OPTOELECTRONICS AND ADVANCED MATERIALS – RAPID COMMUNICATIONS Vol. 2, No. 7, July 2008, p. 446 - 449

Magnetite particle utilization for blood vessel embolization - a practical modeling

GH. IACOB, AL. D. CIOCHINĂ, O. BREDEȚEAN, M. RĂCUCIU[a]*

University of Medicine and Pharmacy "Gr. T. Popa" Iaşi, Romania
[a] *"Lucian Blaga" University, Faculty of Science, Dr.Ratiu Street, No.5-7, Sibiu, 550024, Romania*

Amorphous magnetic microspheres, characterized by suitable magnetic properties and biocompatibility were conducted to obdurate artificial system of blood capillary vessels under magnetic control. Experimental tests were designed aiming to observe the building of the magnetic embolus inside a thin spiral or linear tube and to determine the influence of some parameters on the efficiency of occlusions: the dimensions of magnetic microspheres (1-300 μm), the debit of the liquid (4.66 - 16.5 ml/min), the viscosity of the carrier liquid (1.007 - 7.34 cSt), the direction and the induction of the external magnetic field (340 - 600 Gs), the shape of the tube and the linear length of the deposit (5 - 50 mm). Under pre-established experimental conditions the efficiencies of occlusions were between 67 % and 97 %.

(Received

Keywords: Vessel occlusion, Magnetite microparticles, Magnetic field

---

1. Introduction

Magnetic particles and microspheres have various applications in both technique and biomedicine. Fine magnetic nanoparticles with a narrow diameter distribution are frequently used in the form of colloidal suspensions either in hydrocarbons [1-4] and water [5-7] while magnetic microspheres have been successfully applied in magnetically assisted drug targeting [8-10]. The blood vessel magnetic embolization in laboratory conditions was tested using magnetorheological fluids [11-13], since, from the point of view of surgery medicine, the stopping of the blood flow in certain blood vessels is needed in different diseases, in the ablation of organs, but especially in tumor necrosis. Blood vessel embolization by storage of magnetite microspheres in the presence of a magnetic field was experimented in the frame of laboratory tests described below by varying granulation and rheological parameters.

2. Experimental

An experimental set-up has been designed in order to model and test the magnetic microparticle embolization (Fig.1). It contains silicon rubber system tubes of 1 mm inner diameter – either, spiral or linear – adjustable flow peristaltic pump, supply and collection pools as well as adequate magnetic sources. Amorphous magnetite microparticles (AMMP) were prepared [14] by gas – liquid atomization and ultra fast cooling, being characterized by high sphericity, smooth surface and chemical inertia. Two granulation classes of microparticles were considered for the experimental project: 0-150 μm and 150-300 μm. High energy permanent magnets (NiFeB) with magnetic induction B_0 = 340–1,600 Gs were placed in different regions of the controlled fluid flow. Carrier liquid of magnetic microspheres was consistent with glycerin in various dilutions, i.e. various viscosities.

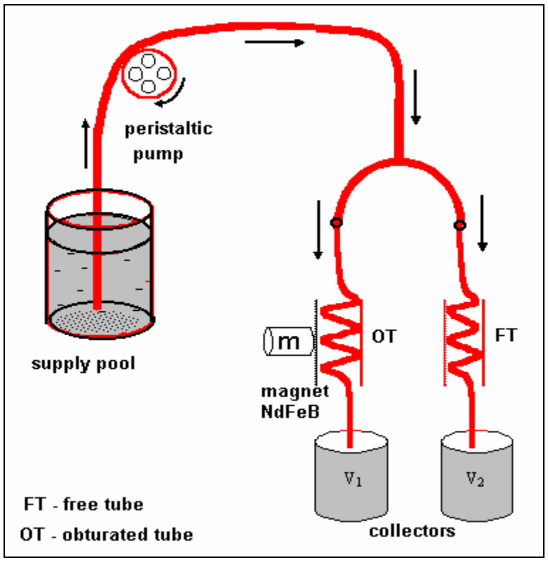

Fig. 1. Experimental set-up.

Embolization modeling was accomplished through the next stages:

- the peristaltic pump debit was adjusted (initial debit statement) by measuring the free leaking rate of the carrier fluid, D1, through the tube planned for obstruction, OT;

- the magnet was placed in certain distinct positions near the OT tube;
- the AMMP were conducted by means of the carrier fluid pumping within the OT tube;
- the variation of the carrier fluid leaking rate was measured, ΔD1, in the OT tube as indicator of embolization efficiency, taken as $E = \Delta D_1 / D_1$.

Various experimental variants were designed to evidence all notable influences of every of the physical parameters taken into account in this study: magnetic induction, microsphere granulation, viscosity and debit of the carrier fluid, tube shape and magnet position relative to the fluid flow direction. In each case the measurements were repeated five times in identical conditions to ensure statistical significance of the results (t-test application).

3. Results and discussion

In the following selected representative data obtained from experimental measurements are presented by means of average values (standard deviation ranged between 2.5% and 3.2%). Two types of magnetic material depositions (Fig.2) were obtained for various experimental arrangements - with different magnetic inductions and positions (orthogonal or parallel to the fluid flow) of the permanent magnets.

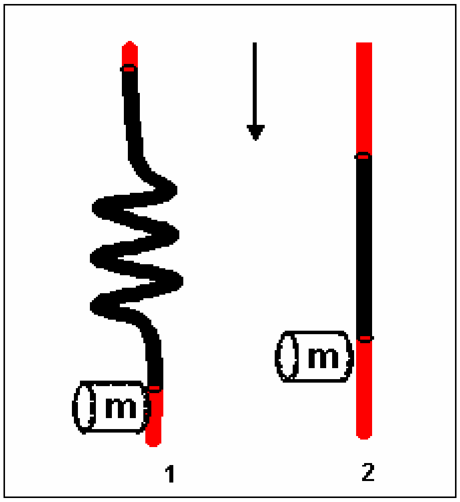

Fig. 2. Geometry of AMMP storage in the blood vessels (m – magnet placed orthogonal; arrow – fluid flow direction): 1- spiral column; 2- linear spiral column.

Most of the AMMP columns length ranged between 10 and 40 mm for both types of tube shape. The experiment A1-A6 –carried out with spiral tubes - has revealed (Fig. 3) that the embolization efficiency was practically the same when the equal values of the magnetic induction and initial debit were applied (A1-A2 and respectively A3-A4). The magnetic microsphere granulation was of 150-300 μm while the carrier fluid viscosity was of 1.007 cSt.

Variant "B" of the same experiment was carried out (Fig. 4), maintaining the same magnetic microsphere granulation class: 150-300 μm, but with more viscous carrier liquid (7.34 cSt) –viscosity ratio – when compared to the first experiment (A1-A6) - corresponding to the highest ratio value of blood (highest hematocrite) versus blood serum.

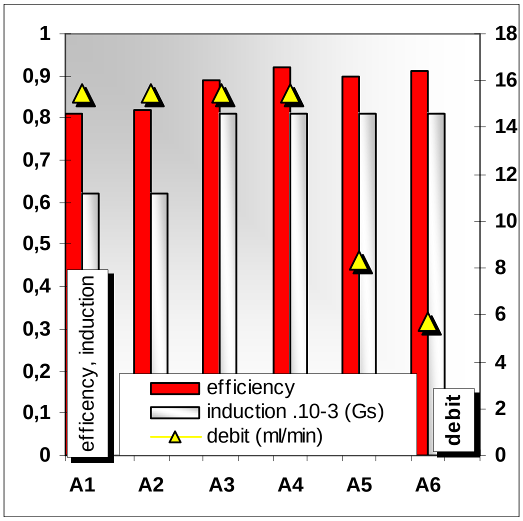

Fig. 3. Embolization efficiency for magnetic microsphere granulation of 150-300 μm and carrier fluid viscosity of 1.007 cSt (spiral tube).

The main issue is given by relatively larger magnetic induction range (340 – 620 - 810 Gs) in comparison to experiment "A" (620-810 Gs) that can result in the same range of the embolization efficiency (0.88 - 0.92 comparatively to 0.81 - 0.91) for increased viscosity (experiment "B").

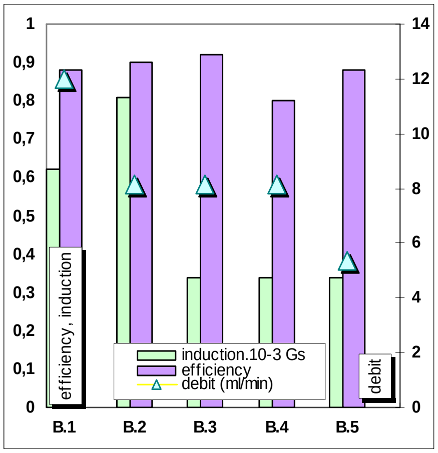

Fig. 4. Embolization efficiency for magnetic microsphere granulation of 150-300 μm and carrier fluid viscosity of 7.34 cSt (spiral tube).

To emphasize the influence of the magnetic field on the magnetic embolus formation in linear tubes, the experimental variant C1-C6 was chosen for exemplification

(Fig. 5), for constant initial debit of 8.0 ml/min and 34 cSt viscosity, the same AMMP granulation category (150-300 µm) being used as before.

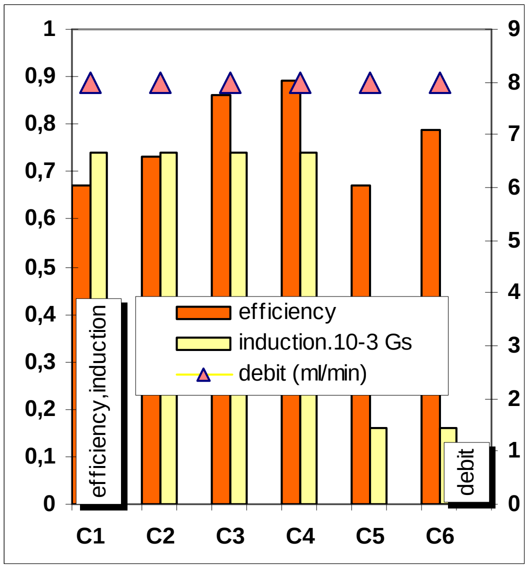

Fig. 5. Embolization efficiency for magnetic microsphere granulation of 150-300 µm and carrier fluid viscosity of 7.34 cSt (linear tube).

The differences obtained for equal magnetic induction (C1-2 versus C3-4) seems to have no relation with the magnetic induction or fluid debit – which are constant - but probably with the length of the AMMP accumulation column (dependence presented in Fig. 7).

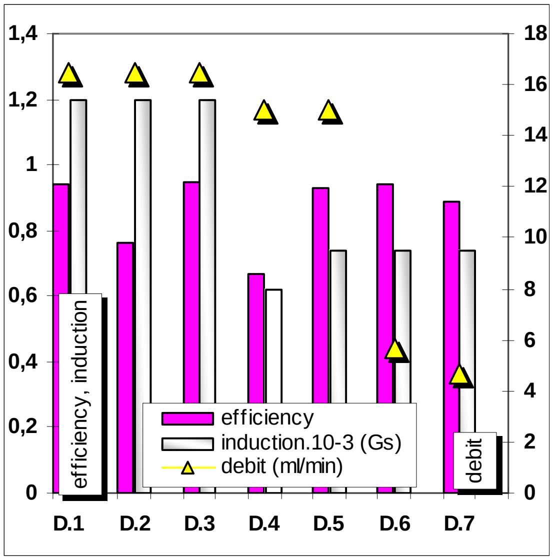

Fig. 6. Embolization efficiency for magnetic microsphere granulation of 0-150µm and carrier fluid viscosity of 3.50 cSt (linear (D1-D3) and spiral tube (D4-D7)).

In Fig. 6 some representative data resulted for the test carried out with the other granulation category: 0-150 µm and half viscosity value in comparison to previous graph (i.e. 3.5 cSt) in both linear (D1-D3) and spiral (D4-D7) tubes are given. In the linear tubes, for relatively high debit (16.5 ml/min) and magnetic induction (1,200 Gs) the embolization efficiency is smaller in D2 than in D1 and D3 though the magnetic induction and the fluid debit are the same. For the case of the spiral tubes (D4-D7) the embolization efficiency is the same for equal induction (D5 and D6) but different debit values (their ratio being higher than three).

4. Discussion

In Fig. 3 some representative embolization data corresponding to relatively low viscosity fluid and spiral tubes are presented, showing that, for constant magnetic induction, the influence of the fluid debit is hardly observable as in the experiments A4-A5-A6: the debit decrease by 50% and respectively by 66% resulted in only several percent diminution of the embolization efficiency. Column length ranged between 12 and 42 mm. Slight relative increase of the embolization efficiency in the case of A4 compared to A3 is related to the highest column length obtained in the spiral tube (dependence illustrated in Fig. 7). From Fig. 4 it results that the variability of the blood vessel obstruction efficiency – to the variation of magnetic induction or initial debit - is higher in the case of relatively high viscosity. The longest AMMP columns were yielded in the frame of this experimental variant: 20 to 52 mm – probably because the higher viscosity of the carrier fluid determines a different way of AMMP packing than for low viscosity. In the experiment "C" the same relatively high viscosity was maintained – as in the experiment "B" – but linear capillary tube response was studied (Fig. 5). The column length was smaller – it ranged between 6 and 30 mm though the viscosity is relatively high – the linear shape allowing probably more compact material deposition. The embolus length ranged between 6 and 30 mm. Although the main interest was related to the modeling of the non-linear shape vessels response – the linear ones representing few particular cases, a direct comparison between spiral and linear tubes response (experiment "D") in Fig. 6 is also presented. The length of AMMP column ranged also between 6 and 30 mm. One might suppose that, for smaller AMMP granulation (0-150 µm) and lower carrier fluid viscosity (3.5cSt), the density of the magnetite microsphere accumulation in the capillary tubes is varying also with the AMMP granulation not only with the capillary shape. Embolization efficiency data corresponding to experiment "D" appear to be not directly correlated to the magnetic induction or fluid debit so it results that the length of the magnetic material column determines the embolization differences – at equal values of both induction and debit (D1-D2-D3); similarly, the equal embolization levels were obtained at equal induction but strongly different debit values (D5-D6-D7). When the correlation between the embolization efficiency and the length of the magnetic accumulation –in both types of tubes – was analyzed (Fig. 7), it has been shown that this correlation is a logarithmic one – considering all numerical data extracted from the above discussed experiments.

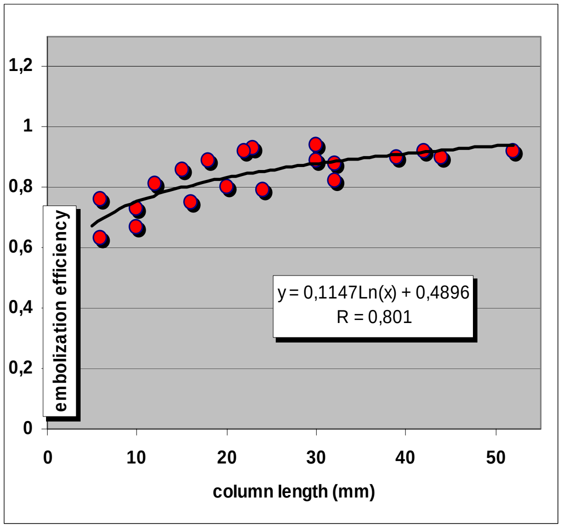

Fig.7. The dependence of the embolization efficiency on the column length.

In all the above presented experiments the fluid debits were chosen corresponding to average blood velocity, of 20-25 cm/s, through approximately 1 mm diameter capillary vessels. In these conditions it was fond that rather efficient embolization could be obtained applying relatively low values of magnetic induction. We mention that AMMP of 150-300 μm remain as a column after the magnetic source removal while the smaller microspheres 0-150 μm are carried by the fluid flow to the collector pools V. Also, arterial diameters reach various values so that the AMMP granulation class should be chosen accordingly to this parameter: for arterial vessels with 2-3 mm diameter, AMMP with maximum size could be most efficient (300 mm) while for 6 to 20 μm diameter capillary vessels, 1 – 3 μm size AMMP could be recommended. To get maximum efficiency (1.0), uniform microsphere of only 1 mm diameter was used (non-published data), which is the next stage of our research.

5. Conclusions

The utilization of magnetic microspheres in blood vessel obstruction revealed that, in laboratory conditions, embolization efficiency can reach 95% and can be controlled through the magnetic field and carrier fluid rheology. Further improvement of this experimental model is planned with monodispersed AMMP while the composition of the magnetic material could be also changed in order to obtain better magnetic features.

References

[1] B. Berkovski, V. Bashtovoy, Magnetic fluids and applications handbook, Begel House Inc., New York (1996).
[2] D. Creanga, C. Cotae, Ind. J. Pure Appl. Phys., **34**, 957 (1996).
[3] R. Massart, IEEE Trans. Magn., MAG-**17**, 1247 (1981).
[4] D. Creanga, Gh. Calugaru, J. Magn. Magn. Mater., **289**, 81 (2005).
[5] C. Gansau, N. Buske, C. Gross, W. Weitschies, Eur.Cell. Mater., **3** (2), 158 (2002).
[6] G. Matei, A. Airinei, D.E. Creanga, Acta Physica Polonica A, **109** (3) 405 (2006).
[7] N. Apetroaie, A. Roca, D.E. Creanga, J. Optoel. Adv. Mater. **7** (6), 2865 (2005).
[8] D. K. Kim, Y. Zhang, J. Kehr, T. Klason, B. Bjelke, M. Muhammed, J. Magn. Magn. Mater, **225** (1-2), 256 (2001).
[9] P. Gangopadhyay, S. Gallet, E. Franz, A. Persoons, T. Verbiest, IEEE Transactions, **41** (10), 4194 (2005).
[10] C. Alexiou, A. Schmidt, R. Klein, P. Hulin, C. Bergemann, W. Arnold, J. Magn. .Magn. Mater., **252**, 363 (2002).
[11] M. Babincova, P. Babinec, C. Bergemann, Zeitschrift für Naturforschung; **Section C**, 909 (2001).
[12] R. Sheng, G.A. Flores, J. Liu, J. Magn. Magn. Mater, **194**, 167 (1999).
[13] J. Liu, G.A. Flores, R. Sheng, J. Magn. Magn. Mater., **225**, 209 (2001).
[14] H. Chiriac, A.E. Moga, Gh. Iacob, O.C. Mungiu, J. Magn. Magn. Mater. **293**, 28 (2005).

---

[*] Corresponding author: mracuciu@yahoo.com