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Cardiac surgery and hemorheological parameters - a literature review

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Content

Abstract

Background. Some reports suggest that cardiac surgery may require monitoring of the patients' hemorheological parameters such as whole blood viscosity (WBV), plasma viscosity (PV), hematocrit (HCT), shear stress and shear rate..

Aim. This review article focuses on changes in hemorheological parameters of blood accompanying surgery for heart valve defects (focusing on aortic stenosis and mitral annulus calcification), coronary artery bypass grafting (CABG), surgical treatment of endocarditis and transplantations.

Material and methods. A comprehensive literature search was conducted using PubMed, Google Scholar and Web of Science with Key words.

Results. Patients who have undergone surgical treatment for heart valve defects suggest that changes in hemorheological parameters may correlate with a higher risk of postoperative death or the development of complications.

Conclusions. Considering the studies discussed in this article, hemorheological parameters may become significant indicators of the patient's condition and prognosis in the future, but the research is not complete yet.

Key words: hematocrit; whole blood viscosity; plasma viscosity; shear rate; heart valve defects; aortic stenosis; mitral annulus calcification; CABG; endocarditis; transplantations

1. Introduction

Cardiac surgery covers the surgical treatment of the heart and large blood vessels in the chest. Each year, the estimated number of open-heart cardiac surgeries performed worldwide exceeds one million [1]. All patients who have had such procedures performed need appropriate postoperative care, which includes, for example, among other things, the administration of anticoagulants because the operated cardiovascular lesions can significantly affect blood properties. In this context, monitoring of hemorheological parameters may seem like an interesting aspect to explore. In the future, they may help minimize cardiovascular complications risk in patients undergoing cardiac surgery. The circulatory system and the blood that circulates within it are not entirely separate entities - they significantly affect each other. Morphological changes or pathological processes within the blood vessels, as well as the performance of surgery with extracorporeal circulation (the so-called heart-lung machine), can cause disturbances in the composition and properties of blood [2].

2. Research results

2.1. Hemorheological parameters

Hemorheological parameters describe blood flow in blood vessels, and therefore, their changes may play a significant role in monitoring, analysing, and implementing treatment in cardiac surgery patients. These parameters are subject to change not only under the influence of environmental factors but also interact with each other, so a change in the value of one parameter can involve a cascade of changes in the values of the rest [3]. Particular attention needs to be paid to WBV. It expresses the resistance to the flow of blood, and its value is determined by external components (temperature, flow velocity) but also by the composition of the blood (HCT value, properties of red blood cells (aggregability and deformability of erythrocytes), composition of plasma proteins) [4]. WBV can increase due to the accumulation of acute phase proteins or increased immunoglobulin levels associated with the persistence of infection [5]. PV, which depends on water and protein content, should also be considered in the process of monitoring and treating cardiovascular surgery patients. The proteins that affect PV are, for example, fibrinogen, α1-globulins, α2-globulins, β-globulins, and γ-globulins. With their increase, the PV (and WBV) increases accordingly [6]. PV is calculated by dividing the shear stress value by the shear rate [7]. Shear stress is the force acting on the wall of a blood vessel. Wall shear stress is a reliable and early biomarker of the progression of abnormal vascular networks [8]. Shear rate is the velocity gradient that is measured across the diameter of the channel in which (in this case) the blood is flowing. The HCT value (which measures the proportion of erythrocytes in the blood volume) can also be clinically important. Both HCT and hemoglobin levels are major determinants of the aforementioned WBV [9].

All of these parameters (as well as others not included in this paper) may be important in assessing the effects of cardiac surgery and predicting the speed of a patient's return to partial or full function. They may also prove to be important indicators for alerting medical personnel since once their values are outside the reference values, they could indicate the administration of appropriate drugs.

2.2. Heart valve defects and hemorheological parameters

Heart valves, which allow blood to flow in one direction and prevent it from flowing backward, play a crucial role in the proper flow of blood through the heart. However, they are often subject to acquired or congenital damage that disrupts the flow and affects heart function. Valvular heart disease typically manifests as a stenosis, which restricts blood flow, or a regurgitation, which causes the blood to flow backward [10]. Heart valve disease can affect all four heart valves, although mitral and aortic valve defects are the most common. All valvular defects require surgical repair or replacement of diseased tissue with mechanical or bioprosthetic options [11]. Research has shown that rheological factors like HCT, blood viscosity, and shear rate affect valve function and flow [12, 18, 19, 20]. Aortic stenosis (AS) is one of the most common heart valve defects, affecting 2-5% of the adult population. The heart valve replacement is one of the most common and safest cardiothoracic surgical procedures. It is believed that the prevalence of heart valve disease increases with advancing age. Aortic valve replacement (TAVR) surgery is performed on an open heart and, therefore, carries some risk. The work of Shvartz V et al. presents research on a group of patients with AS. Hospitalized patients with AS who underwent aortic valve replacement were studied between 2014 and 2020. The study involved 742 patients, including 429 men and 313 women aged 18 to 85. The mortality rate was 3%. The research showed that the initial HCT level was lower in the group that ended in death. The assessment of the HCT index, one of the rheological parameters, before surgery, is an important measure. Reduced HCT can be caused by excessive haemodilution, leading to reduced clotting factor concentrations, reduced oncotic pressure, and interstitial edema. All this increases the risk of postoperative complications. In the study that was conducted, an initial HCT of less than 39% was an independent predictor of death. However, together with other comorbidities, it increases the risk of in-hospital death[12].

In a prospective observational study, Fanning et al. demonstrated that patients undergoing TAVR presented a more prothrombotic hemostatic profile compared to those undergoing percutaneous coronary intervention or surgical aortic valve replacement [13]. Interestingly, a decrease in platelet count has also been observed following TAVR, regardless of the valve type used (Sapien, Sapien XT, Sapien 3, or CoreValve) [14]. Dvir et al. demonstrated that severe thrombocytopenia (platelet count < 50 G/L) in patients after TAVR can be a predictor factor of early- and long-term mortality. Moreover, patients with severe thrombocytopenia experienced higher rates of bleeding, sepsis, major vascular complications, and prolonged intensive care unit stays. It has been shown that patients without thrombocytopenia (platelet count >150 G/L) following TAVR have better outcomes [15]. Interestingly, unlike platelet count, hemoglobin levels were not associated with in-hospital mortality [16]. However, Reddy et al. demonstrated that a decrease in hemoglobin by ≥3 g/dL compared to pre- and post-TAVR levels, without associated bleeding, was linked to increased perioperative mortality compared to the group without a decrease in hemoglobin levels and without bleeding [17].

Blood viscosity is often referred to as a marker of shear stress. It is recognized as a significant risk factor for cardiovascular disease, including aortic valve sclerosis (AVS). It represents resistance to blood flow and contributes to endothelial shear stress [18]. Blood viscosity can be calculated from the HCT and the total protein in the serum at both a low shear rate (LSR) and a high shear rate (HSR). Areas of high turbulent flow and shear stress are often associated with aortic valve damage. In studies by Sercelik A. et al. involving 209 patients, including 109 patients with AVS (77 women and 32 men) and 100 patients without AVS (control group), the association between increased WBV and AVS was investigated. This cross-sectional clinical study with a mean age of 65.5 ± 6.9 years was conducted between August 2014 and November 2016. The results showed that the WBV values in the AVS group were significantly higher than those in the control group. In addition, WBV was independently associated with AVS at both the HSR and LSR levels. These results suggest that WBV may play a critical role in AVS development. Turbulent flow and the resulting oscillatory shear stress on the aortic valve (AV) leaflet surface and coronary sinus area contribute to increased tissue calcification. This underlines the importance of hemodynamic factors in the pathogenesis of AVS [19].

Mitral annulus calcification (MAC) is a common heart valve defect characterized by a chronic, degenerative process in which calcium is progressively deposited along and beneath the mitral annulus. MAC may be associated with atherosclerotic processes in which altered hemodynamic factors are critical [20]. MAC is most often detected incidentally during routine echocardiography. It is thought that shearing stress contributes to endothelial damage and initiates MAC. WBV may be predicted to cause endothelial damage in areas of high mechanical stress. A study by Ozcan et al. from 2015 was conducted to confirm the hypothesis that an increase in WBV may be associated with the presence and incidence of MAC. The study included 317 patients, 184 with MAC and 133 without MAC. It was conducted from January 2013 to January 2014. The aim was to compare WBV values in patients with and without MAC and to assess the correlation of WBV with mitral annular motion velocities. The results showed significantly higher WBV values for both HSR and LSR in the MAC group. In both LSR and HSR, WBV was found to be an independent predictor of the presence of MAC. In addition, significant correlations were observed between WBV and mitral annular velocities in both LSR and HSR. The researchers suggest that a higher WBV may lead to a greater restriction of mitral annular motion and a more severe form of MAC [21].

There is a causal relationship between AS and AVS, suggesting that AS is also influenced by WBV. Increased WBV, which is associated with major atherosclerosis risk factors such as diabetes, obesity, hypertension, elevated cholesterol levels, and metabolic syndrome, can be predicted using formulas that include HCT and serum proteins [22]. The study by Balachandran K et al. included 94 patients with ankylosing spondylitis and 97 individuals in the control group. Both groups had comparable hemoglobin and HCT levels. However, at both LSR (0.5/s) and HSR (208/s), patients with ankylosing spondylitis had high WBV. The study found that WBV at both LSR and HSR was an independent determinant of AS, indicating a potential role of WBV in its development. A correlation was also observed between increased WBV at a given shear rate and increased shear stress. Increased WBV may induce valve inflammation by increasing shear stress. Furthermore, shear stress variations may increase pro-inflammatory gene expression and lead to tissue mineralization [23, 24]. In conclusion, increased WBV was found to be associated with AS at both HSR and LSR.

Defects in the heart valve often cause enlargement of the root of the aorta, which can lead to an ascending aortic aneurysm. Aortopathy can result from genetic predisposition (developmental defects of the aortic valve and aortic wall) or hemodynamic overload associated with turbulent flow in the aorta. Preclinical studies have been performed to demonstrate the influence of rheological parameters on the development and progression of ascending aortic aneurysms using state-of-the-art three-dimensional phase-contrast magnetic resonance imaging. A study by Ayaon-Albarran et al. used an animal model of experimental supravalvular AS and eccentric flow. The lack of genetic factors and bicuspid aortic valve (BAV) characteristics in the subjects enabled the assessment of rheological influences. The results of the study in 24 pigs suggest that rheology may be the cause of aortic enlargement in individuals without genetic predisposition. The study was completed in 20 subjects, 14 of whom developed ascending aortic stenosis and 6 of whom underwent sham surgery. The research suggests that eccentric flow is sufficient to induce an ascending aortic aneurysm in patients with BAV. Eccentric flow and the resulting shear stress contribute to aortic pathology. Eccentric flow in patients with ascending aortic aneurysm is also common in patients with tricuspid aortic valve (TAV) stenosis. The results confirm the experimental assumption and clinical reports that shear stress is the main contributor to the development of aortic enlargement in patients with BAV. Further research is needed to confirm this theory. However, it is promising and confirms the influence of rheological stimuli on the risk of aortic enlargement and aneurysm development [25].

Shear stress, the force acting on the wall of a blood vessel, is directly proportional to blood flow velocity and viscosity and inversely proportional to the vessel radius. It is, therefore, an important rheological parameter, particularly in patients with BAV and aortic regurgitation. Wall shear stress (WSS) may play a role in the development of BAV aortopathy. The oscillatory shear index (OSI) is an important parameter derived from WSS. It correlates with endothelial dysfunction. Importantly, OSI represents changes in WSS during a cardiac cycle, while WSS represents maximum shear applied by blood on endothelial tissue. The study by Trenti et al. aimed to characterize WSS and OSI throughout the cardiac cycle in patients with ascending aortic aneurysms. The study included 87 patients with varying degrees of ascending aortic aneurysms and combined regurgitation and stenosis. A cardiovascular magnetic resonance (CMR) protocol was performed on all patients. Ultimately, 42 individuals were included in the study: 13 with BAV without valvular disease, 14 with BAV with aortic regurgitation, and 15 with BAV with stenosis. The control group comprised 22 individuals with a TAV. The remaining cases were excluded because of moderate or severe regurgitation, moderate or severe stenosis, or poor quality CMR data. The study found that patients with BAV and AS had a higher WSS during diastole than patients with BAV but no valvular disease and patients with TAV. In addition, both BAV groups had higher peak and mean WSS during diastole than TAV. BAV patients with AS also had higher circumferential WSS during systole than those without valvular disease and those with TAV. Both BAV groups also had higher axial and circumferential WSS during diastole than TAV. The OSI was higher in the BAV group with aortic regurgitation than in the other groups. Compared to the BAV group without valvular disease, the BAV group with stenosis had higher axial OSI values but lower circumferential OSI values. The BAV group without valvular disease had a lower OSI value in the circumferential direction than the group with a TAV. To conclude, OSI can be considered a potential risk marker for BAV associated with aortic regurgitation. The results indicate that the outcome parameters of WSS may be related to the severity and progression of aortic disease. Aortic regurgitation may increase the risk of aortic events. AS is characterized by increased peak systolic WSS. Aortic regurgitation is typically associated with increased OSI [26].

The presented research results demonstrate the significant impact of rheological parameters on heart valve diseases. Undoubtedly, these parameters play a role in blood flow and valve function. However, more research is needed to confirm these hypotheses.

2.3. Coronary artery bypass grafting

CABG is a common method of treating coronary heart disease. It typically involves anastomoses of the internal thoracic artery (ITA) and the saphenous vein. Numerous studies suggest that grafts from the ITA are a better choice because they maintain patency longer. Isobe et al. measured shear stress and shear rate values, which were 4-6 times higher and nearly 2-3 times higher for LITA grafts than for SVGs [27]. The authors Grondin et al. point out that retrospective and non-randomized studies indicate that grafts from the ITA maintain better patency during long-term observation than those from the saphenous vein [28]. A study conducted by Cameron et al. revealed that the average survival rate with a single ITA graft is 4.4 years longer compared to using a venous graft alone. A positive correlation was observed between shear stress values and shear rates [29]. Another study by Miller et al. on canine femoral arteries explains the relationship between high shear stress and vessel diameter control. Chronically increased shear stress in canine femoral arteries increases endothelium-derived NO release and blood flow [30], which may explain the better patency of ITA grafts, where higher shear stress is present [27].

Another aspect of CABG surgery is the method of performing the procedure. In the study by Papp et al., authors compare these methods in terms of changes in hemorheological parameters. There are two possible methods of performing CABG: on-pump, where the heart is stopped and circulation is maintained by a cardiopulmonary bypass, and off-pump, which is CABG performed on a beating heart. The dynamics of changes in rheological parameters were measured during surgery, in the postoperative period, and at 2 and 6 months after surgery. It was observed that the changes in hemorheological parameters were significantly smaller with off-pump CABG. Scanning electron microscopy revealed damaged and distorted red blood cells (RBCs) in samples obtained from patients who underwent on-pump CABG. Impairment of RBC deformability was also observed in these samples during filtrometry. As the authors suggest, off-pump CABG procedures seem to be more favorable from a hemorheological standpoint [31]. However, in a randomized clinical trial, no long-term benefits (primary end points included all-cause death and composite endpoint of death or subsequent revascularization) of the off-pump CABG method were demonstrated compared to the on-pump approach [32].

Monitoring the dynamics of rheological parameter changes can aid in patient care and prevent complications after CABG surgery using cardiopulmonary bypass. Hsu et al., in their study, measured PV and WBV in each patient just before surgery, 2 days, and 5 days after surgery. Significant differences in PV were observed before and 5 days after surgery for each shear rate. However, differences in WBV were significantly different between each day of measurement for LSR (2.34 -1 and 7.85 s -1). For higher shear rates, they were not significant (88.6 and 298 s -1) due to the hemodilution applied in CABG surgery; WBV decreased, while it increased after CABG. As the authors suggest, factors that increase WBC may include inflammatory status and changes in the properties of RBCs accompanying such interventions. At shear rates below 26.4 s-1, Hsu et al. demonstrated a significant correlation between fibrinogen levels and WBV [33].

Rotational thromboelastometry (ROTEM) is a diagnostic method for assessing blood clot properties. After cardiac surgery, viscoelastic methods are recommended for monitoring coagulation. Gauger et al. demonstrated that ROTEM measurements can be used to estimate platelet count and fibrinogen levels independently of hematocrit, which may be particularly important in patients following cardiac surgical procedures [34]. In a retrospective cohort study involving 675 patients undergoing CABG, Martinez et al. demonstrated that the use of rotational thromboelastometry (ROTEM), in conjunction with a structured interpretation algorithm, was associated with a reduction in allogeneic blood transfusion requirements, postoperative hematologic complications, and intensive care unit length of stay [35]. Similar conclusions were reported in the meta-analysis by Meco et al., which showed that in patients undergoing cardiac surgery, the use of viscoelastic-guided management of bleeding and coagulopathy (ROTEM and thromboelastography) was associated with a reduction in postoperative bleeding and the need for allogeneic blood transfusions [36].

One marker of inflammatory status is fibrinogen, which increases blood viscosity [37]. Perioperative fibrinogen levels have also been shown to be associated with postoperative blood loss in patients undergoing cardiac surgery [38]. In a large retrospective study, Huang et al. demonstrated that preoperative fibrinogen levels in patients undergoing coronary artery bypass grafting (CABG) are an independent predictor of hospital length of stay and postoperative renal failure. Elevated baseline fibrinogen levels were associated with prolonged hospitalization and a higher incidence of postoperative renal failure [39].

Other inflammatory markers may also increase blood viscosity, thereby increasing the risk of postoperative complications [40, 41]. These studies suggest therapeutic solutions that may prevent complications after CABG surgery [33, 37, 40, 41]. One such solution may be the use of anti-inflammatory drugs such as corticosteroids or nonsteroidal anti-inflammatory drugs. Reducing inflammation will decrease blood viscosity and reduce the risk of complications. What is more, the comprehensive meta-analysis by Schwann et al. demonstrated that perioperative anemia and red blood cell transfusion are associated with an increased rate of late mortality. In contrast to perioperative anemia, intraoperative or postoperative blood transfusions were only marginally associated with late mortality [42].

2.4. Surgical treatment of endocarditis

Endocarditis is an infection of the endocardium, the inner lining of the heart's chambers and valves. The incidence increases with age, peaking at 70-80 years, with an overrepresentation of women. Women have a poorer prognosis than men [43]. One of the more common causes of endocarditis is bacteria of the Staphylococcus family, accounting for up to 26.6% of all cases [44]. The clinical picture of patients is variable, ranging from acute to chronic. However, most patients present fever, night sweats and general fatigue [45]. Diagnosis is based on a blood test to detect bacteria in culture (bacteria that can cause endocarditis) or an ECG of the heart. Treatment is based on antibiotics for bacterial infections or antifungal drugs for fungal infections, but in severe cases, surgical intervention is required [46].

Indications for surgical treatment include valve dysfunction or heart failure. Surgical intervention should also be considered in cases of abscesses, the presence of resistant microorganisms (Pseudomonas family bacteria), and bacteremia [47]. The patient should undergo a strict antimicrobial regimen during surgery. It is imperative that the surgical team is familiar with the echocardiograms to better understand the pathology of the disease. The procedure requires invasive access to the heart by cutting through the sternum. The main aim of the procedure is to remove the microorganisms and, when needed, repair the valves [48].

The relationship between increased blood viscosity due to red cell aggregation being a complication of inflammation is reflected in surgical interventions. A study by Yi-Fan Wu et al., found a relationship between increased blood viscosity in patients undergoing cardiac surgery and CRP and fibrinogen levels [49]. These correlations can be used to monitor patients after surgery and assess the effectiveness of the cardiac surgery treatment applied. It should also not be forgotten that increased blood viscosity can lead to venous thrombosis or myocardial infarction. In such a case, urgent surgery is needed, which is associated with an increased risk of mortality [50].

Another factor weighing on the effectiveness of surgical treatment is blood clotting. One of the main risks during and after surgery is excessive blood loss, which can lead to the death of the patient. Fibrinogen is the main component responsible for coagulation; one method of measuring fibrinogen concentration is the Clauss test. A study by Eline A. Vlot et al. demonstrated a significant correlation between a decrease in fibrinogen levels and increased blood loss among patients undergoing complex cardiac surgery (mainly those who underwent bypass grafting) [51]. On the other hand, the coagulation parameter, being too high, has a negative impact on certain procedures carried out on the heart. In the case of endocarditis, there is an increase in coagulability. In rare cases, endocarditis can lead to the need for a heart transplant. A complicated course of Salmonella endocarditis leading to heart transplantation describes the case of a woman whose infection with a bacterium of the Salmonella family resulted in endocarditis, which qualified the patient for heart transplantation [52]. Heart recipients have an increased risk of thromboembolic disease following the procedure. This is due, among other things, to the use of immunosuppressive drugs. Such patients must be treated with anticoagulants to avoid serious complications such as strokes. According to recent studies, direct oral anticoagulants appear to be the safest drugs for transplant patients [53]. The HCT is also an important factor in the surgical treatment of endocarditis. HCT is the ratio of RBC volume to whole blood volume. Elevated levels may indicate dehydration and may also correlate with an increased risk of hypertension [54]. Knowledge of this relationship is important, as a study by Gyu Bae Lee et al. showed that long-term hypertension is associated with a higher risk of endocarditis [55]. If surgical intervention is required, it is essential to consider the patient's existing hypertension. Increased pressure is associated with a higher risk of myocardial infarction or renal failure. It is considered that it should not be greater than 180/100 mmHg. It is advisable to implement pharmacological therapy, which depends on existing comorbidities [56].

2.5. Heart transplantation

Heart transplantation is a commonly considered option among the available treatments for advanced-stage heart disease [57], such as heart failure, which may have an impact not only on the condition of patients but also on their rheological properties [58, 59]. However, it is important to remember that numerous complications may occur following heart transplantation (HTX), including primary graft dysfunction (PGD), acute cellular rejection (ACR), antibody-mediated rejection (AMR), cardiac allograft vasculopathy (CAV) as well as post-transplant malignancy and renal dysfunction [57].

As far as heart failure is concerned, substantial alterations in hemorheological characteristics (such as heightened WBV and PV and increased RBC aggregation) are presumed to expedite the advancement of the disease as the accompanying tissue hypoxia perpetuates a detrimental cycle, worsening heart failure [60]. For patients in the advanced stage of the disease who are eligible for transplantation, temporary or permanent mechanical circulatory support (MCS) may be considered before receiving a suitable organ. Continuous flow assist devices have become a common strategy, serving as a bridge to cardiac transplantation or destination therapy. Nevertheless, complications associated with these devices, such as bleeding and thrombosis, remain a concern [61].

The influence of mechanical cardiac assist devices (MCAD), such as ventricular assist devices (VAD), on blood, is examined, involving its effects on rheology. Turbulent flow may be enhanced along with increased platelet consumption and platelet degranulation. Moreover, there may be a potential contribution to clot formation in regions of stagnant blood flow [62]. Following the implantation of a VAD, the interplay between the device material and blood disrupts the intricate balance of the hematologic system, potentially leading to significant complications such as thrombosis and bleeding, which are often attributed to mismatches between the VAD surface and blood. Factors associated with a higher risk of bleeding in VADs include acquired von Willebrand syndrome, reduced platelet aggregation, and the absence of pulsatility [61].

What is more, the shear rates produced in left ventricular assist devices (LVADs) may result in decreased platelet aggregation, increasing the possibility of bleeding [63].

Patients who have undergone HTX frequently require oral anticoagulant medications (OACs) because of atrial arrhythmias or thromboembolic incidents. Usually, these medications include direct oral anticoagulants (DOACs) or vitamin K antagonists (VKAs). The main objective of OACs is to prevent thromboembolic strokes in patients with atrial fibrillation and to inhibit the advancement or reappearance of thromboembolic events in patients with venous thromboembolism. Evaluation of complications associated with OACs revealed no statistically notable variances between HTX recipients treated with DOACs and those on VKAs regarding ischemic stroke, thromboembolic events, or OAC-related mortality. However, HTX recipients receiving VKAs experienced a notably elevated incidence of overall bleeding. During instances of bleeding complications, approximately two-thirds of HTX recipients using VKAs exhibited international normalized ratio (INR) levels exceeding the therapeutic range, which is correlated with an increased risk of bleeding [64].

In conclusion, even though there is not enough unequivocal evidence for heart transplantation's influence on blood rheology, perioperative actions, such as the use of MCAD or anticoagulant medications, may indirectly impact these properties.

3. Conclusions

It can be noted, based on the cited research results, that there is a relationship between the values of hemorheological parameters and cardiac surgery procedures. In individual parts of the work, it was indicated that the above parameters may be important in the treatment of patients after surgical treatment of heart valve defects, endocarditis, cancer, CABG, or heart transplantation. Changes in whole blood viscosity, plasma viscosity, hematocrit, and the tendency of erythrocytes to aggregate and deform may be the cause and effect of cardiac procedures.

Although this relationship and the precise interactions between hemorheological parameters and cardiac surgery remain to be investigated, the results of the studies discussed in this paper indicate that this concept should be explored further because it seems important in monitoring, analysing, and implementing the treatment of cardiac surgery patients.

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Resources: AK, KP, SP, KB

Data curation: JS, KS

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