Article:

Sarrami-Foroushani, A., Lassila, T. and Frangi, A.F. orcid.org/0000-0002-2675-528X (2017) Virtual endovascular treatment of intracranial aneurysms: models and uncertainty. Wiley Interdisciplinary Reviews: Systems Biology and Medicine, 9 (4). e1385. ISSN 1939-5094

https://doi.org/10.1002/wsbm.1385

Meta-analysis on the effect of uncertainties in inflow boundary condition, blood rheology, and vascular wall compliance

Data extracted from reference studies and meta-analysis computations are presented in this supplementary material. Three meta-analyses were performed to measure the effect of uncertainties in inflow boundary condition, blood rheology, and vascular wall compliance on the wall shear stress (WSS) predictions made by virtual endovascular treatment models of aneurysms. Random-effects meta-analyses performed on reference studies within each group and computations are presented in tables 1, 2, 3. For each reference study, matched group standardized mean differences (Hedges' g) were computed. The basic and summary data for the reference studies used in each meta-analysis are presented in tables 4, 5, and 6.

Table 1. Random-effects computations on the effect of inflow boundary condition on CFD-predicted aneurysmal WSS.

Reference First Author (Year)	N	Effect Size (g)	Study Variance (V_g)	Adjusted Variance ($T^2 + V_g$)	Adjusted Weight	Percentage Weight	95%-CI
Jansen (2014)	36	0.37	0.011	0.027	36.78	45.5%	0.16 - 0.57
Karmonik (2010)	10	0.07	0.024	0.040	24.91	30.8%	-0.23 - 0.37
McGah (2014)	4	0.48	0.036	0.052	19.11	23.7%	0.11 - 0.85
Pooled	**50**	**0.30**		**0.012**			**0.08 - 0.52**
p-value	**0.003**						
Between-studies Variance (T^2)	0.016						

Table 2. Random-effects computations on the effect of blood rheological model on CFD-predicted aneurysmal WSS. Between-studies variance is set to zero (fixed-effect meta-analysis) as DerSimonian and Laird method of computing between-studies variance resulted in a negative value (Dersimonian and Kacker, 2007)

Reference First Author (Year)	N	Effect Size (g)	Study Variance (V_g)	Adjusted Variance ($T^2 + V_g$)	Adjusted Weight	Percentage Weight	95%-CI
Castro (2014)	10	0.02	0.002	0.002	597.95	52.8%	-0.06 - 0.10
Fisher (2009)	4	0.04	0.013	0.013	75.52	6.7%	-0.26 - 0.19
Morales (2013)	3	0.02	0.002	0.002	459.19	40.5%	-0.07 - 0.11
Pooled	**17**	**0.02**		**0.001**			**-0.04 - 0.07**
p-value	**0.292**						
Between-studies Variance (T^2)	0.0						

Table 3. Random-effects computations on the effect of wall compliance model on CFD-predicted aneurysmal WSS.

Reference First Author (Year)	N	Effect Size (g)	Study Variance (V_g)	Adjusted Variance ($T^2 + V_g$)	Adjusted Weight	Percentage Weight	95%-CI
Torii (2009)	3	0.19	0.011	0.012	80.02	26.6%	-0.02 - 0.40
Takizawa (2012)	10	0.32	0.009	0.010	101.44	33.8%	0.13 - 0.50
Bazilevs (2010a)	4	0.42	0.015	0.016	60.77	20.2%	0.18 - 0.67
Bazilevs (2010b)	4	0.49	0.016	0.017	58.10	19.3%	0.24 - 0.74
Pooled	**21**	**0.34**		**0.003**			**0.22 - 0.45**
p-value	**< 0.001**						
Between-studies Variance (T^2)	0.001						

Table 4. Basic data from three studies performed on the effect of inflow boundary condition on CFD-predicted aneurysmal WSS. Matched group standardized mean differences are reported as Hedges' g for each study.

Jansen et al. (2014)

	WSS (Pa) PSIBC	WSS (Pa) GIBC	Absolute Difference (Pa)
P1	5.0	6.0	-1.0
P2	1.4	1.1	0.3
P3	1.2	2.2	-1.0
P4	2.1	1.9	0.2
P5	3.9	2.3	1.6
P6	0.3	2.8	-2.5
P7	5.9	5.5	0.4
P8	1.8	1.9	-0.1
P9	3.2	3.5	-0.3
P10	1.0	0.0	1.0
P11	1.3	3.0	-1.7
P12	1.7	1.0	0.7
P13	3.4	6.8	-3.4
P14	1.7	1.4	0.3
P15	1.2	4.2	-3.0
P16	0.6	2.9	-2.3
P17	1.8	1.7	0.1
P18	4.3	4.2	0.1
P19	2.7	4.1	-1.4
P20	2.1	0.4	1.7
P21	6.7	12.0	-5.3
P22	0.9	1.6	-0.7
P23	2.5	2.8	-0.3
P24	2.4	3.9	-1.5
P25	0.8	1.5	-0.7
P26	7.9	12.0	-4.1
P27	4.5	6.0	-1.5
P28	2.2	3.9	-1.7
P29	1.7	1.6	0.1
P36	0.0	1.0	-1.0
P31	1.7	6.4	-4.7
P32	1.0	1.1	-0.1
P33	2.4	3.4	-1.0
P34	2.6	2.4	0.2
P35	2.6	3.0	-0.4
P36	2.7	5.7	-3.0
mean	2.5	3.5	-1.0
SD	1.7	2.7	1.6
r	0.81		
N	36		
S_{within}	2.67		
g	0.37		
V_g	0.01		
SD_g	0.10		

Karmonik et al. (2010)

	WSS (Pa) PSIBC	WSS (Pa) GIBC	Absolute Difference (Pa)
P1	2.90	2.60	0.30
P2	0.16	0.22	-0.06
P3	0.03	0.04	-0.01
P4	0.52	0.53	-0.01
P5	0.90	1.10	-0.20
P6	0.90	1.10	-0.20
mean	0.90	0.93	-0.03
SD	0.95	0.85	0.17
r	0.90		
N	6		
S_{within}	0.37		
g	0.07		
V_g	0.02		
SD_g	0.15		

McGah et al. (2014)

	WSS (Pa) PSIBC	WSS (Pa) GIBC	Absolute Difference (Pa)
P1-P10	N/A	N/A	N/A
mean	1.85	4.06	-2.21
SD	1.34	3.57	2.60
r	0.81*		
N	10		
S_{within}	4.24		
g	0.48		
V_g	0.04		
SD_g	0.19		

PSIBC	Patient-specific inflow boundary condition
GIBC	Generalized inflow boundary condition
r	Pearson's correlation coefficient
N	Sample size
S_{within}	Within-study standard deviation
g	Hedges' g
V_g	Variance of the Hedges' g
SD_g	Standard deviation of the Hedges' g

* Only mean and SD values of WSS magnitude were reported by this study, therefore the correlation coefficient was assumed to be equal to that of the most populated study in the meta-analysis, i.e., Jansen et al. (2014).

Table 5. Basic data from three studies performed on the effect of blood rheological model on CFD-predicted aneurysmal WSS. Matched group standardized mean differences are reported as Hedges' g for each study.

Castro et al. (2014)

	WSS (Pa) NRM	WSS (Pa) CRM	Absolute Difference (Pa)
P1	3.53	3.62	0.11
P2	0.78	0.89	0.11
P3	0.85	0.79	-0.06
P4	0.95	1.08	0.13
P5	1.19	1.18	-0.01
P6	0.36	0.35	-0.01
P7	0.76	0.61	-0.15
P8	0.22	0.22	0.00
P9	0.02	0.08	0.06
P10	0.32	0.29	-0.03
mean	0.90	0.91	0.01
SD	0.94	0.97	0.08
r	0.99		
N	10		
S_{within}	0.58		
g	0.02		
V_g	0.002		
SD_g	0.041		

Morales et al. (2013)

	WSS (Pa) NRM	WSS (Pa) CRM	Absolute Difference (Pa)
P1	1.23	1.25	0.02
P2	0.63	0.62	-0.01
P3	0.58	0.58	0
mean	0.816	0.818	0.002
SD	0.30	0.31	0.01
r	0.99		
N	3		
S_{within}	0.09		
g	0.02		
V_g	0.002		
SD_g	0.047		

Fisher and Rossmann (2009)

	WSS (Pa) NRM	WSS (Pa) CRM	Absolute Difference (Pa)
P1	0.34	0.32	-0.01
P2	0.36	0.31	-0.05
P3	0.37	0.40	0.03
P4	0.09	0.10	0.01
mean	0.29	0.28	-0.01
SD	0.12	0.11	0.03
r	0.95		
N	4		
S_{within}	0.10		
g	-0.04		
V_g	0.013		
SD_g	0.115		

NRM	Newtonian rheological model
CRM	Casson's rheological model
r	Pearson's correlation coefficient
N	Sample size
S_{within}	Within-study standard deviation
g	Hedges' g
V_g	Variance of the Hedges' g
SD_g	Standard deviation of the Hedges' g

Table 6. Basic data from three studies performed on the effect of wall compliance model on CFD-predicted aneurysmal WSS. Matched group standardized mean differences are reported as Hedges' g for each study.

Takizawa et al. (2012)

	WSS (Pa) RWM	WSS (Pa) CWM	Absolute Difference (Pa)
P1	11.90	8.91	2.99
P2	3.31	2.40	0.91
P3	27.84	24.26	3.58
P4	10.45	3.30	7.16
P5	23.59	14.16	9.43
P6	20.01	16.17	3.84
P7	5.10	4.58	0.52
P8	2.29	2.17	0.13
P9	16.15	4.76	11.39
P10	29.81	25.97	3.84
mean	16.08	10.97	5.12
SD	11.23	10.66	4.68
r	0.95*		
N	10		
S_{within}	14.81		
g	0.31		
V_g	0.009		
SD_g	0.094		

Torii et al. (2009)

	WSS (Pa) RWM	WSS (Pa) CWM	Absolute Difference (Pa)
P1	42.8	32.9	9.9
P2	43	34.5	8.5
P3	32.6	34.4	-1.8
mean	39.5	33.9	5.5
SD	4.8	0.7	5.2
r	0.95		
N	3		
S_{within}	16.50		
g	0.19		
V_g	0.011		
SD_g	0.107		

Bazilevs et al. (2010a)

	WSS (Pa) RWM	WSS (Pa) CWM	Absolute Difference (Pa)
P1	38.58	35.25	3.33
P2	41.29	27.08	14.21
P3	50.36	38.64	11.72
P4	38.58	36.27	2.31
mean	43.41	34.00	9.41
SD	5.04	4.98	5.12
r	0.95		
N	4		
S_{within}	16.20		
g	0.42		
V_g	0.015		
SD_g	0.124		

Bazilevs et al. (2010b)

	WSS (Pa) RWM	WSS (Pa) CWM	Absolute Difference (Pa)
P1	15.00	12.36	2.64
P2	30.81	28.59	2.22
P3	23.02	17.58	5.43
P4	28.28	26.15	2.13
mean	27.37	24.10	3.26
SD	3.25	4.72	1.53
r	0.95		
N	4		
S_{within}	4.85		
g	0.48		
V_g	0.016		
SD_g	0.127		

RWM	Rigid wall model
CWM	Compliant wall model
r	Pearson's correlation coefficient
N	Sample size
S_{within}	Within-study standard deviation
g	Hedges' g
V_g	Variance of the Hedges' g
SD_g	Standard deviation of the Hedges' g

*Obtaining a correlation for the studies by Torii et al. (2009) and Bazilevz et al. (2010a) was not possible; so all the studies were pooled together and the correlation coefficient was computed.

References

Jansen I, Schneiders J, Potters W, van Ooij P, van den Berg R, van Bavel E, Marquering H, Majoie C. Generalized versus patient-specific inflow boundary conditions in computational fluid dynamics simulations of cerebral aneurysmal hemodynamics. *Am J Neuroradiol* 2014, 35:1543-1548.

Karmonik C, Yen C, Diaz O, Klucznik R, Grossman RG, Benndorf G. Temporal variations of wall shear stress parameters in intracranial aneurysms—importance of patient-specific inflow waveforms for CFD calculations. *Acta Neurochir (Wien)* 2010, 152:1391-1398.

McGah PM, Levitt MR, Barbour MC, Morton RP, Nerva JD, Mourad PD, Ghodke BV, Hallam DK, Sekhar LN, Kim LJ. Accuracy of computational cerebral aneurysm hemodynamics using patient-specific endovascular measurements. *Ann Biomed Eng* 2014, 42:503-514.

DerSimonian, Rebecca, and Raghu Kacker. "Random-effects model for meta-analysis of clinical trials: an update." *Contemporary clinical trials* 2007, 28:105-114.

Castro MA, Olivares MCA, Putman CM, Cebral JR. Unsteady wall shear stress analysis from image-based computational fluid dynamic aneurysm models under Newtonian and Casson rheological models. *Med Biol Eng Comput* 2014, 52:827-839.

Fisher C, Rossmann JS. Effect of non-Newtonian behavior on hemodynamics of cerebral aneurysms. *J Biomech Eng* 2009, 131:091004.

Morales HG, Larrabide I, Geers AJ, Aguilar ML, Frangi AF. Newtonian and non-Newtonian blood flow in coiled cerebral aneurysms. *J Biomech* 2013, 46:2158-2164.

Torii R, Oshima M, Kobayashi T, Takagi K, Tezduyar TE. Fluid–structure interaction modelling of blood flow and cerebral aneurysm: significance of artery and aneurysm shapes. *Comput Method Appl M* 2009, 198:3613-3621

Takizawa K, Brummer T, Tezduyar TE, Chen PR. A comparative study based on patient specific fluid-structure interaction modeling of cerebral aneurysms. *J Appl Mech* 2012, 79:010908.

Bazilevs Y, Hsu M-C, Zhang Y, Wang W, Kvamsdal T, Hentschel S, Isaksen J. Computational vascular fluid–structure interaction: methodology and application to cerebral aneurysms. *Biomech Model Mechan* 2010a, 9:481-498.

Bazilevs Y, Hsu M-C, Zhang Y, Wang W, Liang X, Kvamsdal T, Brekken R, Isaksen J. A fully coupled fluid-structure interaction simulation of cerebral aneurysms. *Comput Mech* 2010b, 46:3-16.