribution of T_1, the microporosity fraction can be computed, as well as several voxel-average porosities. Since T_1 and T_2 encode different pieces of information, fusion image techniques can improve the characterization of the pore space, showing simultaneously, on the same image, maps of the two parameters. Examples are given of application to a water-saturated travertine core and to a pig femur. Different kinds of look-up tables were tried by varying two of the three dimensions of the HSV color space in such a way as to optimize both the T_1 and T_2 contrasts simultaneously.

NMR ACQUISITION AND SAMPLES

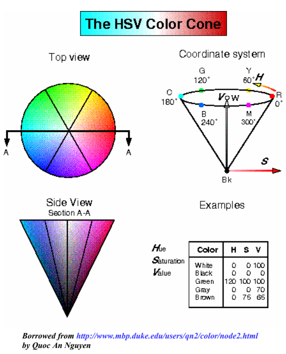


Quantitative Relaxation Tomography (QRT)[1,2] in porous media saturated by water furnishes maps where each pixel represents T_1 or T_2 or another parameter related to the evolution of the nuclear magnetization of ^1H in the voxel. Thanks to the correction of the signal density for the T_2 decay in each voxel, QRT permits evaluation of the porosity at different length scales, from the sample, to the voxel. Because T_1 of water confined in a porous material can, under favorable circumstances, distinguish regions with the same value of average porosity (local porosity), but with different values of average Surface-to-Volume (S/V) ratio (local S/V), QRT allows one to describe[2] how porosity is shared among voxels characterized by different local S/V. Moreover, parameters can be introduced such as the Micro-Porosity Fraction (MPF), defined as the pore volume fraction with T_1 less than a given cutoff time, and several voxel average porosities (VAP's), defined as the average porosities of the voxels characterized by particular classes of T_1 (and local S/V). As each time parameter encodes a different piece of information on the structure confining the water, combinations can help improve the characterization of the pore space. Fusion image techniques allow showing simultaneously on the same image the maps of two parameters, so that it is possible to see by visual inspection of the fused image the regions where the two parameters change in different ways. For example it is easy to detect regions in the examined section where one of the parameters is constant but the other changes more or less quickly. QRT can be applied to quantify different kinds of porosities in Region of Interest (ROI) chosen by inspection of the fused image.



T_1 and T_2 maps were acquired by means of ARTOSCAN™ (Esaote SpA, Genova, Italia) at 8 MHz. Data acquired at increasing echo-time for T_2 maps (SE multislice sequence) and at increasing delay time for T_1 maps (SR multislice sequence) were processed with in- house software[2] in order to generate T_2, T_1, and spin density (M_0) corrected for the proper T_2 decay of each voxel. The software generates T_1, T_2, and M_0 maps and histograms weighted by the signal in user-defined ROI's, so that MPF and VAP's in each selected ROI can be computed. Samples used were a travertine core (5 cm in diameter, 7 cm in height) and a pig proximal femur preserved in ice from immediately after slaughter up to the MRI examination.

IMAGE FUSION IN HSV COLOR SPACE AND VISUALIZATION

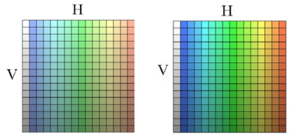


Color	H	S	V
White	0	0	100
Black	0	0	0
Green	120	100	100
Gray	0	0	70
Brown	0	75	65

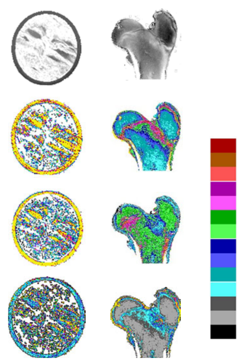
Borrowed from http://www.mbp.duke.edu/users/qn2/color/node2.html by Quoc An Nguyen

In HSV color space (see figure on the left) the entire spectra is represented by a cone; H is measured by an angle with Red located at 0 degrees, Green at 120 degrees and Blue at 240 degrees. S ranges from 0 along the center line of the cone (the V axis) to 1 on the edge of the cone. V ranges from 0 (dark) to 1 (bright). Pure Red is at (H; S; V) = (0;1;1). Shades of Gray all have S = 0, with various values of V from 0 (Black) to 1 (White).

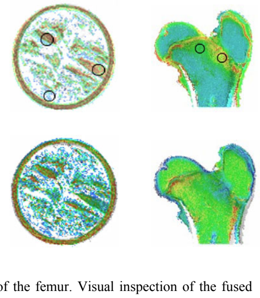
The choice of the most suitable color map is a crucial issue in the visualization of fused T_1 and T_2 images. Different kinds of look-up tables (LUT) of the fused maps were tried by varying the three dimensions of HSV (H=Hue, S=Saturation, V=Value) color space[3] in order to support more appropriately the mechanism of human vision and to improve the contrast detection with respect to Red-Green-Blue. It turns out that the best visualization of the fused images is obtained by keeping S fixed (at 0.225 for the travertine and at 0.5 for the femur, see figure below), and by associating changes of V (giving the gray scale) in the range 0.5 V_{max}- V_{max} (where V_{max} is a known function[3] of S and H) and H (giving the color scale) to T_1 and T_2, respectively, or *vice versa*.



The figures on the right show on the left an internal section of the travertine while on the right a section of the pig proximal femur. From top to bottom the images show M_0, T_1, T_2 and T_1/T_2 with the corresponding LUT. The ranges of the parameters are: $0 < T_1 < 3000$ ms, $0 < T_2 < 600$ ms, and $0 < T_1/T_2 < 14$ for the travertine and $0<T_1<600$ms, $0<T_2<130$ms, and $0<T_1/T_2<20$ for the femur.



RESULTS



On the right, in order, the fused images of T_1 (associated with H) with T_2 (associated with V), and of T_2 (associated with H) with (T_1 associated with V). The computation of MPF (cutoff-time=1.5s) in a ROI excluding the external annulus of water gives about 60%. In the fused images it is easy to distinguish regions with particular characteristics: for example, the ROI's selecting red regions have the same T_1 (the same color) and very different T_2. In both ROI's the VAP is of the order of 70%. In the third ROI, T_1 is lower, as well as the VAP (5%). In general, an increase of the VAP value with relaxation time is observed: the lower the local S/V in the voxel (larger T_1) the larger the average porosity of the voxel. This behavior is observed also after damaging the sample by many freezing-thawing cycles (images not shown). The figure shows on the right the analogous images for a section of the femur. Visual inspection of the fused images shows regions with similar T_1 and very different T_2. The two ROI's are characterized also by different VAP values (60% in the ROI at the left, with high T_2, 40% in the ROI at the right, with a lower T_2). Even if in this sample marrow ^1H are present not necessarily belonging to water, errors from variations in bone marrow composition are predicted to be small and usually negligible[4], so that VAP value is not greatly affected by the marrow composition.

CONCLUSIONS

The choice of the most suitable color map is a crucial issue in the visualization of medical and porous media NMR images. We have tried different kinds of LUT, by varying two of the three dimensions of the HSV color space. It turns out that the best visualization of the fused images is obtained for variation of Hue (H_{min} = 0° ; H_{max} = 240°) and Value (V_{min}= 0.33 ; V_{max}= 1) and having kept S fixed to 0.25.

ACKNOWLEDGMENT

The instrumentation and the data processing were funded by MURST (5% Multimedialità) and by University of Bologna (Funds for selected research topics). The authors wish to thank C. Garavaglia, F. Peddis, B. Ravaglia, and C. Vescogni for technical assistance and R.J.S. Brown for useful discussions.

REFERENCES

1. *K.P. Nott, S.D. Evans, L.D. Hall, Quantitative Magnetic Resonance Imaging of fresh and frozen-thawed trout, Magn. Reson. Imaging, 17:445-455, 1999.*
2. *G.C. Borgia, V. Bortolotti, P. Fantazzini, Changes of the local pore space structure quantified in heterogeneous porous media by ^1H magnetic resonance relaxation tomography, J. Appl. Phys., 90, No.3, 2001.*
3. *K.R. Castleman, Digital image processing, Prentice Hall, Englewood Cliffs, New Jersey 07632, 1996.*
4. *M.A. Fernandez-Seare, H.K. Song, F.W. Wehrli. Trabecular bone volume fraction mapping by low-resolution MRI. MRM 2001;46:103-113.*

Corresponding author: mirko.gombia@mail.ing.unibo.it