A Two-Phase Blood Flow over a Catheterized Artery and the Impact of a Magnetic Field

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ABSTRACT
This study investigates the mathematical modeling of a two-phase blood flow through a catheterized artery under the influence of a magnetic field, revealing insights into plasma velocity reduction with increasing catheter size and the subsequent decrease in volumetric flow rate, providing potential applications for optimizing fluid transport systems in Mines, Metals, and Fuels industries. To determine the effect of a magnetic field on a two-phase blood flow via a catheterized artery, a mathematical model is created an image of blood flowing continuously in two phases may be created by considering blood as a suspension of erythrocytes in plasma. Analytical solutions to the problems posed by the mathematical model developed through numerical calculations. It has been noted that plasma velocity drastically decreases as catheter size increases. The volumetric flow rate will decrease because of the magnetic field gradient. It is biologically accurate that when hematocrit increases, volumetric flow rate similarly falls.
Keywords: Catheterized artery, Hematocrit, Magnetic field, and Two-phase.
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INTRODUCTION

Numerous studies have been conducted on the use of magneto hydrodynamic principles in biology and medicine, according to the biofluids literature (see Vardanyan[1], Sud et al.[2]). Because of the iron oxide in red blood cells' hemoglobin molecules, the blood is a bio magnetic fluid (RBCs). Thus, blood oxygenation in a magnetic field outside of the RBC causes a change in its magnetic moment. As a result, the magneto hydrodynamic (MHD) features of blood flow can be applied to the human vascular system (see Katz and Kolin [3])

Kolin was the first to apply electromagnetic fields to medical studies [4]. Later research by Koechevskii and Marochunik [5] shown that the application of a magnetic field may regulate the human circulatory system, which will be helpful in the treatment and recovery of a number of cardiovascular disorders., including those where blood circulation is accelerated, like ailments such as hemorrhages and hypertension.

Vardanyan [1] studied the effects of magnetic fields on blood flow theoretically.. Later, Sud et al.[2] provided support for Vardanyan's findings by considering several models. Recent studies by Misra and Shit [6] have looked into the impact of magnetic fields on blood flow while assuming that the arterial wall is elastic. This study considers a situation in which the flow is transverse to a magnetic field that has been imposed.

The catheter has become a crucial tool in the detection and treatment of vascular disorders in contemporary medicine. Medical-grade polyvinyl chloride and thermoplastic polyurethane with a polyester base are the main components of a catheter. An annular zone naturally arises between the catheter and the artery walls when a catheter is implanted, according to Jayaraman's literature [7]. As a result, the flow field will change, changing the way pressure is distributed and raising resistance. As a result, it is crucial to research blood flow in catheterized arteries. In clinical research to assess biological flow parameters such as flow velocity or flow rate, arterial blood pressure and pressure gradient, it is useful to insert the proper catheter-tool equipment into the artery. A one-phase model is used in the majority of blood flow models (see Chaturani and Samy [8] Lightfoot [9]). Some blood's mechanical characteristics viz. blood pressure in arteries is measured in clinical research using transducers connected to catheters (see Gabe and Bergel [10]). For a pressure reading, an estimation of the difference in inaccuracy between a catheterized and non-catheterized artery is necessary. Using the available experimental data for a human stenotic artery, Daniel N. Riahi[11] explored unstable two-phase blood flow in a catheterized elastic artery stenotic, where the shape and degree of the stenosis are determined.

Based on studies done on a controlled dog, Kanai et al. [12] studied the need for an appropriate-sized catheter for every experiment to eliminate error at the catheter tip. Bojorno and Petterson [13] conducted experimental research on the hydrodynamic and hemodynamic effects on catheter-induced vessels and with and without stenosis, coronary artery catheterization was covered by Back et al. [14]. Sreenivasa Veena Beleyur et al.[15] examined a two-phase unsteady model of blood flow in a tapered stenosis artery while a transverse magnetic field was applied externally. Veena B.S. et al. [16] examined how blood flow in stenosed arteries that are tapering is affected by an externally applied transverse magnetic field. This work contributes significantly to our understanding of the connections between biomechanics and vascular disease. This study is helpful to medical professionals in creating new atherosclerosis treatment methods since the solution

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found may predict the behaviour of significant flow parameters under various conditions. A review of the literature reveals that no attempt has been made to investigate how a field of magnetic affects a catheter-created artificial artery filled with blood in a two-phase macroscopic model. Still, a two-phase model appears to be more appropriate in explaining blood flow since blood is a suspension.

With the aforementined information in mind, we simulate the flow of whole blood as a model of suspended particles in an artificial artery made by a catheter in order to examine the effects of an external magnetic field on a two-phase model. The goal of the research on Two-Phase Blood Flow across a Catheterized Artery and the Effect of a Magnetic Field is to better understand the complex dynamics of fluid flow in catheterized arteries when a magnetic field is present. The scope extends to the potential applications of this study in optimizing fluid transport systems, enhancing the understanding of medical interventions in cardio vascular system, and exploring the feasibility of utilizing magnetic fields to improve efficiency in measuring the performance capacity of circulatory system. By bridging the gap between biomedical insights and medical industry processes, the research seeks to offer innovative solutions for fluid management, medical interventions, and process optimization in resource extraction industries.

Mathematical Formulation

The artery is viewed as a cylindrical tube in the formulation of the physical problem. The flow is laminar, fully formed, and directed along the axis. Blood flows through an artery because of a constant pressure gradient along its axis. In practical applications, there is no change in pressure gradient between the two stages. Blood flows like a radius coaxial cylinder $\mathbf{a_1}$ between the annular region , the catheter and artery of radius 'a' (Fig. 1). Red blood cells suspended in plasma is a two-phase macroscopic Newtonian fluid model for blood. We ignore the entrance effects since the artery's diameter is too modest compared to its length. On the catheterized artery, an even transverse magnetic field (H_0) is applied. Srivastava and Srivastava [17] and Drew [18] are the authors to provide the governing equations for the physical model.

$$(1-C)\left(u_f \frac{\partial u_f}{\partial z}+v_f \frac{\partial v_f}{\partial r}\right)=(C-1)\frac{\partial p}{\partial z}-(C-1)\mu_s(C)\nabla^2 u_f - CS\left(u_f-u_p\right)+\mu_m M_p C\frac{dH_0}{dz} \tag{1}$$

$$\rho_f(1-C)\left(u_f \frac{\partial v_f}{\partial z}+v_f \frac{\partial v_f}{\partial r}\right)=-CS\left(v_f-v_p\right)-(1-C)\frac{\partial p}{\partial r}-(C-1)\mu_s(C)\left(\nabla^2-\frac{1}{r^2}\right)v_f \tag{2}$$

$$\frac{\partial}{\partial z}\left((1-C)u_f\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r(1-C)v_f\right)=0 \tag{3}$$

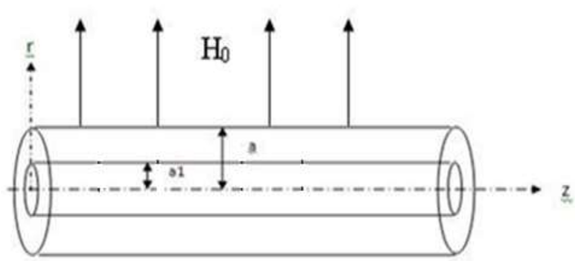

Fig. 1: A catheterized narrow artery's geometry

$$C\left(u_p \frac{\partial u_p}{\partial z}+v_p \frac{\partial u_p}{\partial r}\right)\rho_p=-\left(CS\left(u_p-u_f\right)+C\frac{\partial p}{\partial z}\right) \tag{4}$$

$$C\left(u_p \frac{\partial v_p}{\partial z}+v_p \frac{\partial v_p}{\partial r}\right)\rho_p=-\left(CS\left(v_p-v_f\right)+C\frac{\partial p}{\partial z}\right) \tag{5}$$

$$\frac{\partial}{\partial z}\left(C u_p\right)+\frac{1}{r}\frac{\partial}{\partial r}\left(r\, C v_p\right)=0 \tag{6}$$

where $\nabla^2=\frac{\partial^2}{\partial z^2}+\frac{\partial^2}{\partial r^2}+\frac{1}{r}\frac{\partial}{\partial r}$

the cylindrical polar coordinates represented by (r, z), where r is measured normal to the tube axis and z is measured along the tube axis, are represented by the Laplacian operator; ρ_f , ρ_p are the true densities of the substances that make up the phases of particles and fluids respectively, In the z and r axes, respectively, (u_f, u_p), (v_f, v_p) represent the velocity components of the phases of (fluid particle). The fluid and particle phases are indicated by the subscript s f and p, respectively. C the hematocrit, Cρ_p and (1-C) ρ_f are the actual densities of the materials that make up the particle and fluid phases, in that order; the μ_s(C)= μ_s is the fluid's effective or apparent viscosity; for a single phase's force, S is the interaction drag, and p is the pressure coefficient. *Mp* represents RCB's magnetization, μ_m stands for the magnetic permeability of the red cells and $\frac{dH_0}{dz}$ for the gradient of the magnetic field.

Due to Brownian motion, the diffusivity terms are ignored. The particles' Hematocrit C is presumably constant (see Drew [18]. Due to the low particle concentration, the field interaction between the two phases is ignored (see Srivastava et al.[19]).

(See Srivastava and Srivastava [19]) The drag coefficient S and suspension viscosity s have been expressed using the following expression:

$$\mu_s \cong (C)\mu_s = -\frac{\mu_0}{mc-1}, \tag{7}$$

$$m = \exp\left[\left(\frac{1107}{T}\right)\exp(-1.69C) + 2.49C\right]0.07 \tag{8}$$

$$S = 4.5\left(\frac{\mu_0}{a_0^2}\right)\left\{\frac{3C + 3\left[8c - 3C^2\right]^{1/2} + 4}{(2-3C)^2}\right\} \tag{9}$$

here a_0 is the red cell radius, T is the absolute temperature, and μ_0 is the plasma viscosity. As proposed by Charm and Kurland [20], the empirical relation for the suspension viscosity μ_s is found to be fairly accurate up to C = 0.6 (i.e. 60% hematocrit). Eq. (9) reflects the traditional Stokes drag for small particles and was determined by Tam [21]

Finding the answer to Equations (1) to (6) looks to be a tough challenge. Due to the complicated makeup of blood and the circulatory system, any attempt to precisely examine circulatory system issues is highly challenging. Small blood vessels can be thought of as brittle, cylindrical tubes (see McDonald [22]). As a result, small arteries with a diameter of around 2400 m can be used to depict a two-phase macroscopic model of blood (see Srivastava [19]). Narrow arteries experience unidirectional blood flow (see Charm and Kurland [20]]).

These findings enable the construction of the more straightforward equations that control the flow, which are

$$\frac{dp}{dz}(1-C) = \mu_m M_p C\frac{dH_0}{dz} - CS(u_f - u_p) - (C-1)\frac{\mu_s}{r}\frac{\partial}{\partial r}\left(r\frac{\partial}{\partial r}\right)u_f \tag{10}$$

$$\frac{dp}{dz} = -\frac{1}{C}\left[CS(u_f - u_p)\right] \tag{11}$$

Given by are the proper boundary conditions for the flow.

$$u_f = 0 \quad on \quad r = a,$$
$$u_f = 0 \quad on \quad r = a_1 \tag{12}$$

Method of solution

We solve equations (10) and (11) using the following method to arrive at the formulas (12) for the plasma velocity u_f and the erythrocyte velocity u_p: (12).

$$u_f = \frac{a^2}{4(C-1)\mu_s}\left(\frac{dp}{dz} - H\right)\left\{1 + \frac{(\varepsilon^2-1)\log(r/a)}{\log\varepsilon} - (r/a)^2\right\} \tag{13}$$

$$u_p = \frac{a^2}{4(C-1)\mu_s}\left(\frac{dp}{dz} - H\right)\left\{1 - \frac{4(C-1)\mu_s}{Sa^2} + \frac{(\varepsilon^2-1)\log(r/a)}{\log\varepsilon} - (r/a)^2\right\} \tag{14}$$

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$$where \quad a\varepsilon = a_1 .$$

Using the formula to calculate the volumetric flow rate Q,

$$Q = Q_p + Q_f$$

$$= \frac{\pi a^4}{8(C-1)\mu_s}\left(\frac{dp}{dz} - H\right)\left\{1 + \frac{\left(1-\varepsilon^2\right)^2}{\log \varepsilon} - \frac{8C(C-1)\mu_s\left(1-\varepsilon^2\right)}{Sa^2} - (\varepsilon)^4\right\} , \tag{15}$$

where $Q_f = 2\pi(C-1)\int_R^{R_1} r\, u_f\, dr$ and $Q_p = -2\pi c \int_R^{R_1} r\, u_p\, dr$

when $\varepsilon \to 0$, i.e., when the catheter is absent, the equations (13) through (15) decrease to the following set of equations, which is then the case when the catheter is present.

$$u_f = -\frac{a^2}{4(C-1)\mu_s}\left(\frac{dp}{dz} - H\right)\left\{(r/a)^2 - 1\right\} \tag{16}$$

$$u_p = \frac{a^2}{4(C-1)\mu_s}\left(\frac{dp}{dz} - H\right)\left\{1 - \frac{4(C-1)\mu_s}{Sa^2} - (r/a)^2\right\} \tag{17}$$

$$Q = \frac{\pi(1+\beta)a^4}{8(1-C)\mu_s}\left(\frac{dp}{dz} - H\right) \tag{18}$$

In this case, $\beta = \dfrac{8c(1-c)\mu_s}{Sa^2}$ and $H = \mu_m M_p C \dfrac{dH_0}{dz}$

Results and discussions

This mathematical model investigates the effects of the hematocrit C, catheter size, and produced magnetic field gradient H on the velocity, volumetric flow rate, and wall shear stress of a two-layer magnetic fluid flowing via a catheterized artery.

Numerical values for the analytical solutions at a temperature of 37^0C have been produced to analyze the study's findings (see Srivastava et al.[23]). Particle diameter $2a_0$ (erythrocyte diameter) = 8μm and artery radius $a = 70\,\mu m$ are chosen as the parameter values (see Young [24], Back [25], Srivastava [26], and Srivastava and Rashmi Srivastava [27]).

Figures 2 to 4 show plasma velocity profiles against the aspect ratio *r/a* for both catheterized, $\varepsilon \neq 0$ and non-catheterized, $\varepsilon = 0$ arteries. The magnitude of the velocity profiles is smaller for catheterized arteries and higher for non-catheterized arteries. This shows that inserting a catheter significantly lowers blood flow in an artery, and the parabolic type profiles are found between the catheter and the arterial wall. When an artery is non-catheterized, its velocity is highest close to its axis and significantly decreases as *r/a* or the arterial wall, increases.

The plasma velocity is seen to decrease as the fluid's Hematocrit level rises in Fig. 2's plot of plasma velocity against aspect ratio *r/a* for different hematocrit C values. This indicates that when the amount of red blood cells in the blood flow rises, the fluid's plasma velocity also increases , and the aspect ratio *r/a* decrease.

Fig. 3 depicts how the aspect ratio *r/a* and the magnetic field gradient H affect plasma velocity. The magnetic field gradient H and the hematocrit C have similar effects. This effect is brought on by a decrease in plasma flow rate brought on by the magnetic field gradient H, which is important in practical matters.

As can be seen in Fig. 4, the plasma velocity falls noticeably when the catheter size ε increases. It also reduces as the artery's aspect ratio, or *r/a*, increases, meaning that less blood enters the annular space between the artery wall and catheter wall, which is an important physical phenomenon.

Figs. 5 and 6 use experimental data from Shu's Table 1 [28] in an effort to analyze the biological importance of erythrocyte velocity u_p increase for diseased blood for catheter and non-catheter situations. Both in the case of non-catheterized and catheterized, it has been found that normal blood moves at a higher velocity than diseased blood, which is biologically accurate in nature.

In both catheterized $\varepsilon = 0$ and non-catheterized $\varepsilon \neq 0$ cases, Table 2 displays the computed volumetric flow rate Q for various pressure flow rates (*dp/dz*) and magnetic field gradients (H). For all fixed parameters, the rate of volumetric flow, Q, rises for any ε with *dp/dz*. In comparison to a non-catheterized artery, the volumetric flow rate Q assumes a noticeably smaller magnitude in catheterized arteries. The volumetric flow rate Q will decrease because of the magnetic field gradient. This is because blood flow is constantly slow down by the magnetic field gradient, but blood flow will also rise with higher *dp/dz*, which is consistent with all-natural fluids.

The predicted volumetric flow rate Q at various pressure flow rates (*dp/dz*) and hematocrits (C) in catheterized and non-catheterized instances is shown in Table 3. With all other flow parameters fixed, it is seen that Q rises for any ε with *dp/dz*. In a catheterized artery compared to a non-catheterized artery, Q assumes a substantially smaller value. We see that when C increases, the volumetric flow rate Q falls. This is because blood flow is always slowed down by hematocrit C; yet, if *dp/dz* increases, blood flow will also increase, this being consistent with all other fluids in nature.

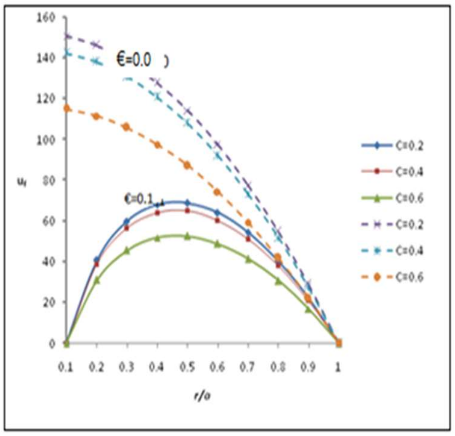

Fig.2: Plasma velocity profile, u_f for values of C, ε= 0.0 & ε=0.1in an artery diameter of 70μms

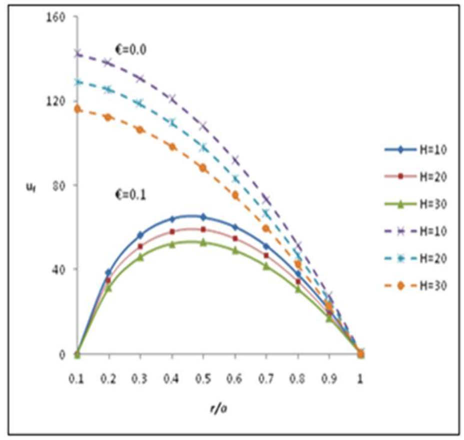

Fig. 3: Plasma velocity profile, u_f for values H for ε=0.0, ε=0.1 in an artery diameter of 70 μms & C=0.4

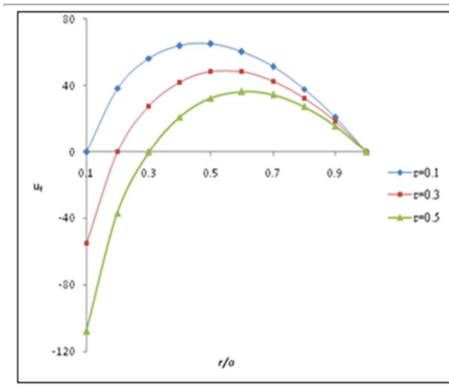

Fig.4: Plasma velocity profile u_f, for values of ε in an artery of diameter of 70 μms for H=10

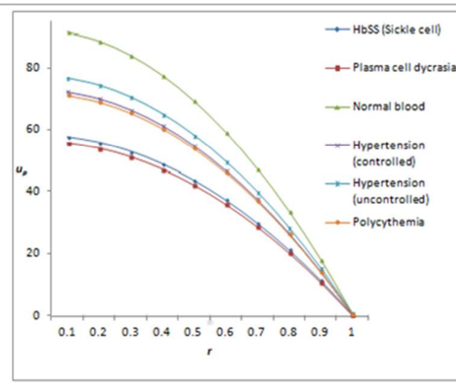

Fig.5: Erythrocyte velocity profile u_p, for catheter size ϵ=0.0, for normal and diseased blood in an artery diameter of 70 μms.

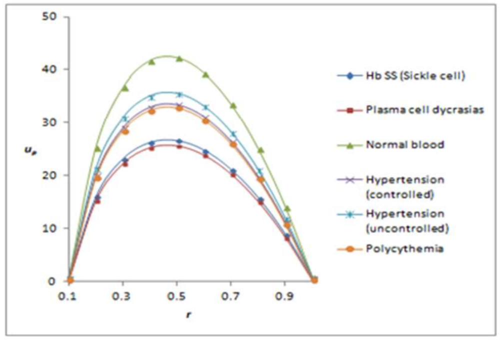

Fig. 6: Erythrocyte velocity profile u_p,for catheter size ϵ=0.1, for normal and diseased blood in an artery of diameter 70 µms for H=10 C=0.4, H=10.

Table1: Experimental data for diseased and normal blood of diameter of 70µm

Disease	Hematocrit(%)	$\mu_0\,(cp)$	$\mu_s\,(cp)$
Hb SS (Si kle ell)	24.80	1.30	5.10
Plasma cell dysrasias	28.00	3.09	5.43
Normal blood	42.60	1.24	4.03
Hypertension (controlled)	43.25	1.52	5.15
Hypertension (uncontrolled)	43.31	1.28	4.86
Polycythemia	63.20	1.50	7.69

Table 2: Volumetric flow rate for values of with catheter ($\mathcal{E}$=0.1) and without catheter ($\mathcal{E}$ =0.0) in an artery of diameter of 70µm for C=0.4

dp/dz dyne/cm³ (× 10[illegible])	Q. mm/s(× 10[illegible])					
	$\varepsilon = 0.1$			$\varepsilon = 0.0$		
	H=10	H=20	H=30	H=10	H=20	H=30
20	3126.826	1651.784	176.7412	5425.77	2866.229	306.6871
30	5427.761	3952.718	2477.676	9418.426	6858.884	4299.343
40	7728.693	6253.652	4778.61	13411.08	10851.54	8291.999
50	10029.63	8554.587	7079.544	17403.74	14844.2	12284.65
60	12330.56	10855.52	9380.479	21396.39	18836.85	16277.31
70	14631.5	13156.46	11681.41	25389.05	22829.51	20269.97
80	16932.43	15457.39	13982.35	29381.71	246822.16	24262.62
90	19233.37	17758.32	16283.28	33374.36	30814.82	28255.28

Table 3: Volumetric flow rate for values of hematocrit C with catheter ($\mathcal{E}$=0.1) and without catheter ($\mathcal{E}$=0.0) in a 70μm diameter artery for H=10

dp/dz dyne/cm^3 ($\times 10^3$)	Q. mm/s(× 10[illegible])					
	$\varepsilon = 0.1$			$\varepsilon = 0.0$		
	C=0.2	C=0.4	C=0.6	C=0.2	C=0.4	C=0.6
10	1589.603	825.8919	74.2858	2753.282	1433.114	129.311
20	3929.081	3126.826	2008.489	6805.391	5425.77	3496.224
30	6268.56	5427.761	3942.693	10857.5	9418.426	6863.137
40	8608.039	7728.695	5876.897	14909.61	13411.08	10230.05
50	10947.52	10029.63	7811.101	18961.72	17403.74	13596.96
60	13287	12330.56	9745.304	23013.83	21396.39	16963.87
70	15626.47	14631.5	11679.51	27065.94	25389.05	20330.79
80	17965.95	16932.43	13613.71	31118.05	29381.71	23697.7
90	20305.43	19233.37	15547.92	35170.16	33374.36	27064.61

CONCLUSION:

In summary, the effects of a magnetic field on two-phase blood flow through a catheterized artery—which may be thought of as a suspension of erythrocytes in plasma-have been thoroughly studied using a mathematical model. Numerical computations have yielded analytical solutions that have provided important new information, most notably the observation of a considerable drop in plasma velocity as catheter size increases. The resulting decrease in the volumetric flow rate as a result of the magnetic field gradient is consistent with biological reality, as a greater hematocrit also results in a lower volumetric flow rate. These results not only advance our knowledge of fluid dynamics in biological settings but also provide insightful ideas for possible uses in a variety of domains, such as materials science, and medicine. The study aims to improve fluid transport systems by understanding two-phase blood flow dynamics over catheterized arteries influenced by a magnetic field. It also aims to enhance safety and efficiency of medical interventions in metabolic processes and explore the feasibility of incorporating magnetic field-assisted processes for improved communication between the two systems namely metabolic and circulatory systems which is essential for maintaining overall health and balance in the body

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