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Lionnet *et al.*[1] recently reported a high prevalence of retinopathy (RET) and otologic disorders (OTD) in patients with sickle cell-hemoglobin C disease (SC), while a significant number of patients had renal diseases (mainly glomerulopathy; GLO) and osteonecrosis (OST). The pathophysiological processes of these complications in SC are not well defined, although blood hyperviscosity has been suspected, but never tested to the best of our knowledge, as responsible for several chronic complications in SC disease[1,2].The aim of this study was to analyze the associations between hematological and hemorheological parameters and chronic complications in adult SC patients.

Ninety consecutive adults with SC (M/F: 40/50; mean age: 38 ± 13 yr)were enrolled in the study. All patients were at steady state at study entry, i.e., no phlebotomy orblood transfusions in the previous three months, and absence of acute episodes (infection, vaso-occlusive crisis (VOC), acute chest syndrome (ACS), stroke, priapism) at least three months before enrollment. Pregnancy or breast feeding were also exclusion criteria. The study was conducted in accordance to the Declaration of Helsinki, and approved by the Regional Ethics Committee (registration number: 2010-A00244-35). Written informed consent was obtained from all participants.

History, presence of chronic disorders, and acute event occurrence during the previous year of study were obtained from retrospective chart review by two physicians.Patients under regular phlebotomy protocols, but without any phlebotomy in the 3 months preceding the study were identified. Phlebotomyis usually performed in symptomatic SC patientsto avoid recurrent acute events[3],and has been prescribedby some when hemoglobin and/or hematocrit rise above 11 g/dL or 32%, respectively,to prevent complications with suspected blood hyperviscosity[1,4]. The optimal target hemoglobin level to reach under phlebotomy is unknown but our Sickle Cell Centre usually tries to reduce hemoglobin to 9.5-10.5 g/dL.In our study, SC patients with

values greater than 11g/dL and 32% but no clinical assessment of blood viscosity were categorized as having “theoreticalhyperviscosity”.

Measurements of hematological and hemolytic parameters (bilirubin, lactate dehydrogenase, aspartate aminotransferase) were performed using standard methods[5].Blood viscosity, red blood cell (RBC) deformability, aggregation and disaggregation threshold (i.e., RBC aggregates strength) were measured as described[6,7].

Unpaired Student’s t-test and chi-square or Kappa coefficient test were used for continuous and categorical covariates, respectively. Association between several parameters was tested by Pearson correlation. The hemolytic component value was derived from hemolytic markers (bilirubin, lactate dehydrogenase, aspartate aminotransferase and reticulocytes) by principal component analysis[8].

The most prevalent chronic complications in our SC cohort were RET (60%), GLO (micro-/macro-albuminuria, 40%), OST (31%), and OTD (20%). Leg ulcers, pulmonary hypertension and cerebral vasculopathy/stroke were extremely rare (2% each), as were ACS (2%) and VOC (5%) during the study period.Few males (8%) had a history of priapism.

Patients with OTD (OTD+) had higher RBC count ($p<0.05$), and a tendency to higher hemoglobin level than patients without OTD (OTD-; $p<0.1$; Table 1). Blood viscosity was increased by 9.1% in OTD+ compared to OTD- patients ($p<0.05$). SC RET+ patients had lower RBC deformability than RET- ($p<0.05$; Table 1). No association was observed between hematological or hemorheological parameters and OST or GLO. Nevertheless, OST+ and GLO+ patients were older than OST- and GLO- individuals ($p<0.001$ and $p<0.01$, respectively).An association was found between RET and OST, with higher frequency of

OST+ in the RET+ (38%) than in the RET- (18%; $p<0.05$) groups. No association was found between the other complications.

In our cohort, 43% SC patients underwent phlebotomy, 74% of them on a regular basis (every 3 months). The frequency of RET+ and RET- patients treated by phlebotomy was not different, as 57.6% RET+ patients had phlebotomy vs. 42.4% RET- patients. Only a trend towards greater phlebotomy use was observed in OTD+ patients (64%; $p<0.1$). Most patients (88.6%) with "theoreticalhyperviscosity" (hemoglobin>11g/dL/hematocrit>32%)were phlebotomized ($p<0.01$). Comparing patients with or without theoreticalhyperviscosity demonstrated no significant difference in blood viscosity (7.50±1.03 vs 7.22±.35 cP, respectively), whilehemoglobin and hematocritwere higher in the theoreticalhyperviscositygroup (11.8±1.0 vs 11.2±1.3 g/dL and 32.3±2.5 vs 30.6±3.2 %, respectively; $p<0.01$), as expected. Thecohort was divided according to the median measured viscosity, and patients with blood viscositygreater than median value were considered as having"true hyperviscosity".No significant association was found between theoreticaland truehyperviscosity (Kappa coefficient=0.09), or between blood viscosity and hemoglobin or hematocrit, ($r=0.19$ and $r=0.18$, respectively; $p=0.16$ in both cases).

Elevated blood viscosity was hypothesized to cause ischemia at the labyrinthine artery level, leading to cochlear damage[9].This is in agreement with our cohort where OTD+ patients had higher blood viscosity than OTD-. However, OTD+ had only a trend towards higher hemoglobin and similar hematocrit as OTD-. Blood viscosity is influenced by several factors, including hematocrit and hemoglobin, hence their clinical use to prescribe phlebotomy. However, this relationship was not significant in our cohort. Blood viscosity depends also on the rheological properties of RBCs: i.e., deformability and aggregation. For a given hemoglobin level, increased RBC deformability lowers blood viscosity while increased RBC

aggregation causes a rise. The complex contribution of each hemorheological factor on blood viscosity makes that blood viscosity may be elevated in some patients despite “normal” hematocrit and hemoglobin levels.

More importantly, most patients with “theoretical hyperviscosity” did not have high blood viscosity, and only 44% of patients with measured “true hyperviscosity” were phlebotomized. Thus, as periodic phlebotomy could be useful to decrease blood viscosity in hyperviscous SC patients as it is in patients with polycythemia vera[10] or cyanotic congenital heart disease[11], our findings strongly suggest that blood viscosity measurements would allow better identification of SC patients at risk for OTD.

In contrast to OTD, RET was not associated with blood hyperviscosity. Instead, RBC deformability was decreased by 10% in RET+ compared to RET- patients. RBC deformability is critical for optimal tissue perfusion and adequate blood flow in the micro-/ macro-circulation[12], and reduced RBC deformability is associated with diabetic retinopathy[13,14]. The effects of phlebotomy on RBC deformability in SC patients with RET have never been investigated, calling for further studies to address this question.

In conclusion, our study provides new data on the pathophysiology of several frequent chronic complications in SC disease. They clearly show that the clinical use of hemoglobinand hematocrit as surrogates for high blood viscosityin SC patients is not satisfactory for establishing treatment or determining risk for OTD. A prospective study to evaluate the relationships between blood rheology and the occurrence of acute complications iswarranted.

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Authorship and Disclosures:

N.L., Y.L., M.R., M.D.H.D., B.T., M.L.L.M., M.E.J. and P.C. designed the protocol. N.L., Y.L., X.W., D.M. and P.C. performed the experiments. N.L., Y.L., M.R., M.D.H.D., F.L., X.W., V.T., B.T. and P.C. analyzed and interpreted the data. N.L., Y.L., M.R., M.D.H.D., F.L., X.W., V.T., D.M., B.T., M.L.L.M., M.E.J. and P.C. wrote the article.

We declare no conflict of interest.

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Table 1: Hematological and hemorheological determinants of otologic disorders, retinopathy, osteonecrosis and glomerulopathy in SC patients.

	Otologic disorders (OTD)		Retinopathy (RET)		Osteonecrosis (OST)		Glomerulopathy (GLO)	
	OTD- (n = 64)	OTD+ (n = 16)	RET- (n = 33)	RET+ (n = 49)	OST- (n = 62)	OST+ (n = 28)	GLO- (n = 51)	GLO+ (n = 34)
Age (years)	40 ± 13	37 ± 14	39 ± 14	39 ± 13	35 ± 12	45 ± 13***	36 ± 13	43 ± 13**
White blood cells ($x10^9L$)	7.4 ± 2.6	7.0 ± 2.4	7.4 ± 2.4	7.4 ± 2.6	7.6 ± 3.0	7.0 ± 2.4	7.4 ± 2.9	7.6 ± 2.4
Platelet count ($x10^9L$)	306 ± 154	292 ± 151	298 ± 166	302 ± 145	308 ± 156	278 ± 139	301 ± 152	308 ± 152
Red blood cells ($x10^{12}L$)	4.3 ± 0.6	4.7 ± 0.7*	4.3 ± 0.7	4.4 ± 0.7	4.4 ± 0.7	4.4 ± 0.6	4.4 ± 0.6	4.3 ± 0.6
Hemoglobin (g/dL)	11.2 ± 1.1	11.8 ± 1.3$	11.3 ± 1.2	11.4 ± 1.2	11.4 ±1.3	11.3 ± 1.1	11.5 ± 1.1	11.2 ± 1.2
Hematocrit (%)	31.0 ± 2.7	32.1 ± 3.8	31.0 ± 2.9	31.3 ± 3.1	31.1 ± 3.2	31.4 ± 2.9	31.4 ± 2.8	30.8 ± 3.1
Hemolytic index (relative unit)	0.01 ± 0.98	-0.21 ± 0.96	-0.12 ± 1.07	0.02 ± 0.93	0.02 ± 0.99	-0.03 ± 1.03	-0.06 ± 0.94	0.08 ± 1.08
Blood viscosity (cP)	7.38 ± 1.17	8.10 ± 0.85*	7.60 ± 1.10	7.28 ± 1.32	7.40 ± 1.14	7.50 ± 1.42	7.51 ±1.22	7.34 ± 1.16
RBC deformability (a.u)	0.43 ± 0.07	0.41 ± 0.06	0.45 ± 0.06	0.41 ± 0.05*	0.43 ± 0.07	0.42 ±0.07	0.42 ± 0.07	0.43 ± 0.07
RBC aggregation (%)	49 ± 8	47 ± 11	50 ± 8	48 ± 10	47 ± 8	50 ± 10	47 ± 10	50 ± 8
RBC disaggregation threshold (s^{-1})	320 ± 126	312 ± 132	317 ± 101	319 ± 140	306 ± 115	330 ± 141	312 ± 144	314 ± 91

Means ± SD. - = absence of complication and + = presence of complication.Sensorineural OTD (requiring hospitalization or not) were recorded using previously defined criteria[1]. Criteria used to define VOC and ACS events (within the previous year of study) were similar to those used in

previous studies performed in SCA adults[7].Criteria used to define osteonecrosis and glomerulopathy were similar to those used in previous studies[5,15].Difference between groups (*p<0.05; **p<0.01; ***p<0.001).[$]Statistical trend (p<0.1).