Supplementary Material

Patients Characteristics	n=199		
Sex	Female	Male	Unknown
	131 (66%)	45 (23%)	23 (11%)
Age	Older	Younger	Unknown
	80 (40%)	93 (47%)	26 (13%)
Hospital	UIC	AGH	HUH
	53 (26%)	81 (41%)	65 (33%)
Aneurysms Characteristics	n=270		
Status	Ruptured	Unruptured	Unknown
	60 (22%)	188 (70%)	22 (8%)
Blebs	Yes	No	
	97 (36%)	173 (64%)	

Supplementary Table I: Patients, aneurysm characteristics, and bleb presence in the IA aneurysm databases. Age groups have been defined as “Older” >=57y and “Younger” <57y. UIC=University of Illinois at Chicago, AGH=Allegheny General Hospital, and HUH=Helsinki University Hospital.

Characteristics	Variable	Definition	Measures
Flow Strength	VEL	Mean velocity (cm/s)	Flow speed
	VO	Mean vorticity (1/s)	Fluid rotation
	SR	Mean shear strain rate (1/s)	Viscous dissipation
WSS Distribution	WSS	Mean wall shear stress (dyne/cm^2)	Frictional force magnitude
	OSI(max)	Maximum oscillatory shear index	WSS oscillation
	RRT	Mean relative residence time (s)	Local flow retardation
	WSSGRAD	Mean WSS gradient (dyne/cm^3)	WSS spatial variation
	GON	Mean gradient oscillatory number	WSS gradient oscillation
Bleb Location	DINF	Distance to inflow along streamlines (%)*	Closeness to inflow
	Dome	Location on dome (60-100% of max distance to neck)	Location on aneurysm sac
	Body	Location on body (20-60% of max distance to neck)	
	Neck	Location on neck (0-20% of max distance to neck)	

Supplementary Table II: Variables computed for the characterization of bleb hemodynamic conditions as well as their location relative to the inflow and on the aneurysm sac.

*Mathematically: $DINF = \frac{1}{N}\sum_{i=1}^{N} L_I^i/(L_I^i + L_O^i)$, where L_I^i is the distance from the ith seed to the inflow, L_O^i is the distance from the ith seed to the outflow, and N is the number of nearby streamlines for each bleb region.

Characteristic	Variable	Ratio (thin/atherosclerotic)	P-value
Flow Strength	VEL	4.42 ± 7.64	0.4609
	VO	3.96 ± 4.31	0.1094
	SR	3.78 ± 4.04	0.1094
WSS Distribution	WSS	4.74 ± 5.71	0.0781
	OSI(max)	0.38 ± 0.39	0.0156*
	RRT	0.98 ± 1.57	0.7422
	WSSGRAD	4.40 ± 4.38	0.1094
	GON	1.40 ± 1.95	0.1484
Bleb Location	DINF	0.53 ± 0.39	0.0234*

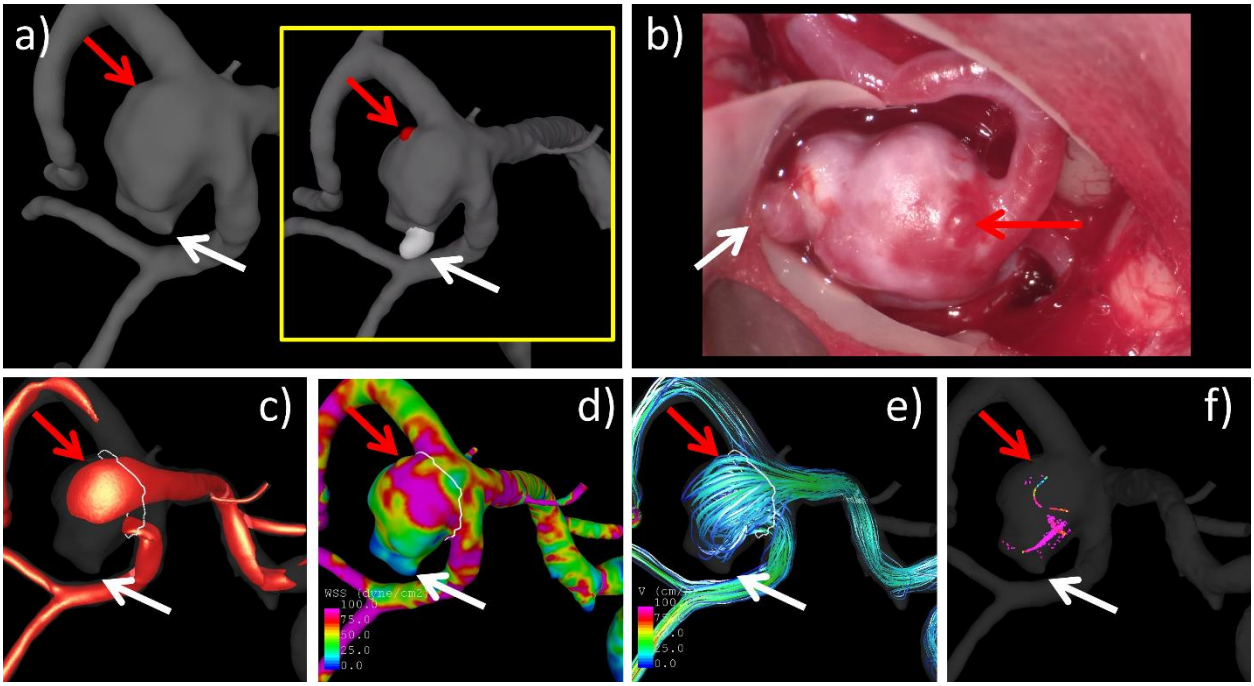
Supplementary Table III. Ratio of hemodynamic parameters of thin over atherosclerotic blebs of the same aneurysm (n=8), compared against 1 using single-sample Wilcoxon tests. Values are given as mean ± standard deviation. These tests indicate whether the variables were larger (ratio>1) or smaller (ratio<1) in the thin blebs compared to the atherosclerotic blebs of the same aneurysm. The p-values indicate whether the ratios were significantly different from 1 (null hypothesis was that the values were similar in thin and atherosclerotic blebs). Significant differences (95% confidence, $p<0.05$) are marked with a "*".

Aneurysms	Unruptured	Ruptured	
	Number	Number	Ruptured at bleb
Aneurysms with a single bleb			
Thin bleb	5	5	4
Atherosclerotic Bleb	8	4	2
Total	13	9	6
Aneurysms with multiple blebs			
Thin + Atherosclerotic Blebs	5	3	2 (1 T, 1 A)
Multiple Thin Blebs	2	0	0
Multiple Atherosclerotic Blebs	0	0	0
Total	7	3	2

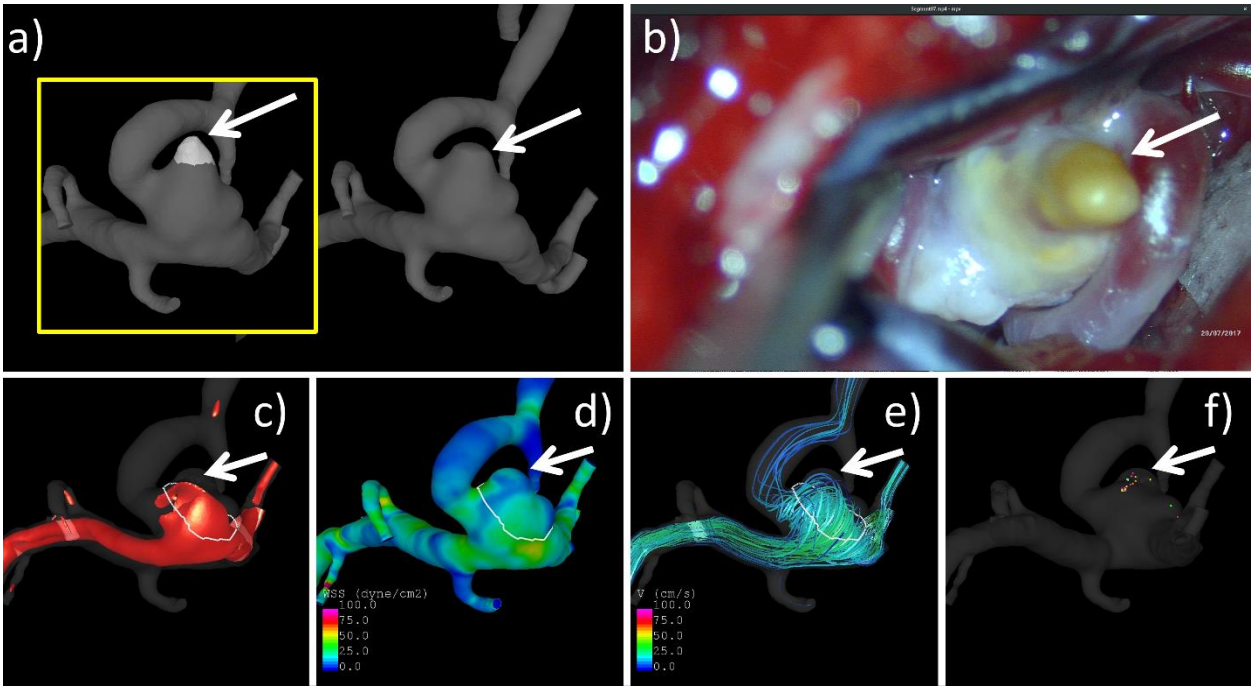
Supplementary Table IV. Number of ruptured and unruptured aneurysms with blebs visible in intra-operative videos. T=Thin, A=Atherosclerotic.

Variable	Location on aneurysm sac			P-values		
	Dome	Body	Neck	dome/body	dome/neck	body/neck
VEL	0.392 ± 0.328	0.399 ± 0.375	0.284 ± 0.341	0.8976	0.4472	0.1894
VO	0.627 ± 0.495	0.752 ± 0.558	0.828 ± 0.671	0.1585	0.4107	0.9651
SR	0.731 ± 0.558	0.860 ± 0.609	0.920 ± 0.697	0.1848	0.3990	0.9826
WSS	0.448 ± 0.353	0.571 ± 0.477	0.610 ± 0.534	0.1722	0.5118	0.9477
OSI(max)	0.542 ± 0.294	0.461 ± 0.349	0.484 ± 0.428	0.1593	0.6694	0.9825
RRT	2.478 ± 1.903	2.152 ± 2.431	2.910 ± 3.151	0.1366	0.7786	0.6777
WSSGRAD	0.614 ± 0.432	0.794 ± 0.529	1.059 ± 0.676	0.0522	0.0567	0.3470
GON	0.931 ± 0.430	0.973 ± 0.563	0.782 ± 0.365	0.8491	0.4985	0.4311
DINF	50.84 ± 19.76	55.50 ± 32.04	80.20 ± 35.34	0.4568	0.0032*	0.0339*

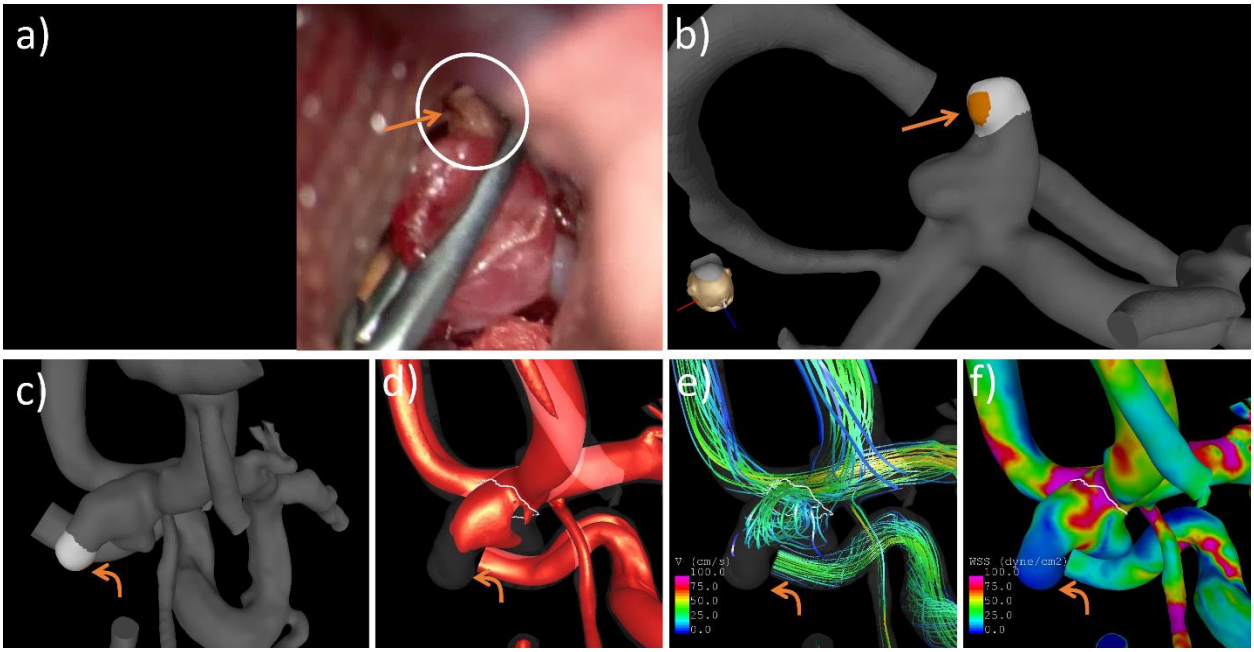
Supplementary Table V. Pairwise comparison of (normalized) hemodynamic quantities between blebs located at the neck, body, or dome of the aneurysms. Values are given as mean ± standard deviation. Significant differences (95% confidence, $p<0.05$) are marked with a "*".



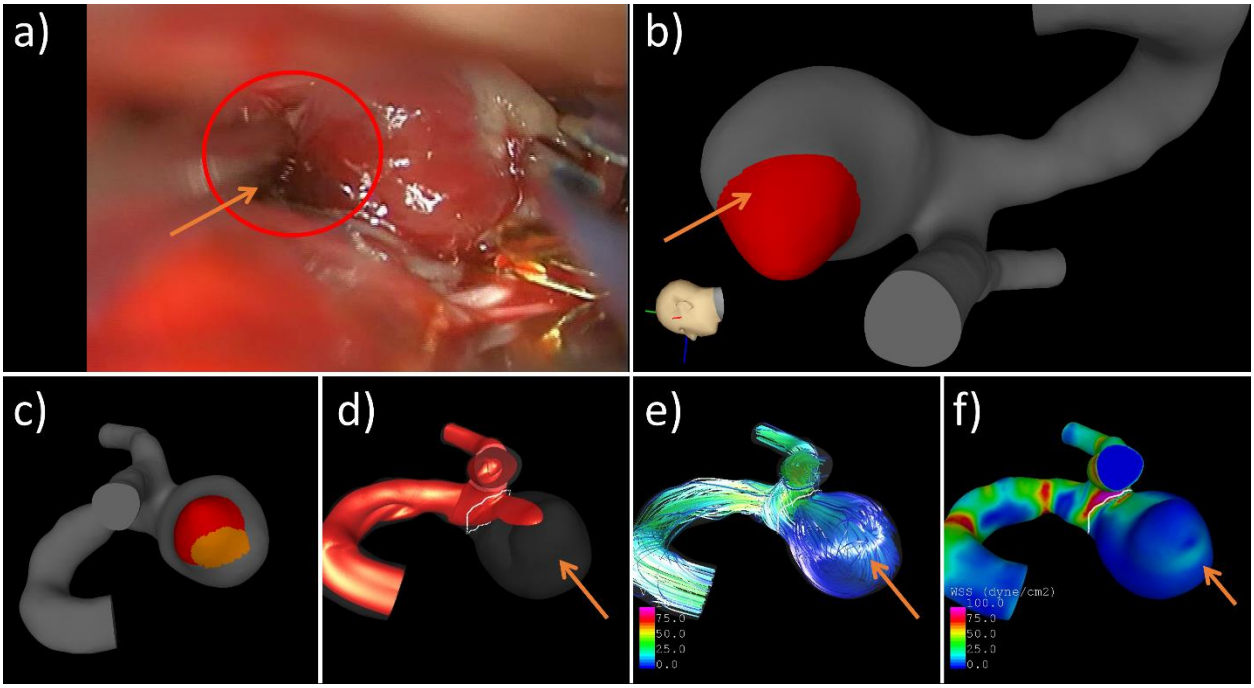
Supplementary Figure I. Example of an aneurysm with a thin bleb (red) and a slightly hyperplastic (white) bleb: a) anatomical model with blebs removed (insert shows the two marked blebs), b) thin red bleb (red arrow) observed in intra-operative video, c) hyperplastic bleb (white arrow) in video, d) visualization of inflow stream, e) WSS distribution, f) flow pattern visualized with streamlines, and g) flow structure visualized with vortex corelines. All flow visualizations correspond to peak systole. Arrows point to the regions of each bleb formation. Note that the red bleb is located closer to the inflow and with higher flow conditions than the white bleb.



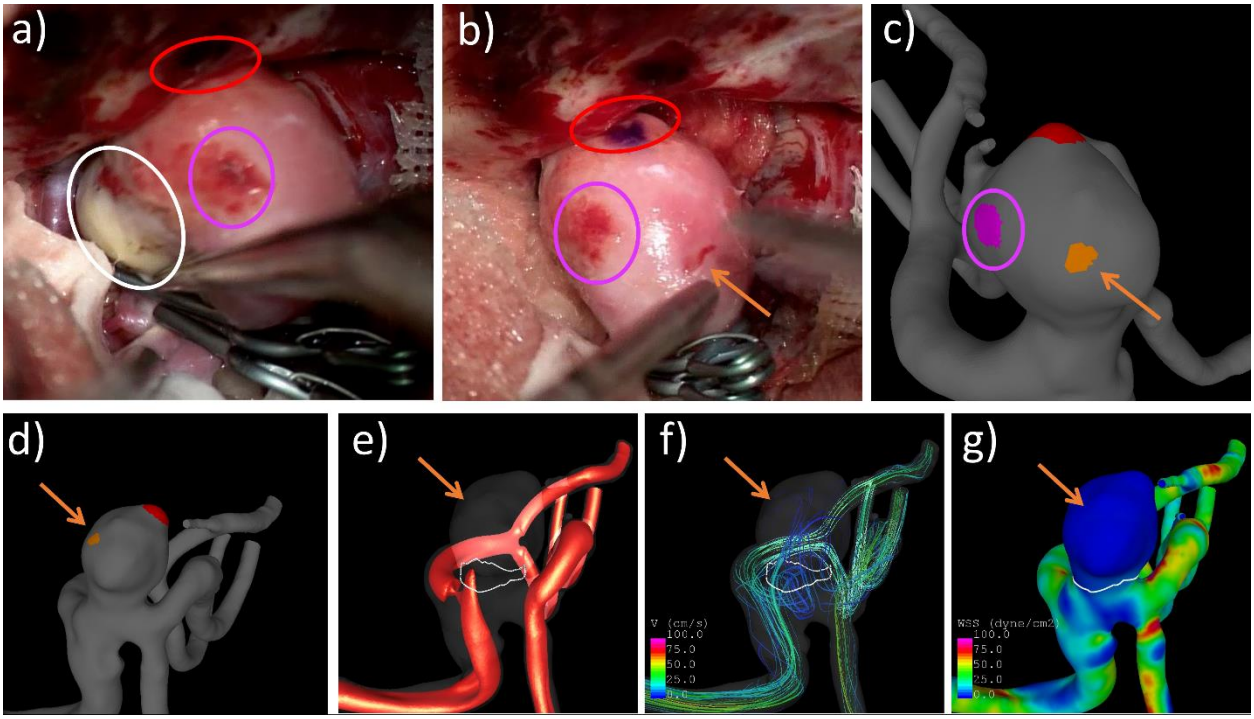
Supplementary Figure II. Example of an aneurysm with an atherosclerotic (white) bleb: a) anatomical model with bleb removed (insert shows the marked bleb), b) atherosclerotic yellow/white bleb (white arrow) in video, c) visualization of inflow stream, d) WSS distribution, e) flow pattern visualized with streamlines, and f) flow structure visualized with vortex corelines. All flow visualizations correspond to peak systole. Arrows point to the regions of bleb formation. Note that the bleb is located near the outflow and under low WSS conditions.



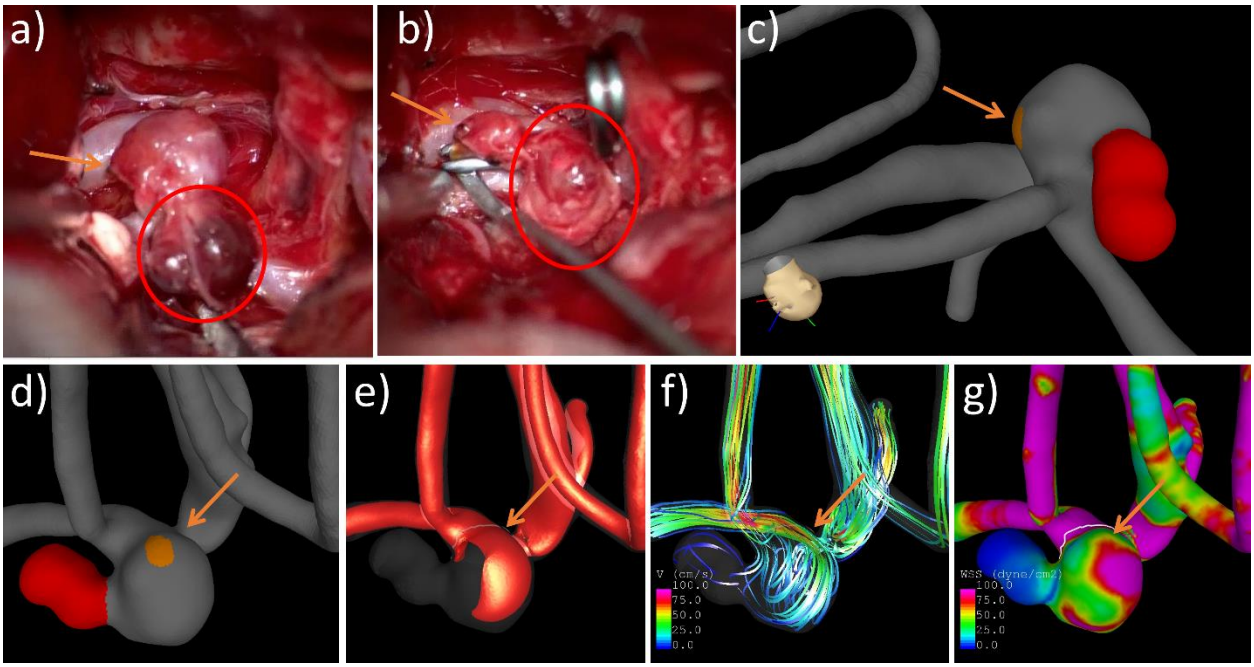
Supplementary Figure III. Example of aneurysm that ruptured at an atherosclerotic bleb: a) video frame showing white bleb with rupture point, b) bleb (white) and rupture point (gold) marked on vascular model, c) vascular model with marked bleb, d) visualization of inflow stream, e) visualization of flow pattern, f) WSS distribution. All flow visualizations correspond to peak systole. Gold arrows point to the rupture site. Note that in this case the aneurysm ruptured at an atherosclerotic bleb subjected to low flow conditions. In the video (a), the rupture site is visible as a darker region of the atherosclerotic bleb (small hematoma) once a clip has been placed.



Supplementary Figure IV. Example of aneurysm that ruptured at a thin red bleb: a) video frame showing the red bleb with the rupture point, b) bleb (red) marked on vascular model (arrow point to rupture site), c) vascular model with marked bleb and rupture site, d) visualization of inflow stream, e) visualization of flow pattern, f) WSS distribution. All flow visualizations correspond to peak systole. Gold arrows point to the rupture site. Note that in this case the aneurysm ruptured at the flow impingement site within the thin bleb. In this case, the rupture site was observed as a hematoma towards one side of the red bleb region. This part of the aneurysm tip was briefly visible in the video while the aneurysm was being manipulated by the surgeon.



Supplementary Figure V. Example of aneurysm harboring a thin and an atherosclerotic bleb that ruptured at the dome away from the blebs: a) video frame showing the atherosclerotic bleb (white ellipse), the thin bleb (red ellipse) and a red region of the sac (pink ellipse), b) video frame showing the thin bleb marked with a surgical pen (red ellipse, note the purple dot), the red region of the sac (pink ellipse), and the rupture site (gold arrow), c) marked vascular model showing the thin bleb (red) the red region of the sac (pink ellipse) and the rupture site (gold), d) vascular model with marked bleb and rupture site, e) visualization of inflow stream, f) visualization of flow pattern, g) WSS distribution. All flow visualizations correspond to peak systole. Gold arrows point to the rupture site. Note that in this case the aneurysm ruptured at the dome away from the blebs and the entire aneurysm is under low WSS. In this case, each bleb was briefly visible in the video at different times while the aneurysm is being manipulated and clipped. The red region marked with the pink ellipse was associated with an external attachment that was surgically removed, and we used it as a reference to locate the rupture point on the sac. The rupture site was observed as a small tear or hole in the wall once the aneurysm was clipped. The surgeon then slightly squeezed the aneurysm and blood was seen exiting the aneurysm through this hole, confirming this was the rupture site.



Supplementary Figure VI. Example of aneurysm harboring a thin bleb that ruptured at the body away from the bleb: a) video frame showing the thin bleb (red ellipse), b) video frame showing the thin bleb (red ellipse) and the rupture site (gold arrow), c) marked vascular model showing the thin bleb (red) and the rupture site (gold), d) vascular model with marked bleb and rupture site, e) visualization of inflow stream, f) visualization of flow pattern, g) WSS distribution. All flow visualizations correspond to peak systole. Gold arrows point to the rupture site. Note that in this case the aneurysm ruptured at the body near the inflow impingement region and away from the bleb. In this case, the red bleb was also seen to be partially thrombosed (a), which explains the slight geometrical differences between the vide and the 3D angiography image. The rupture point became briefly visible in the video as a small dark hematoma after the aneurysm was clipped and the aneurysm was shifted by the surgeon.