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RESEARCH PAPER

A review of the Effects of Magnetic Field on main blood cells: in vivo and in vitro experiments.

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A B S T R A C T:

Background: Magnetic field has being used in diagnostics for decades such as MRI. Sources of magnetic field were found in electronic devices and may emit extremely low intensity of magnetic field. Beside the daily use of electronic devices, there are some concerns regarding to side effects of magnetic field produces on living cells. Main Blood cells parameters were considered, and Red blood cells have targeted as the main and most affected by magnetic field. Concerns to blood, any abnormality in shape, aggregation, count may cause inflammations or chronic diseases such as anemia.

Objective: In this review, we evaluated the previous works carried out to investigate the effect of static and time varying magnetic fields on rheological properties (blood parameters, viscosity and DNA strand break) of blood between periods from 1980-2019. We provided up-to-date state of research articles and the latest progress. Different intensities of magnetic fields (week, moderate and strong) were looked at.

Result: Seventy two published research articles were reviewed. This shortened to thirty eight articles in respect to our goal. The chosen articles studied the biological effect of magnetic field on human and animal in vivo and in vitro experiments. A few theoretical studies were pointed to. Inconsistent results were compared.

Conclusion: Magnetic fields can be static or time varying as frequency is not zero. Blood counts responded to external magnetic field with altering in counts, aggregations, change in viscosity and DNA strand break. RBCs aggregation increased as blood is affected by magnetic field. Whole blood viscosity enhanced the aggregation of red blood cells. Raise in aggregation changed the time flow of blood in microcirculations.

KEY WORDS: Magnetic field; blood counts; hematological parameters.
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1. INTRODUCTION

Magnetic fields (MF) can be static or pulsed (time varying field). Static magnetic field (SMF) is known as a zero hertz, whereas, pulsed magnetic field (PMF) has non-zero frequency. SMF is generated using a DC current or obtained from a permanent magnet whereas the direction of charges is constant. The strength of SMF intensity is classified into categories: week magnetic field [Vergallo and Dini, 2018]. PMF is generated from alternating current in which the direction of the field varies regarding to the frequency. The PMF of extremely low frequency (ELF) is known as a field with frequency below 300 Hz [Hashish et al., 2008].

Sources of MF are varieties. Moderate sources of SMFs include transportation system (electric trains, metro, trams, cars,…ect), industrial process (aluminum production) and some medical diagnostic machines. A 2 mT of SMF produces inside trams exposing users living cells. SMF and PMF were detected in metros and cars [Halgamuge et al., 2010, Chadwick and Lowes, 1998]. MRI generates a high SMF. ELF-EMF produces in heaters, high voltage

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transmission lines, some household appliances and domestic installations.

Research articles revealed influences of ELF on blood cells [Dasdog et al., 2002, Salem et al., 2005, Amara et al., 2006 and Zaghloul, 2011]. The effects of chemical substances on biological system were introduced intensively. [Qader and Hawezy, 2019, Maulood and Mahmud, 2016]. Yet, the biological effect of non-ionization radiation is controversial [Ismail, H., 2015]. The effect of MF on living cells, red blood cells (RBCs) aggregations, rotations and magnetizations [Iino, 1997 and Sağdilek et al., 2012], DNA single and double stand break [Ali, 2018 and McCann, 1998], viscosity of blood [Kenjereš, 2008 and Mohaseb et al., 2017], heating, body weight, oxidative stress, blood pressure, brain tissue, circulation system, blood proteins, PH and ect. were studied. Similar and contradict results were introduced. Most of in vivo radiobiological experiments were conducted on rats and mice. Therefore, a few studies were conducted on human. The results are controversial.

Blood is known as a biomagnetic fluid due to excising positively and negatively charged particles and molecules such as proteins and erythrocytes. The negatively and positively molecules are due to unbounded (or free) electrons in outermost shells. Existing electrically charged molecules can be a reason where rheological properties of blood respond to MF. Blood parameters can act as paramagnetic or diamagnetic. However, RBCs act in two different ways: paramagnetic or diamagnetic, depending on their oxygenated state [Bansi et al., 2018].

RBCs are large molecules with mean volume of (90 μm^3) and major diameter of (8 μm) [Haik et al., 2001]. They surrounded with a special membrane which allows the cells to bend and stretch while they are passing through tiny blood vessels [Ye et al., 2016 and Kizilova et al., 2018]. Inside RBCs, there is tremendous number of hemoglobin (Hb). Hemoglobins are molecules carrying oxygen and carbon dioxides. Each Hb has four binding sites attached to iron molecules. Hemoglobin iron molecules can be another reason where RBCs can behalf as paramagnetic [Haik et al., 2001].

To study the effect of MF on blood cells, a wide range of researches were conducted theoretically and practically. Investigations have shown RBCs are aligning in a direction of applied external magnetic field (magnetization). The same behavior was approved to platelets (PLTs) [Bansi et al., 2018]. PLTs and RBCs aggregations were also investigated [Keating et al., 2008 and Keating et al., 2011]. Generally, there are a multiple types of aggregation recognized. First, in normal blood itself, specific particles and molecules intermediate closing cells or aggregations. This is called rouleaux. The second is closing or aggregating molecules in blood under the effect of an external force (MF). Regarding to the effect of magnetic field, temperature stability must be preserved.

2. RED BLOOD CELLS AGGREGATION

Aggregation is the main effect causes blood viscosity [Iino, 1997]. Under no effect of magnetic field, limited range of RBCs aggregations were investigated in vivo and in vitro experiments. These types of aggregations are called rouleaux formation and they are reversible [Rmpling et al., 2004, Bäumler et al., 1999 and Kizilova et l., 2018]. The process of rouleaux formation and disassociation are continuous. Explaining the aggregation pattern can be simple. Tiny molecules and proteins exist in blood and contribute in rouleaux formation [Iino, 1997 and Sağdilek et al., 2012].

In this review, we highlight important results of published research articles regarding to the effect of MFs on blood parameters and rheological properties, published from period 1980-2019. Red blood cell aggregation, WBCs, PLTs, blood viscosity and DNA strand break are considered. Effects of SMF and time-varying MF effects will be discussed.

3. LITERATURE REVIEW

Blood flow and microcirculation were studied intensively during last decades. In vitro and in vivo experiments showed variations of blood flow under the effect of MF. The effect of SMF on blood flow of mice was investigated by [Xu et al., 2001]. Tibialis anterior muscle blood was measured using fluorescence epi-illumination system. An exposure of SMF as small as 1 mT for

10 min increased the blood velocity in range of 20% to 45% at 45 min post exposure. However, no increase was seen during the exposure. The same experiment was repeated for time varying MF (50 Hz). Compare to SMF, blood velocity has raised 26% during the exposure. At lower exposure (0.3 mT), both SMF and time varying MF showed zero effect. Exposed animals with SMF at 10 mT changed the blood velocity simultaneously, from 15% to 45% from the beginning to the end of the exposure respectively. The researchers set 1 mT as the threshold valued of hematological change in mice blood.

A similar research was carried out by [Gmitrov et al., 2002] using a higher dosage of MF. They studied the effect of SMF on blood circulation of cutanous tissue in ear lobe of rabbit. Irradiation with MF at 0.25 T during 40 min increased 20% to 40% of the blood flow velocity in microcirculation in the tissue. This is in compare to control samples. The changes started significantly after 10 min of exposure and continued till 20 min after exposure. Concluded that, at a high dosage of exposure, SMF starts to alter flow velocity during exposure.

Peripheral hemodynamic was examined under the effect of 8 T by [Ichioka et al., 1998]. The in vivo experiment observed changes in microcirculatory hemodynamic of dorsal skin of rats using videomicroscopy. Blood flow rate raised 17% at post exposure, 1-5 min after exposure. However, the flow returned to its normal condition after 10 min of exposure. The same researchers [Ichioka et al., 2000] curried out another experiment and studied the whole blood flow property. A field intensity of 8 mT was used. In compare to their previous experiment, changes of blood flow started during exposure simultaneously. They concluded that blood flow of skin reduces at the baseline and returns to baseline 20 min after exposure.

[Schuhfried et al., 2005] studied the effect of time varying magnetic field on microcercuation and temperature alteration of volunteer human feet. Low dose-low frequency (100 μT, 30 Hz) and a higher dose-low frequency (8.4 mT, 10 Hz) field were exposed to 12 healthy male and female volunteer. Treatments were applied to individuals for one week similarly at the same time every day. Both microcirculation and temperature were measured from great joys and dorsum of the foot every 5 min during and 5-10 min after exposure. For both conditions of exposure, a decrease in microcirculation and temperature drop was reported. However, no significant changes of blood parameters were seen. As a conclusion, exposure did not improve microcirculation in healthy human. At the same pattern, [Lim et al., 2009] has studied the temperature dependence shear stress on aggregation. Shear rate examined at 4, 10, 20, 30 and 40 ^{0}C. Shear rate decreased as temperature increased.

Blood flow was examined under a higher dosage of MF. [Ueno et al., 1986] studied the time varying MF effect on blood flow using laser Doppler flowmeter. Hands of volunteers exposed with magnetic field (16, 32 and 48 mT, 3.8HZ). Blood flow reduced at exposure of 32 and 48 mT. This result shows the non-similar pathological effect of PMF and SMF at a higher intensity as shown by [Gmitrov et al., 2002].

A change of blood viscosity alters blood flow rate and velocity in blood vessels. Viscosity of blood was studied under the effect of MF. Blood viscosity was measured directly or indirectly. In addition, time flow of blood in capillary tubes was also studied as a mirror of blood viscosity. The effect of SMF on human blood viscosity was studied by [Haik et al., 2001]. They measured time flow of blood using capillary tube (3 mm in diameter) considered change in blood viscosity. The tube was set between sources of MF. First, time flow of blood was measured under the effect of gravity and then under the effect of SMF. Increasing the field intensity increased time flow continuously. The 10 T of SMF decreased blood flow rate by 30%. They believe that this reduction is due to an increase in blood viscosity under the effect of SMF. The torque exerted by the SMF will increase association of plasma particles to aggregate RBCs which causes blood viscosity to increase. This result is inconsistent to that shown by [Ueno et al., 1986] using a closely similar MF exposure as they present the flow rate increases under the effect of SMF.

Blood viscosity dependency on high SMF was examined by [Yamamoto et al., 2004]. Oxygenated blood samples were collected from healthy human. 1.5 T has applied to blood samples passing through an Ostwald viscometer tube. Results showed an increase of blood viscosity. They believe that oxygenated blood and shear rate of blood flow selects the status of blood

viscosity. Additionally, 1.5 T can alter the blood flow rate.

Relative blood viscosity can be measured easily using classic techniques or tools. [Elblbesy, 2014] has measured relative blood viscosity using a syringe. Easily, 2 mL of blood was loaded into a 5 mL syringe and allowed the blood to flow under normal gravitation. The time of flow was measured. The same experiment was repeated for de-ionized water and then relative blood viscosity was measured. This method can be used to study the effect of magnetic field on blood flow by leaving the syringe between two magnets, similar technique as used by [Haik at al., 2001].

Blood viscosity can also be measured using digital viscometer or rheometers such as microviscometer of brookfied viscometers. The advantage of using digital viscometers is that where small amount of blood samples are required and also results can be achieved more accurately. Blood viscosity can also be measured under different shear rates. Brookfield DV-III Programmable Rheometer was used to measure blood viscosity directly [Baieth, 2008] for blood collected from albino rats at in-vivo experiments. Sixteen coils were used to form a setup of magnetic field. The field was exposed to rats directly and bloods were collected after exposure. Blood viscosity reduced as magnetic field exposure increased. 0.3, 0.5 and 1 mT (50Hz) changed the blood viscosity continuously in compare to control samples. This result is inconsistent to that shown by [Haik et al., 2001] used SMF. Shear rate reduced as viscosity increased. RBCs counts and HTC percentages increased significantly as animals' espoused under 0.5 mT.

One mathematical model studied the effect of non-uniform magnetic field on blood flow [Kenjereš, 2008]. The effect of MF on Oxygenated and deoxygenated blood were examined. A cylinder with a size similar to arties programmed to study the blood flow time. A 10 T of MF affected oxygenated blood slightly and less significantly than that of de-oxygenated blood, due to the fact that magnetic susceptibility of deoxygenated blood is higher than that of oxygenated blood. Blood viscosity was measured experimentally under the effect of SMF using rheometers of different shear rates [Marcinkowska, 2013]. The experiment was performed in vitro for healthy blood samples. No significant changes reported.

In another experiment blood viscosity has determined for human blood samples under different shear rates. A rheometer was used. Relative blood viscosity reduced under the effect of magnetic fields. Drookfield DV-lll viscometer was also used by [Mohaseb et al., 2007] to measure the blood viscosity. Rats were exposed to 0.3 mT (50 Hz) for 21 and 45 days. Both groups of espoused animals showed a significant increase of whole blood viscosity compare to control samples. Their result was obtained using optical microscopic images.

Blood viscosity of polycythemia disease was examined under 1.5 T MRI magnetic field [Kadhim et al., 2016]. The U-tube viscometer and mathematical formula were employed to extract the viscosity of blood samples. Exposure time was extended from 1 min to 21 min. Samples were collected from unhealthy men ages between 28-48 years old. The results showed a decrease of blood viscosity as magnetic field is increased. The 1 and 15 min of exposure resulted the maximum alteration.

Hematological parameters such as RBCs, WBCs and PLTs counts were studied under the effect of MF. Abnormality of blood cell counts cause cardiovascular diseases. An Increase of leukocyte counts cooperate an increase of death risk caused by ischemic heart disease with 65%. Blood viscosity and oxygen supply causes by haemoglobin concentration and associate with ischemic heart disease in men [Maulood, 2018]. [Dasdog et al., 2002] studied PMF effect on blood rheological properties. 16 male wielders (subjected 3-4 hrs per day and each has experienced 10 years fin welding) and 14 healthy males (as control group) were participated. Samples were selected with no chronic diseases and all having regular life style. The result shows a significant difference in hematocrit. However, other blood parameters such as RBCs, WBC and PLTs are almost similar to that of control groups.

Treating blood with micro molecules are paid attention in hematological research area. The effect of SMF (one hr per day for 30 selective days) on blood parameters were studied by [Salem at al., 2005] for blood of albino rats with and without zinc treatment. Untreated Rats and treated rats with zinc were exposed to SMF. Blood

samples were withdrawn and examined. Inconsistent to that shown by [Dasdog et al., 2002], the results showed an increase in blood parameters: Hb, WBCs, RBCs. The hematocrit has not changed. WBCs and PLTs have not increased under the zinc treatment. Hematocrit is almost unchanged with zinc or without zinc treatment. This result drives the rule of zinc molecules to resist alteration of blood parameters under the force produced by SMF.

Wistar rats were exposed with 128 mT of SMF in a duration of one hr/ 30 [Amara et al., 2006]. Groups of a six wistar rats were prepared under ambient condition. Each group was exposed for a selective week or weeks. The first week of exposure did not change the body weight and blood parameters significantly. From the second week till 14 days, body weight and blood parameters started to change rapidly. By the end of the month, the average body weight reduced from 215-200 gr. WBCs, RBCs, Hb, Ht% and PLTs have changed from 11.35 ± 0.16 - 13.68 ± 1.42, 7.29 ± 0.03 - 7.82 ± 0.15, 11.98 ± 0.15 - 13.2 ± 0.26, 34.06 ± 0.32 - 35.37 ± 0.69 and 566.33 ± 15.08 - 626 ± 14.04 respectively.

A similar experiment was conducted by [Chater et al., 2006]. 128 mT of a SMF applied on Wistar Pregnant rats at day 6 to day 19, each day for 1 hr. Thirteen days of exposure changed some blood properties: hematocrit increased by 6%, Hb by 12%, and blood glucose increased. Releasing insulin decreased and that leads to diabetes. Body weight reduced slightly due to MF exposure. RBCs changed from 7.36 ± 0.24 to 7.78 ± 0.48, WBCs changed from 10. 61 ± 0.72 to 10. 28 ± 0.37.

[Cakir et al., 2009] has studied the hematological properties of blood in vivo experiments under the effect of extremely low frequency MF. Female wistar rats were divided into a control and two exposed groups (50 days and 100 days). Each group was irradiated with 0.97 mT for 3 hrs a day. Hb and eosinophil were decreased significantly for 50 days exposure in compare to control group. Body weight, lymphocyte, monocyte, leukocyte, neutrofil, and basophil, counts have not changed significantly. RBCs have reduced slightly under the effect for 50 days (7.77 ± 0.27 - 6.76 ± 1.9). Therefore, RBC has increased slightly after 100 days of exposure (7.34 ±1.27 - 7.59 ± 0.54). WBCs reduced slightly for 50 and 100 days of exposure.

[Hashish et al.,2008] have studied the biological effect of whole body exposure of SMF (2.9 mT) and ELF-EMF (50 Hz) on mice at in vitro experiment. They designed two systems of exposure: one SMF and anther ELF-EMF. Mice were exposed with either field equally for 30 days. In some of the obtained results they showed that mice loss weights similarly under the effect of both exposure. Total protein reduced significantly. Blood parameters reduced similarly under the both fields: PLTs and monocytes counts, peripheral lymphocytes and T and B lymphocytes levels. They concluded that both fields produce physiological disturbances in mice. both fields altered blood parameters similarly. For example, WBCs changed from 4.87 ± 0.53 (control) to 4.47 ± 0.59 and 3.67 ± 0.45 under the effect of SMF and ELF-EMF respectively. Losing body weight may be due to MF or some other biological factors such as loosing body fluid or proteins.

A similar MF as [Chaterst al., 2006] and [Amara at al., 2006] was used by [Sihem et al., 2006] to study the biochemical and hematological parameter changes under the effect of SMF in rats. Rats were exposed directly at in vivo experiments with 128 mT for one hour per day during 10 days. Hb and HCT have risen in compare to control groups. RBCs, WBCs, PLTs increased significantly. 7.26 ± 0.31(10^{12}/L) to 8.09 ± 0.58 (10^{12}/L), 7.81 ± 0.73 (10^{9}/L) to 9.12 ± 0.91(10^{9}/L) and 536.10 ± 36.92 (10^{9}/L) to 783.02 ± 53.78(10^{9}/L) respectively. They believe that the change in Hb is related to magnetic force on RBCs.

[Wyszkowska et al., 2018] studied extremely low frequency time varying MF (7 mT and 50 Hz) effect on hematological parameters in vivo experiments. Groups of rats were exposed to MF for 1 hr/7 days and another group for 24 hrs. The 24 hrs exposure caused WBCs, lymphocytes, haematocrit and haemoglobin to increase. Therefore, one hr exposure for 7 days did not alter measured hematological parameters.

Decades ago, [Battocletti et a., 1981] exposed rhesus monkeys with 2 T of magnetic field. Monkeys with age one and half and two years were chosen. Animals divided into sub groups and irradiated for 63, and 67 hrs. Blood samples were taken before irradiation, after irradiation immediately and two weeks after irradiation. WBCs, neutrophils and lymphocytes changed considerable. Neutrophils increased two

folds for the exposed animals. Lymphocytes reduced to half and WBCs decreased by 50% due to exposure and increase after the exposure.

[Mohammed, 2017] has studied the effect of low SMF on biological properties of rats in vivo experiments. Each group of animal was irradiated for 2 hr/day and from 2 days to 7 days period in sequence. Erythrocytes were reduced from an insignificant to a significant from 2 days to 7 days of exposure respectively. The most significant changes was reported at 7 days of exposure, RBCs counts from 3.8 ± 0.07 to 3.0 ± 0.03.

[Strieth et al., 2008] performed an experiment on Syrian golden hamsters to examine the RBCs velocity flow in muscle capillaries during exposure of SMF. They showed that the short time of exposures with 150 mT reduces the RBCs velocity and segmental blood flow in tumor microvessels significantly.

Red blood cells are main cause of increasing blood viscosity. [Iino, 1997] studied the RBCs aggregations (called erythrocyte sedimentation rate- ESR) and sedimentations under the effect of static magnetic field. Blood was withdrawn from male healthy human. ESR enhanced slightly in a saline solution, and significantly in plasma under the effect of 6.3 T. Blood parameter responded MF 20 min from the exposure. The sedimentation has increased continuously in respect of time. Ht level reduced as ESR increased. They believe that the MF causes the cell orientation and thus Enhanced ESR.

0.2 mT time varying MF (50 Hz) was applied on albino rats to examine the RBCs variation [Ali et al., 2003]. Four groups of animal were prepared, A (Control), B (exposed for 15 days) and C (for 30 days) continuously. Group D rats were suicide after 45 days to study the effect of post exposure. Their result showed the elasticity of erythrocyte membrane and permeability decreased and, Hb structure and RBCs physiological structure changed. Irregular shape starting to grow up as time of exposure increases.

Time varying magnetic field effect on PLTs aggregation was studied [Sağdilek et al., 2012]. A 50 Hz - 1 mT and 6 mT was applied. Blood were collected from healthy human and exposed for 90 min and 120 min. Measurement was taken for control and exposed blood samples. Results show an increase of aggregation at 1 mT only. They concluded that the magnetic fields act as an activation of PLTs aggregation.

[Fasshauer et al., 2018 and Brand et al., 2015] examined the effect of MIR on DNA double strand break. They found no evidence where MRI causes DNA double strand break. [Selmaoui et al., 1996] studied the effect of time varying magnetic field (10 μT, 50 Hz) on blood parameters and blood immunity components. Humans were exposed to MF for 24 hrs, continuously. Their result shows no effect of low frequency magnetic field on blood immunity and functions.

Impact of homogeneous static magnetic fields on biological system has studied by [Milovanovich et al., 2016]. SMF has exposed on Male Swiss Webster mice with different orientation to see the effect of SMF at varies orientations. 128 mT was generated using cyclotron. Each group of animal has exposed for 5 days and each day for 1 hr. Results showed the obvious effect of SMF on some specific organs and blood parameters with different orientations rather than whole body. This depends on the field orientation to the same degree. The upward exposure of the field reduced counts of WBCs and serum lymphocytes. Inflammations increased in kidney. Granulocytes dropped down in spleen. However, the only downward exposure produced inflammation in liver and serum granulocytes dropped down.

RBCs and PLTs orientation has observed under 4 T and 3 T of magnetic fields [Yamagishi, 1990]. The degree of orientation increased in respect to MF. PLTs has fully oriented at 3mT. There is an insignificant difference between oxygenated and deoxygenated RBCs unless; both were saturated at 6T. Similar result was found theoretically by [Riberiro et al., 1981]. [Higashi et al., 997] also showed the cell orientation occur under the effect of high MF.

Table 1 summarizes the data collected from the reviewed literature of the effect of MF on rheological properties of blood in vivo and in vitro experiments. The effects are mainly connected to the main blood parameters such as RBCs, WBCs and PLTs, DNA strand break and blood viscosity. The outcome shows that certain intensities of MF can change the blood counts significantly, alter blood viscosity as well as enhance cell

orientations. There is no significant clue of the impact of MF on DNA strand break.

Table 1. literature works; effect of MF on blood rheological properties

Study reference	Sample type	Study parameter –field types	Effect
Amara et al., (2006)	Male wistar rats - in vivo	SMF 128 mT (1 hr/day) during 5 days)	WBC increased insignificantly RBC increased insignificantly PLT and HB increased insignificantly Ht increased insignificantly Water consumption increased Body weight increased
		SMF 128 mT (1 hr/day) during 30 days)	WBC increased by 17% RBC increased by 7% PLT and HB increased by 10% Ht increased Water consumption increased Body weight increased
Haik et al., 2001	Human blood - in vitro	SMF: 1 Tesla to 10 Tesla	Blood flow Time reduced continually Blood viscosity increased
Fasshauer et al., 2018	Human blood - in vivo	SMF: 3 T MRI source	No evidence of DNA double strand break.
Brand et al., 2015	Human blood - in vivo	SMF: 3 T MRI source	No evidence of DNA double strand break.
Selmaoui et al., 1996	Human blood - in vivo	ELF-MF (50 Hz, 10 μT)	No evidence of effect on blood components and blood immunity components.
Chater et al., 2006	Wistar Pregnant rats - in vivo	SMF (128 mT for 13 days)	WBC reduced slightly RBC increased slightly PLT increased slightly Hb increased slightly Ht increased considerably.
Strieth et al., 2008	Golden hamsters - in vivo	SMF (149 - 580 mT)	RBCs velocity reduced
Lino, 1997	Human blood - male - in vitro	SMF: 6.3 T	ESR and sedimentation increase as the function of time Htc reduced as a function of ESR.
Ali et al., 2003	Albino rats - in vivo	0.2 mT, 50 Hz	elasticity of erythrocyte membrane and permeability decreased RBCs irregularity increases
Sağdilek et al., 2012	Human blood- in vitro	1 mT and 6 mT for 1.5 and 2 hrs	Platelet aggregation increased
Yamamoto et al., 2004	Human blood- in vitro	1.5 T	Blood viscosity increased Shear rate changed
Milovanovich et al., 2016	Male Swiss Webster mice -	SMF: 128 mT - orientation effect	Upward exposure: WBCs counts and serum lymphocytes

	in vitro		reduced, Inflammations increased in kidney, PLTs counts reduced , Hb increased Downward exposure: produced inflammation in liver and serum granulocytes dropped , PLTs counts reduced, Hb increased
Baieth, 2008	Albino rats - in vivo	0.3 mT, 0.5 mT and 1 mT (50 Hz)	Viscosity reduced as magnetic field increased. Shear rate increased as magnetic field increased RBCs cunts and Ht increased under 0.3mT, 0.5 mT but decreased under 1 mT
Kenjereš, 2008	Mathematical model	10 T	Blood flow changed insignificantly
Marcinkowska, 2013	Human blood samples - in vitro	----------	Relative blood viscosity reduces as a function of applied magnetic field.
Mohaseb et al., 2017	Albino rats - in vivo	0.3 mT (50Hz).	Blood viscosity increased significantly after 21 and 45 days of exposure
Mohammed, 2017	Albino rats - in vivo	0.8 mT (50Hz)	RBCs reduced significantly Hemoglobin content reduced significantly
Kadhim et al., 2016	Human blood samples with polycythemia disease	1.5 T (1 min- 21min) SMF	Blood viscosity decreased as time of exposure increased.
Haik et al., 2001	Human blood: in-vitro	1-10 T	Blood flow decreased and viscosity increased by 30%
Okano and Ohkubo, 2001	Rabbits	1 mT (30 min) SMF	Vasodilatation reduced significantly Vasomotion enhanced Blood pressure reduced Vasoconstriction reduction in smooth muscle

4. CONCLUSIONS

Blood rheological properties were reviewed under the effect of MF. SMF and time

varying magnetic fields resulted impacts mainly on blood parameters, viscosity and blood flow. A few in vivo and in vitro research articles introduced no effect of low dosage MF on blood rheology. However, most of the published research articles revealed the side effect of MF at low, intermediate and high intensity of exposure. RBCs aggregation enhanced, red cell shapes altered as they tend to orient parallel to applied MF. No evident found where DNA strand break enhances under reviewed intensity of magnetic field. White and Red blood cells were found as accepting the highest responded blood parameters to MF. One research found an increase of 17% and 7% of WBCs and RBCs counts respectively as they exposed to a moderate MF. As blood behaves differently in response to applied MF, we believe that a continuous and sequence research is required to investigate the most effective exposure line of magnetic field on blood in vitro and in vivo worlds.

Conflict of Interest: The authors declared that they have no conflicts of interest.

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