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Magnetic Properties of Human Blood

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ABSTRACT. Magnetization measurements have been performed on various erythrocyte samples: untreated, CO-treated, and $NaNO_3$-treated as an oxidizer. For all samples measured, the magnetization approaches saturation only at temperatures close to 4 K. Oxidization has been found to enhance the saturated magnetic moment, to almost double the moment of the untreated sample. Carbon monoxide reduces the moment of the untreated blood to about half the saturation moment. It is believed that $NaNO_3$ and CO may saturate the dangling bonds (Fe^{+3} and Fe^{+2}, respectively) affecting differently the overall magnetic moment of the Fe-ions in blood.

Introduction

Magnetic fields are used frequently for medical diagnosis and therapy. In magnetic resonance imaging, high magnetic fields are employed to generate very detailed images of the internal structures inside the body. In magnetotherapy, static and time-varying magnetic fields are employed to treat many diseases of the ambulatory system, nervous system, and skin. Therefore, it has become of great interest to study the effects of magnetic fields on human biological systems, in particular the blood.

Many studies of the magnetic behavior of blood were conducted but the information on this subject is fragmentary and often inconsistent due to the narrow range of temperatures and magnetic fields at which these studies were performed. In 1845, the English physicist and chemist Michael Faraday investigated the magnetic properties of dried blood but he never obtained any quantitative results. More than 90 years later, Pauling and Coryell (1936) were the first to report that the susceptibility of completely oxygenated arterial blood differed by as much as 20 percent from the susceptibility of completely deoxygenated venous blood. From their measurements they were able to derive the value for the effective magnetic moments of the Fe^{+2} complex, which appears in the hemoglobin of the red blood cells.

During the last few years, a study by Higashi *et al.* (1997) showed that erythrocytes in a static magnetic field were oriented with their disc planes parallel to the magnetic field because of the diamagnetism of the cell membrane components (lipid bilayer and transmembrane proteins). Another study by Bartoszek *et al.* (2001) found that hemin, the prosthetic group for hemoglobin that contains the iron atom, shows a high-field-induced magnetic anisotropy, which, similar to susceptibility, increases with decreasing temperature.

This study investigates the magnetic behavior of human erythrocytes exposed to high magnetic fields at low temperatures under different oxidation states of iron in the blood. The magnetization of the samples was measured in the temperature range 2-100 K and in magnetic fields up to 90000 Oe.

Materials and Methods

Freshly drawn samples of arterial blood were obtained from the KFUPM Medical Center. The samples were contained in evacuated blood collection tubes (Sherwood Medical, Ballymoney, Northern Ireland) containing EDTA as an anticoagulant. Within one hour after blood withdrawal, blood samples were gently centrifuged to separate the erythrocytes. The plasma and buffy coat were removed by suction and the sediments were washed at least three times with 0.9% NaCl (w/v) saline solution to obtain packed erythrocytes. The cells were then divided into three samples. One sample was kept in its present condition assuming it contains oxyhemoglobin (O_2Hh) since normally O_2 saturation in arterial blood is greater than 95%. The second sample was treated with sodium nitrate ($NaNO_3$), which oxidizes ferrous iron (Fe^{+2}) to ferric iron (Fe^{+3}) within a hemoglobin molecule. Thus, the hemoglobin is oxidized to methemoglobin (MetHb) and loses its ability to bind and transport oxygen. The third sample was saturated with carbon monoxide, which has a much higher affinity for hemoglobin than oxygen producing carboxyhemoglobin (COHb) in the blood. The three samples then were left to dry under steady flow of nitrogen gas. The dried cells from each sample were packed in a special holder that is used for magnetization measurements.

Magnetic properties of the samples were studied in the temperature range 2–100 K using a computer controlled PAR-Lake Shore 4500/150A vibrating sample magnetometer (VSM) system. The magnetic moment was calibrated using a standard Ni-sample. Temperature was monitored using a calibrated carbon-glass resistor. The temperature accuracy was 0.01 K. The maximum sweeping field was 9 Tesla.

Results and discussion

Figure 1 presents the magnetization M for erythrocytes as a function of the magnetic field H measured at a temperature of 2 K. The figure shows that the CO-saturated cells (B3) have the lowest magnetization for all applied fields. Initially, the magnetization rises linearly having a slope of 2.125×10^{-2} emu/g/kOe. The magnetization rises to a saturation value of about 0.13 emu/g before it starts dropping. The drop may indicate the strengthening of the diamagnetic behavior, which is exhibited by most biological molecules, over the weak paramagnetic behavior. The low saturated magnetization for these cells reflects a lower contribution of Fe^{+2} ions to the magnetization.

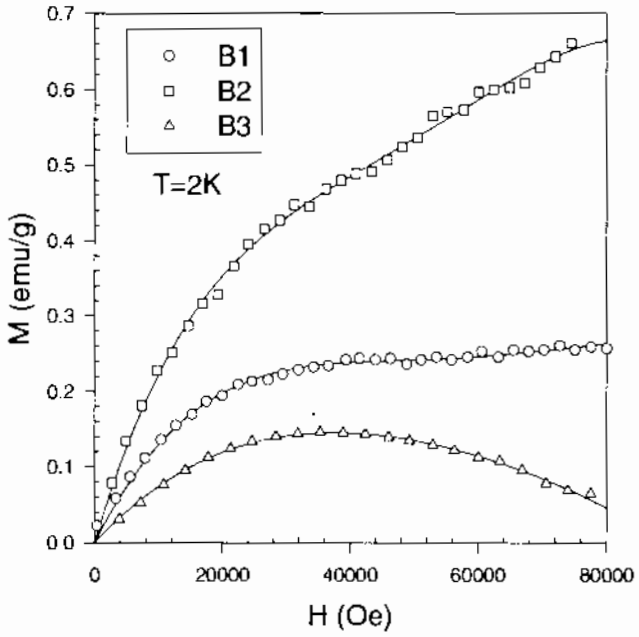

Fig. 1. Magnetization of erythrocytes as a function of magnetic field measured at 2 K. B1: untreated cells, B2: $NaNO_3$-treated cells, and B3: CO-saturated cells.

On the other hand, the same figure shows that the $NaNO_3$-treated cells (B2) have the highest magnetization for all applied fields. The slope of the initial rise of magnetization for B2 is 3.3×10^{-2} emu/g/kOe and the saturation value for B2 is about 0.25 emu/g, both of which are much higher than the corresponding values for B3. These differences in magnetization between B2 and B3 cannot be explained in terms of the changing shape anisotropy of blood cells (Bartoszek and Drazga, 1999). Instead, these differences may reflect the different iron atom content of the two oxidation states Fe^{+2} and Fe^{+3} in each sample. Therefore, the high saturation value of the magnetization in $NaNO_3$-treated cells may be due to the presence of Fe^{+3} ions, where Fe^{+3} has a higher magnetic moment than Fe^{+2}.

The magnetization for the untreated cells (B1) lies in between the other two samples with an initial slope of 2.3×10^{-2} emu/g/kOe and a saturation magnetization of about 0.18 emu/g. This reflects the fact that the untreated cells contain a mixture of Fe^{+2} and Fe^{+3} ions, but to a lesser extent than the $NaNO_3$-treated cells.

The temperature effect on the magnetization is studied for the untreated cells (B1) and the data is presented in figure 2. The figure shows the magnetization M for the untreated cells in the temperature range 2–20 K. The magnetization at the lowest temperature approaches saturation in magnetic fields above 3 Tesla. As the temperature increases to above 10 K, the magnetization starts increasing linearly with the field. This behavior indicates that the sample is exhibiting paramagnetic behavior at about 10 K, in agreement with the results of Bartoszek *et al.* (2001). This group investigated the magnetic susceptibility of hemin and found an anomalous drop of about 60% in the range 2–10 K.

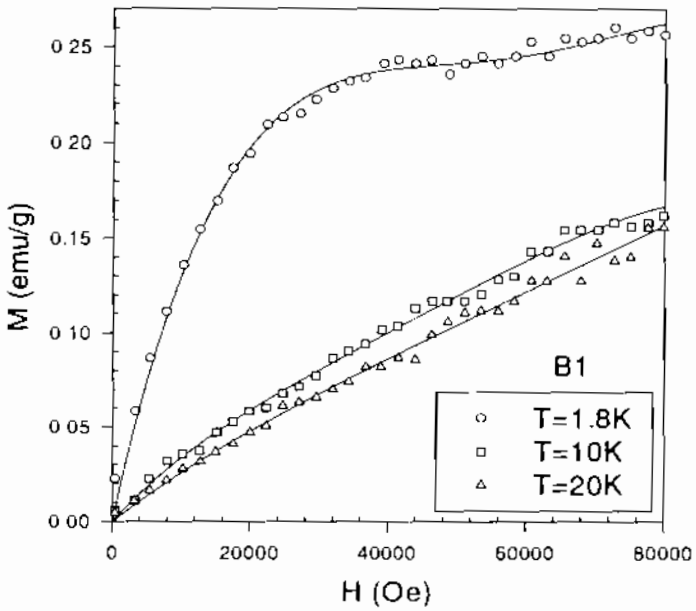

Fig. 2. Magnetization of untreated erythrocytes as a function of magnetic field measured at temperatures in the range 2–20 K.

The magnetic energy, as represented by the area under the magnetization curves, is shown in figure 3 for the untreated cells. The energy drops sharply as the temperature approaches 10 K, above which temperature, the magnetization shows pure paramagnetic behavior. Once again, the energy drop in the rauge 2–10 K is similar to the drop in the magnetization.

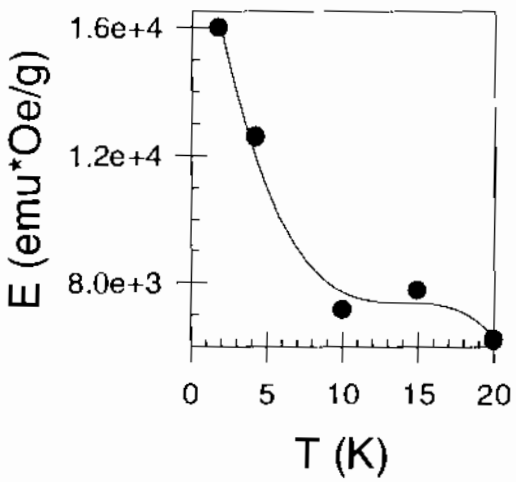

Fig. 3. Magnetic energy of untreated erythrocytes as a function of temperature.

Conclusion

Magnetic measurements have shown that the more the Fe^{+3} content in a blood sample the higher its saturation magnetization. Erythrocytes treated with $NaNO_3$ had higher concentrations of Fe^{+3} than untreated cells and therefore exhibited the highest

magnetization. Erythroeytes treated with CO had minimal concentrations of Fe^{+3} than untreated cells and thus showed significant reduction in their saturated magnetization.

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الخصائص المغناطيسية لدم الإنسان

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المستخلص. تم قياس المغناطيسية لعينات دم متنوعة غير معالجة، ومعالجة بغازات مختلفة (الأكسجين وأول أكسيد الكربون). قاربت المغناطيسية حدّ الإشباع في كافة العينات عند درجات حرارة أقل من ٤ كالفن. وُجد أنّ الأكسجين يزيد من عزم التشبع المغناطيسي إلى حوالي ضعف العزم للعينة غير المعالجة، وأنّ أول أكسيد الكربون يقلل من عزم التشبع المغناطيسي إلى حوالي نصف العزم للعينة غير المعالجة. من المعتقد أن التشبّع بالأكسيجين وبأول أكسيد الكربون قد يشبع الروابط الحرة التي تؤثّر على العزم المغناطيسي الكلي لأيونات الحديد في الدم بطرق مختلفة.