Self-corrected Hemodynamic Analysis of Blood Viscosity for Detection of Endothelial Injury in Atherosclerosis using MRI

Supplementary Materials

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Section 1: Measurements of the viscosity of 40% glycerol aqueous solution at 23.5℃

The glycerol aqueous solution (2 liters, 40% (w/w)) was prepared by weighing the required amount of 99.5% glycerol (Shanghai Aladdin Biochemical Technology Co., LTD) and diluting it with distilled water. To measure the viscosity, this solution was firstly sampled and poured into a calibrated 0.4 mm capillary viscometer (with an instrument constant c = 0.005392 mm^2/s^2), which can measure liquid sample viscosity by measuring fall time driven by gravity in capillary. Then the solution was sent to the phantom for viscosity measurement by the MRI and PBV estimation. At the end, it was submerged in a water bath (23.5°C).

When the solution viscosity measured by capillary viscometer, the density ρ was also measured by using a glass densitometer (Weier Instrument & Meter Factory) to be 1120 $kg \cdot m^{-3}$.

The fall time t was recorded by a stopwatch as 575.2 s, 587.1 s, and 578.1 s in three independent capillary viscometer tests, respectively. The corresponding viscosities were 3.470 mPa·s, 3.541 mPa·s, and 3.498 mPa·s (calculated using the Formula S1). The average value of these viscosities is 3.503 mPa·s.

$$\mu\ (\mathrm{Pa \cdot s}) = \frac{c\ (\mathrm{mm^2 \cdot s^{-2}}) \cdot t\ (\mathrm{s}) \cdot \rho\ (\mathrm{kg \cdot m^{-3}})}{10^6\ (\mathrm{mm^2 \cdot m^{-2}})} \qquad (S1)$$

Section 2: Supplementary Figures & Tables

Table S1 The Reynolds number in rats' left carotid arteries

Group	Rat No.	Day 0	Day 10	Day 22	Day 31	Day 41
HLP	1	225.68	265.96	558.39	878.76	553.90
	2	630.13	614.36	1031.24	759.13	409.44
	3	263.88	564.42	468.41	835.62	785.03
	4	213.16	455.64	889.23	563.17	730.54
	5	520.11	171.17	828.42	847.99	555.83
NC	6	762.14	1005.11	604.13	727.69	590.46
	7	193.34	673.94	670.13	655.01	915.87
	8	349.18	670.88	929.61	642.29	300.90
	9	622.37	305.80	728.56	583.48	739.41
	10	534.59	482.74	841.93	578.94	851.47

*The maximum value of Reynold's number among common, internal and external carotid artery in each rat is shown in this table. If the Reynold's number $Re<2000$, the blood flow is laminar under the corresponding conditions.

Table S2 Sample size for each parameter (post-hoc)

Parameter name	Cohen's d (t-test)/ Effect size f (rmANOVA)	Minimum sample size per group (alpha=0.05, 80% power)	Actual sample size per group
LDL-C (rat)	3.85	3	5
LDL-C (rabbit)	7.01	3	3
$TAWSS_{min}$ (Day 31)	2.77	3	5
OSI_{max} (Day 42)	1.90	5	5
Low WSS level (W4)	3.43	3	5
LCCA diameter (W7)	1.56	7	7
Hematocrit (rat)	2.04	4	5
Diet (rat, rmANOVA)	0.70	3	5
Diet×PBV (rat, rmANOVA)	0.93	3	5
Diet (rabbit, rmANOVA)	0.37	5	5
Diet×PBV (rabbit, rmANOVA)	0.48	4	5

*LDL-C: low-density lipoprotein cholesterol, TAWSS: time-averaged wall shear stress, OSI: Oscillatory shear index, WSS: wall shear stress, LCCA: left common carotid artery, PBV: personalized blood viscosity.

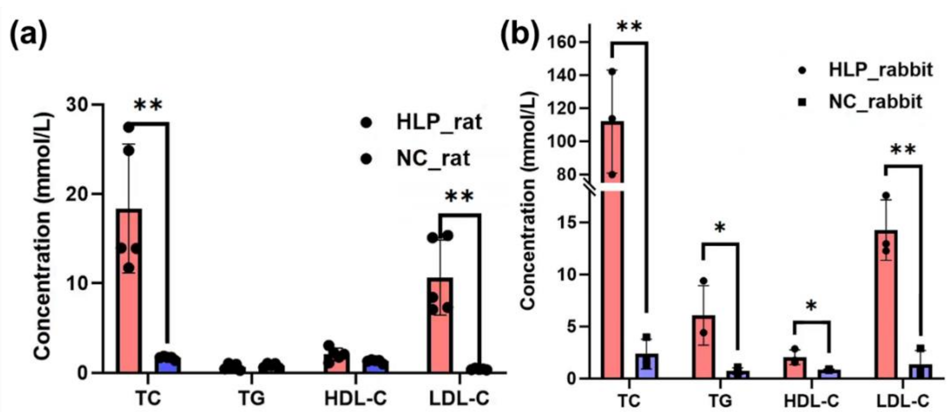

Fig.S1 Blood lipid profiles in rats (Day 42, n=5) and rabbits (Week 4, n=3). (a) HLP-rat group showed elevated TC and LDL-C compared to NC-rat group. (b) HLP-rabbit group exhibited combined hyperlipidemia. *: $p<0.05$, **: $p<0.01$ (unpaired t-test).

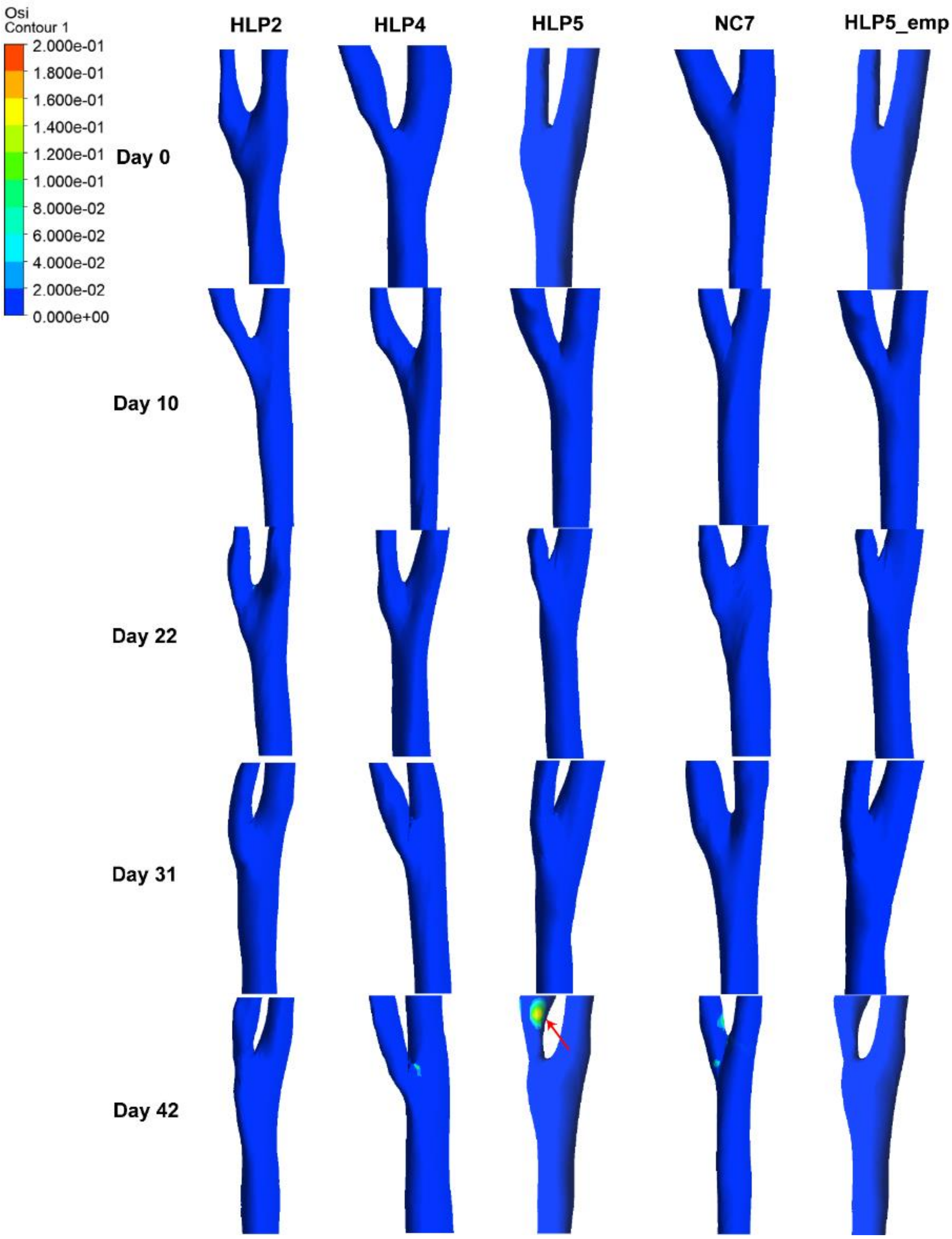

Fig.S2 Oscillatory Shear Index (OSI) maps in rats. HLP2, HLP4, and HLP5 columns are three series of OSI maps from the HLP-rat group, while the maps in NC7 column are from NC-rat group. The HLP5_emp column shows OSI results using the empirical power-law blood viscosity model. Arrows indicate regions of high OSI (>0.3).

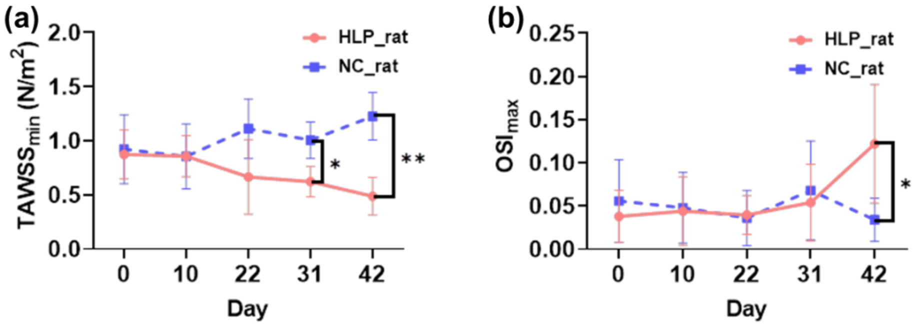

Fig.S3 Temporal evolution of time-average wall shear stress (TAWSS) and oscillatory shear index (OSI) in rats (a) Minimum TAWSS values in HLP-rat and NC-rat groups with PBV correction. (b) Maximum OSI values. Data presented as mean ± SD. *: $p<0.05$, **: $p<0.01$ (n=5, unpaired t-test).

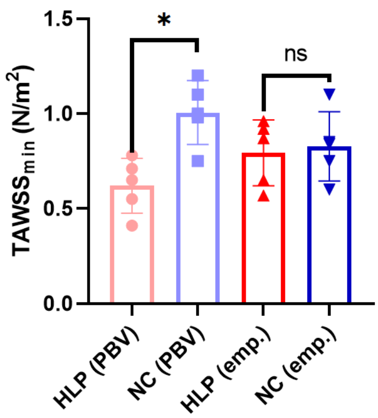

Fig.S4 TAWSS differences between HLP-rat and NC-rat groups on Day 31. PBV-corrected TAWSS values (0.62 ± 0.13 Pa vs. 1.00 ± 0.15 Pa, $p<0.05$), empirical model TAWSS values (0.79 ± 0.15 Pa vs. 0.83 ± 0.16 Pa, $p=0.77$). (n=5, unpaired t-test).

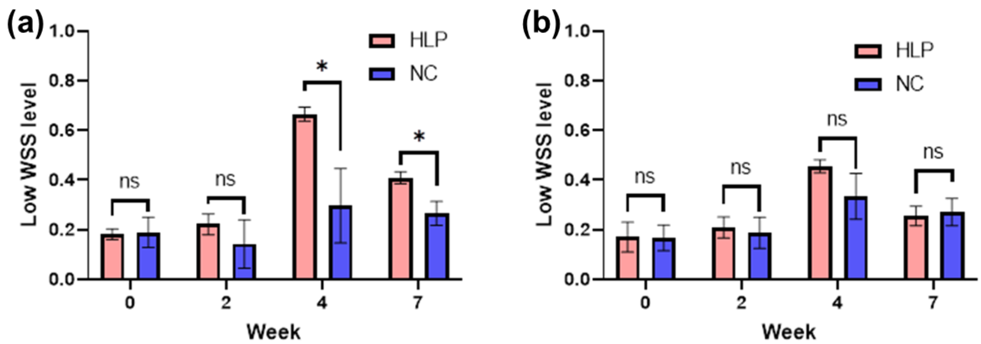

Fig. S5 Low WSS area quantification in rabbits. (a) PBV-corrected results showing significant differences between HLP-rabbit and NC-rabbit groups at Week 4 and Week 7. (b) Empirical model results showed no significance. *: $p<0.05$ (n=5; unpaired t-test).

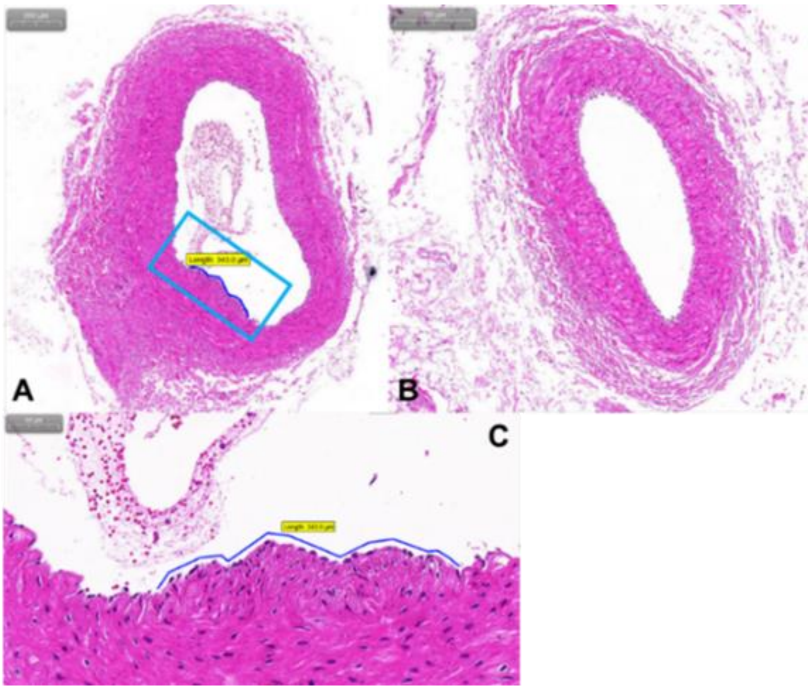

Fig.S6 H&E-stained sections of HLP rabbit (A) and healthy rabbit (B) at week 4 (scale bar: 200 μm). The magnified image of the smooth muscle proliferation lesion is shown in Figure C (scale bar: 50 μm).

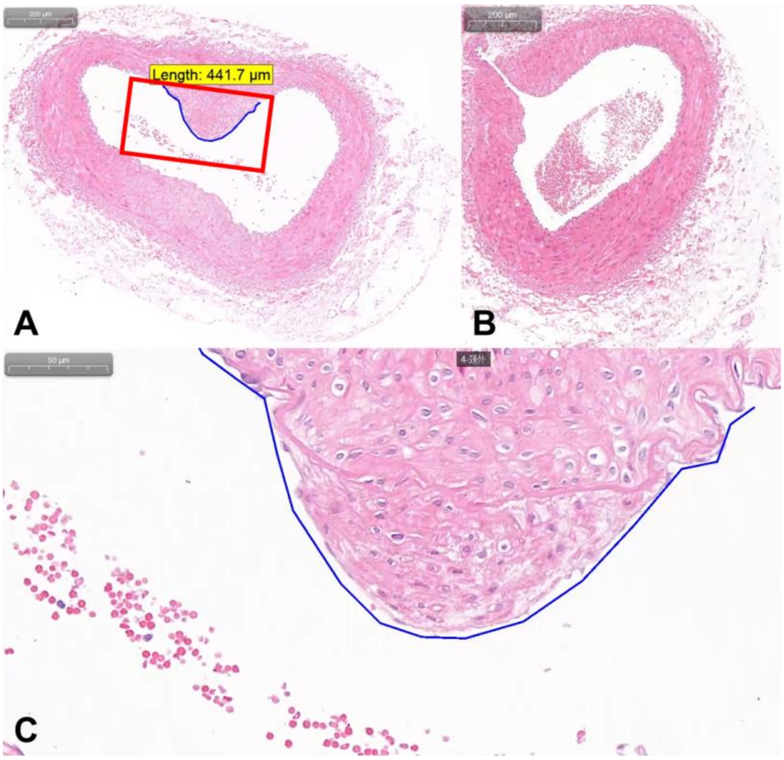

Fig.S7 H&E-stained sections of HLP rabbit (A) and healthy rabbit (B) at week 7 (scale bar: 200 μm). The magnified image of the Atherosclerosis lesion is shown in Figure C (scale bar: 50 μm).

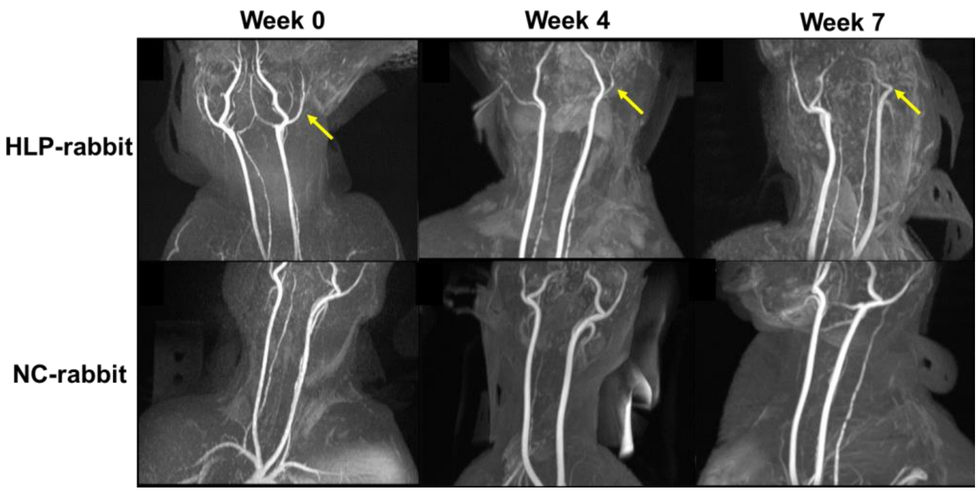

Fig.S8 The typical TOF-MRA image of hyperlipidemia rabbit and healthy rabbit at Week 4 and Week 7. The signal of the left external carotid artery highlighted by yellow arrows disappeared over time due to the change of vascular geometry.

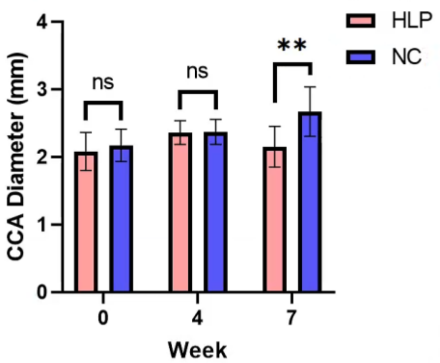

Fig.S9 The rabbits' left common carotid arteries diameters at week 0, 4 and 7 in the TOF-MRI image. **: p=0.01 (n=7, unpaired t-test).

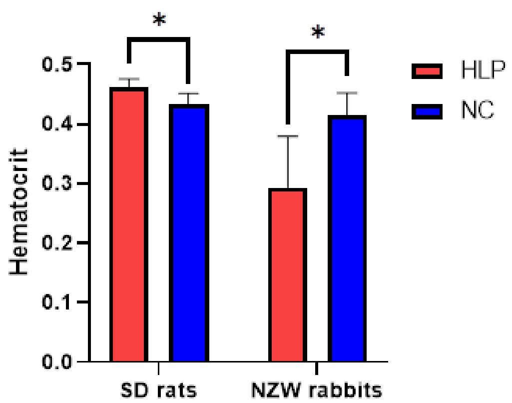

Fig.S10 Hematocrit results of SD rats (on Day 42) and NZW rabbits (at Week 7) with high-fat diet and conventional diet. *: $p<0.05$ (n=5, unpaired t-test).