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Unruptured intracranial aneurysm volume change patterns and association with age, sex, location in vascular tree, and common risk factors: a single-centre retrospective study

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ABSTRACT

Introduction. Unruptured intracranial aneurysms pose a significant clinical and decision-making dilemma. Increase in dome size is one of the crucial indications for treatment. Almost no data exists as to how aneurysms change in size over time.

Material and methods. 102 patients (76 women) who had a total of 501 CT examinations were included in the study. Inclusion criteria were: at least three CT angiography studies, an observation period of at least three years, or bleeding during the follow-up period. In each study, the volume of each aneurysm was measured at least four times by two experienced neuroradiologists with the use of dedicated tools. Collected data was used to obtain numerical volume change models for each aneurysm.

Results. 149 aneurysms were analysed in the study (118 in women) No significant differences in location, size or age of observation were detected between men and women. Median follow-up was 5.64 years (IQR 4.17–7.71) and total aneurysm observation time amounted to 964.59 years. There were 57 branching zone aneurysms (women 46), 44 sidewall aneurysms (women 36), 20 anterior communicating artery aneurysms (women 16), 20 posterior communicating artery aneurysms (women 13), and eight posterior circulation aneurysms (women 7).

78 (52%) aneurysms remained stable (women 59), 24 (16.6%) increased their volume (women 20), and five (3.4%) decreased (women 4). In 42 (28%) cases, we observed non-uniform routes of volume changes over surveillance (women 35). In the last group, analysing the whole period of follow-up, 29 (69%) did not change volume (women 24), 11 (26%) grew (women 10), and two decreased in size (4.8%, women 1). Bifurcation zone aneurysms, lower aspect ratio, lower patient age, and higher initial volume were associated with an increased risk of aneurysm growth. Posterior circulation aneurysms presented the lowest rate of volume increase.

Conclusions. A substantial amount of followed up aneurysms could change volume in a non-uniform way, and an increase in volume may not lead to aneurysm rupture.

Keywords: unruptured intracranial aneurysm, volume, CTA, risk factors, guidelines

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Introduction

The reported prevalence of unruptured intracranial aneurysms (UIAs) is c.3% [1]. The most feared complication of an intracranial aneurysm (IA) is its rupture and subarachnoid haemorrhage (SAH), which has a 30-day mortality of 40% and leaves half of survivors disabled. With the growing availability of brain imaging, the number of incidentally detected UIAs is increasing. This poses a substantial decision-making problem for clinicians worldwide [2–5]. Because of the devastating consequences of SAH, many UIAs undergo preventive treatment [4]. However, both surgical and endovascular techniques carry a non-negligible risk of complications [4, 6]. Most incidentally detected aneurysms are small and have low risk of rupture [7–9]. Multiple studies have attempted to stratify the risk of these vascular pathologies to optimise clinical strategies and protocols [5, 10, 11]. For aneurysms with the lowest possible risk, computed tomography angiography (CTA) or magnetic resonance angiography (MRA) study follow-up has been advised in some papers, in order to detect sack size increase or shape change, which are thought to increase the risk of rupture substantially [12, 13].

In our institution, we use repeated CTA studies [14] for surveillance of patients.

Most research into aneurysm size change in follow-up is based on comparisons of this feature at the beginning and end of the follow-up. However, it has not been confirmed that the growth of UIA is a linear process [15, 16] because there is no data describing this process.

In the present study, we address the abovementioned issues by analysing different patterns of aneurysm volume change using 3D volumetry as the most reliable and accurate measurement of aneurysm size [17] in multiple measurements. We also analyse how factors such as hypertension (HT), cigarette smoking (CS), polycystic kidney disease (PKD), familiar history of SAH (FH), multiplicity of aneurysms, sex, age, and location in the vascular tree influence this process.

Clinical rationale for study

Understanding the volume change pattern of intracranial aneurysms will guide future follow-up protocols and may help with treatment decision making.

Material and methods

Patients with UIAs at our department were followed by CTA between May 2006 and March 2021. Inclusion criteria were: at least three CTA studies, an observation period of at least 1,095 days (three years), and/or two studies and bleeding during the follow-up period. Analysis of data from the Radiology Information System (RIS) and further CTA studies allowed for the identification of 102 patients meeting the criteria. In three cases, IA eventually bled during the follow-up period. A total of 501 CTA studies were included and analysed.

Aneurysm measurements and volumetry

CTA studies were collected from the Picture Archiving and Communication System (PACS) in the form of DICOM files. All measurements were performed with the use of 3D Reconstructor software, which was developed by our team [14, 18, 19] (Figure 1). Two dedicated measurement tools were introduced for strictly perpendicular measurements of the neck and sack of the aneurysms. The second tool was enhanced with the ability to conduct semiautomatic aneurysm volume measurement. This used two well-known algorithms to achieve best

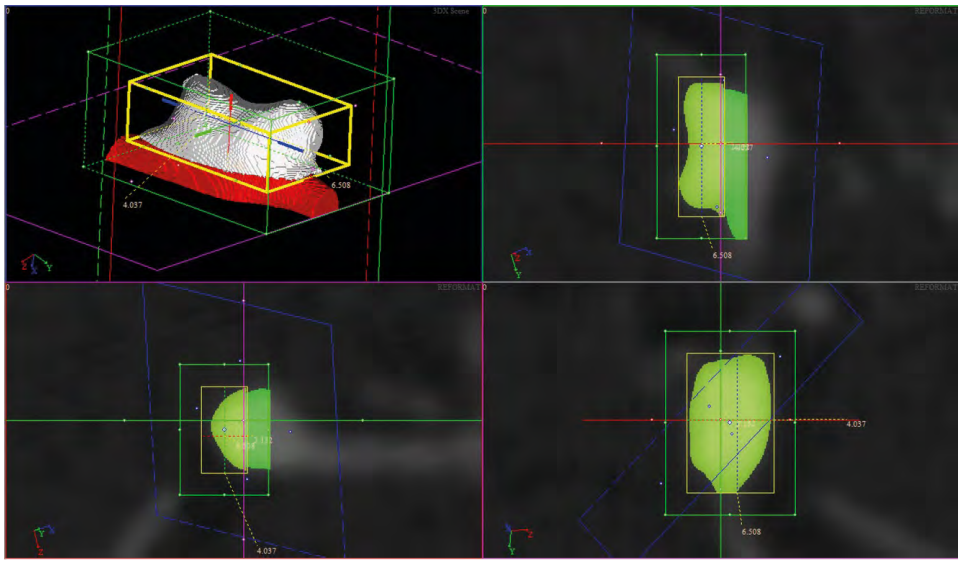

Figure 1. Tools used for aneurysm sack and neck measurements

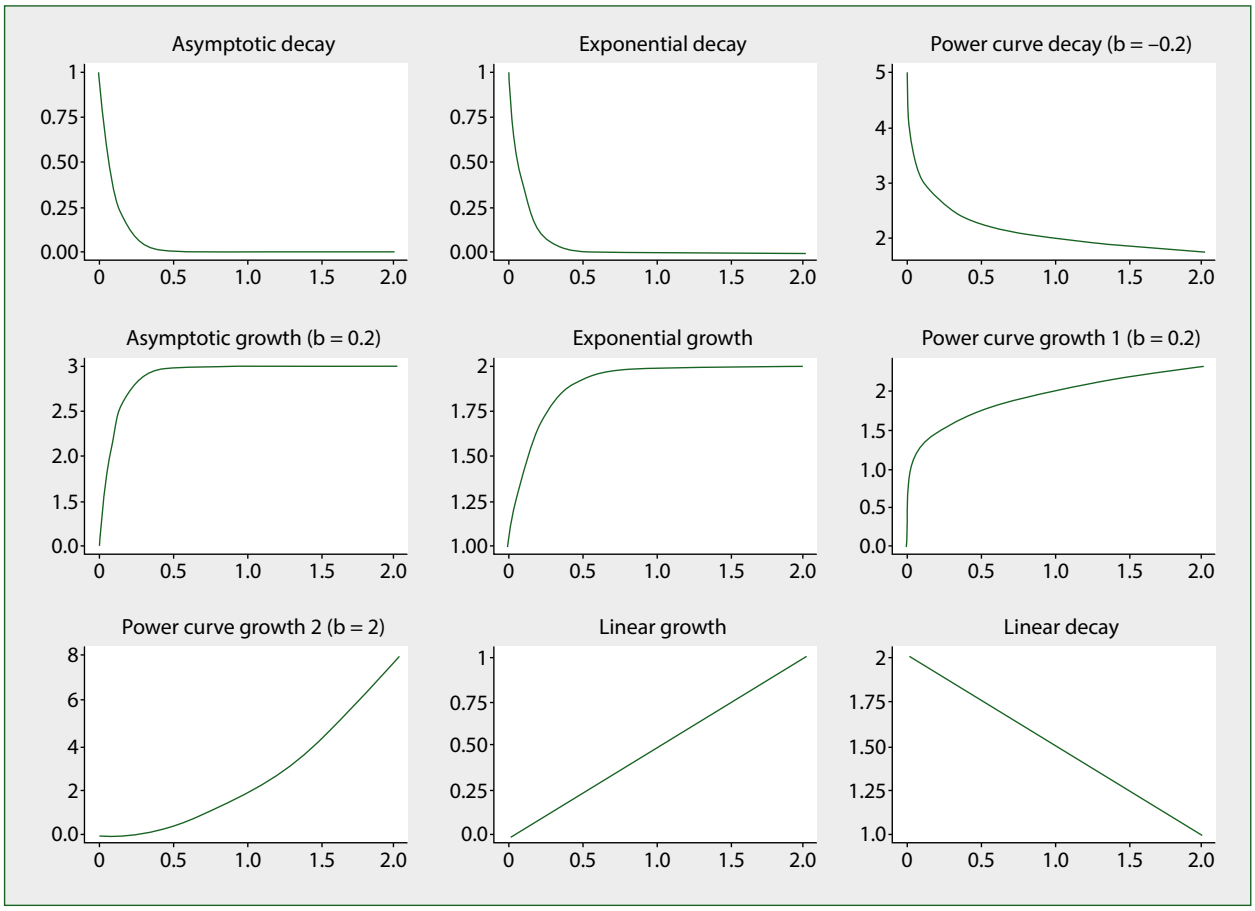

Figure 2. Curve types used for data fitting in sack volume changes analysis

and reputable results: thresholding and region expansion. In each study, measurements on each aneurysm were performed at least twice by two experienced neuroradiologists.

The results of the sack and neck measurements were then automatically transferred to a dedicated database using the PostgreSQL 11.0 64bit engine.

Numerical and statistical analysis

Numerical and statistical analysis concentrated on aneurysm sack volume changes obtained from volumetry and their transformation into mathematical models allowing robust analysis. This approach was chosen because of the non-uniform periods between follow-up studies.

The first step was transforming raw data in the domain of individual ages into sets of periods of uniform volume change (UTS — uniform time segments) and then fitting them into selected mathematical models. To achieve this, segments covering periods between consecutive studies were established and first derivatives calculated. For each time point other than end points, sign changes of these derivatives were searched and marked (SCP — sign change point). Periods between SCPs were marked as uniform. If there were no SCPs, the whole presenting follow-up period was marked as a UTS.

In the next step, linear regression models were constructed for neighbouring segments and tested for statistically significant differences between them. If they were not detected ($p > 0.05$), the SCP was rejected and both segments combined into one. This step was introduced to avoid oversensitivity of the algorithm in the case of wave-shape curves.

For each UTS, linear regression was applied and, based on its results, a general type of change was determined: increasing volume (I), stable volume (S), or decreasing volume (D). Aneurysms for which the volume change over time was represented by more than one segment of various types were categorised as various (V). The last group was then analysed with a linear regression model for the whole period of observation and assigned to be increasing (VI), or decreasing (VD), or stable (VS). The same operation was performed for all analysed aneurysms dividing them into overall increasing (OI), decreasing (OD), or stable (OS).

Each UTS was further fitted into one of the selected mathematical models: linear, asymptotic, exponential, and power, each in growth and decreasing types (Figure 2). Fitting was done with the use of R DRC library (Analysis of Dose Response Curves). Comparing root-mean square error (RMSE) for each fit, the best model was selected and assigned to the analysed segment.

Similarities in the shapes of presented groups of mathematical functions allowed for their reduction into six geometrical approximation groups, and finally into three groups of basic volume change, as set out in Supplementary Table 1.

Only saccular type aneurysms were analysed. To allow robust statistical analysis, taking into account differences in risk of rupture and growth [3, 20, 21] we distinguished five types of aneurysm. The first of these was a branching zone (BZ) consisting of ICA, MCA (including early branch) and BA bifurcation aneurysms. The second was anterior communicating (AC). The third was posterior communicating (PCom) consisting of only ICA PCom — no pure PCom. The fourth was posterior circulation (PC) consisting of all other UIAs located on VA or BA. The last group were sidewall aneurysms (SW), defined as aneurysms located on ICA and ACA, arising in the zones of perforators or small branches of parent vessels including ophthalmic, anterior choroidal, Heubner's arteries etc.

The obtained data was related to patient gender and location of the aneurysm in the vascular tree, the presence of multiple aneurysms, and previous subarachnoid haemorrhages, as well as age at the beginning of follow-up or UTS, and collected clinical data including hypertension (HT), cigarette smoking (CS), family history of SAH (FH), and polycystic kidney disease (PKD).

Results

Basic group characteristics

102 patients (F = 76) were included in the study. The median age at the beginning of follow-up was 57.88 years (range

Table 1. IUAs volume change patterns in identified volume change groups divided into various vascular tree locations

Group	Volume change pattern	Overall n = 61	BZ n = 28	PCom n = 14	AC n = 9	PC n = 6	SW n = 4	p-value*
Increasing (I)		n = 24	n = 13	n = 3	n = 3	n = 1	n = 4	
	LI	12 (50%)	7 (54%)	1 (33%)	2 (67%)	1 (100%)	1 (25%)	0.3
	IS	11 (46%)	6 (46%)	2 (67%)	0 (0%)	0 (0%)	3 (75%)	
	PI2	1 (4.2%)	0 (0%)	0 (0%)	1 (33%)	0 (0%)	0 (0%)	
Decreasing (D)		n = 5	n = 3		n = 2			
	DS	3 (60%)	1 (33%)		2 (100%)			0.4
	LD	2 (40%)	2 (67%)		0 (0%)			
Various Increasing (VI)		n = 11	n = 3	n = 5	n = 2	n = 1		
	S, LI	5 (45%)	0 (0%)	4 (80%)	1 (50%)	0 (0%)		0.092
	S, IS	4 (36%)	2 (67%)	1 (20%)	0 (0%)	1 (100%)		
	PI2, LD, IS	1 (9.1%)	1 (33%)	0 (0%)	0 (0%)	0 (0%)		
	S, PI2	1 (9.1%)	0 (0%)	0 (0%)	1 (50%)	0 (0%)		
Various Decreasing (VD)		n = 2	n = 1		n = 1			
	S, LD	1 (50%)	1 (100%)		0 (0%)			> 0.9
	S, LI, LD	1 (50%)	0 (0%)		1 (100%)			
Various Stable (VS)		n = 19	n = 8	n = 6	n = 1	n = 4		
	LI, S	5 (26%)	3 (38%)	0 (0%)	1 (100%)	1 (25%)		0.3
	S, LI	3 (16%)	1 (13%)	2 (33%)	0 (0%)	0 (0%)		
	LD, S	2 (11%)	0 (0%)	2 (33%)	0 (0%)	0 (0%)		
	IS, LD	1 (5.3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)		
	IS, LD, S	1 (5.3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)		
	LD, IS, S	1 (5.3%)	0 (0%)	0 (0%)	0 (0%)	1 (25%)		
	LD, S, LI, S	1 (5.3%)	0 (0%)	0 (0%)	0 (0%)	1 (25%)		
	LI, DS, S	1 (5.3%)	0 (0%)	1 (17%)	0 (0%)	0 (0%)		
	S, IS	1 (5.3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)		
	S, LD	1 (5.3%)	0 (0%)	1 (17%)	0 (0%)	0 (0%)		
	S, LD, S	1 (5.3%)	0 (0%)	0 (0%)	0 (0%)	1 (25%)		
	S, LI, LD	1 (5.3%)	1 (13%)	0 (0%)	0 (0%)	0 (0%)		

I — increase; D — decrease; VI — various with overall increase; VD — various with overall decrease; VS — various with overall stable volume; S — stable; LI — linear increase; IS — increase with stabilisation; PI2 — power increase; LD — linear decrease; *Fisher's exact test

Table 2. Summary of general logistic analysis, optimal models for prediction of UIA sack volume change types

Predictor	Sack volume change type								
	D	VD	OD	S	VS	OS	I	VI	OI
Hypertension				(+)***	(-)**				
AR	(+)**		(+)**	(-)^	(+)**				(-)*
Multiple aneurysms		(-)*							
Age		(+)^		(+)*		(+)*	(-)***		(-)*
Cigarette smoking	(-)^		(-)^						
Initial volume				(-)*		(-)*	(+)**		(+)*
Branching zone				(-)**	(+)				
BN							(-)^		
Follow-up length							(-)^	(+)*	
Sidewall aneurysms							(-)*		

*p < 0.01; **p < 0.001; ***p = 0; ^p < 0.05

18.30–80.67). Multiple aneurysms were found in 69 (68%) patients, with an average of 2.15 aneurysms per patient. Previous SAH occurred in 21 (21%) patients (F = 16). In 34 patients, at least one aneurysm was treated before surveillance.

For 92 patients, there was reliable data about HT, CS, FH and PKD. HT was present in 47 patients (51%, F = 34), cigarette smokers comprised 18 patients (20%, F = 13), FH was positive in two cases (2%, F = 1), and PKD occurred in two patients (2%, F = 1).

No significant differences were found between men and women regarding all the above features.

Of 150 analysed aneurysms, three bled during surveillance. One aneurysm (ICA bif) clotted in the very early stage and was excluded from further analysis and so 149 UIAs were included in the study. One aneurysm formed *de novo* during follow-up in a patient with previous SAH from an ACoA aneurysm. This aneurysm was treated endovascularly just after detection due to its initial size exceeding 7 mm in diameter. One patient died during follow-up due to progressive cardiac failure with no SAH.

Median time of follow-up was 5.64 years (IQR 4.174–7.714; range 2.83–13.67). Total aneurysm observation time amounted to 964.59 years.

The dominant UIAs were BZ (n = 57, 38%) represented mostly by MCA bif aneurysms (75%). The second most common were SW aneurysms (n = 49, 33%) dominated by ICA locations (80%). The third most common were AC and PCom aneurysms, both n = 20, 13%. No significant differences between men and women were found (see Supplementary Table 2).

Aneurysm volume change analysis using linear regression model

All four expected types of changes were detected using linear regression model for each UIA (see Supplementary Table 3).

52% of aneurysms were in the S group, 28% in the V, and in 16% volume increases were stated. Five aneurysms (3.4%) shrank during follow-up. No significant differences were detected between men and women (p > 0.8).

In the V group (see Table 4), the most common were VS aneurysms, consisting of c.70%. 26% increased their volume significantly (VI), and less than 5% shrank (VD).

Analysis of the whole period of surveillance showed that 72% of observed UIAs presented no significant growth (OS), 23% grew (OI), while 5% shrank (OD) (see Supplementary Table 5).

Analysis of time segments patterns

In the next step, volume change curves (VCC) mathematical approximations were analysed in detail. Patterns of these curves were identified for I, D and all types of V UIAs. The results with distinction into vascular tree locations are set out in Table 1.

UIAs increasing volume (I)

Two dominant patterns of growth in this group were found: linear increase (LI) and initial increase with subsequent stabilisation (IS). Both combined types comprised 96% of cases. IS was dominant in cases of PCom and SW UIAs. PI2 type of growth was observed only in one case in AC aneurysms.

UIAs decreasing volume (D)

Volume decrease was rare and was detected only in BZ and AC locations. For BZ aneurysm, linear course of volume decrease dominated. In the case of AC location, an initial relatively fast volume decrease was observed followed by stabilisation.

UIAs presenting various volume changes, increasing volume during whole follow-up (VI)

11 UIAs of the V group presented this type of behaviour, with nine of them (82%) experiencing growth after the period of stable volume. In all BZ growing UIAs, at last one period of fast

volume increase was observed (PI2 and IS segments), whereas 80% of PCom aneurysms in this group presented stable, linear growth.

UIAs presenting various volume changes, decreasing volume during whole follow-up (VD)

Only two UIAs of the V type presented overall volume decrease, and interestingly also only in BZ and AC locations. In one case there was one segment of significant volume increase detected during follow-up.

UIAs presenting various volume changes, maintaining constant volume during whole follow-up (VS)

In this group, we found the highest number of possible volume change courses, but three predominated: linear increase preceded by stabilisation (LI, S); period of stable volume preceded by linear increase (S, LI); and linear decrease with preceding stabilisation (LD, S). As presented in Table 1, periods of stabilisation could be interrupted by both growth and volume decrease and occur in various patterns.

Relationship of aneurysm location in vascular tree to volume change type

This analysis was conducted for identified groups of UIAs. Additionally, volume changes over the whole period of follow-up were analysed (OS, OI and OD) (see Supplementary Table 6).

The highest percentage of S aneurysms was observed for PC and PCom UIAs (88% and 80% respectively). On the opposite side, BA aneurysms presented the highest percentage of I (28%) and lowest S (67%).

Differences in length of stable segments for stable and various growth type aneurysms

Detailed analysis of particular segment lengths for each type of aneurysm showed statistically significant differences in the length of S segments for V and S type of aneurysms (see Supplementary Table 7).

The shortest periods of sack volume stabilisation were recorded for VD and VI UIAs. Stable (S) and variable with final no volume change (VS) UIAs presented significantly longer stable volume segments.

Factors predicting aneurysm volume change type using general logistic model

Factors such as HT, CS, FH, PKD, multiplicity of aneurysms, patient age at the beginning of follow-up, aneurysm initial volume, aspect ratio, and bottle-neck ratio were analysed as predictors of aneurysm volume change type. Table 2. sets out the results of the best general logistics models for predicting various types of aneurysm sack volume changes. Two factors i.e. patient initial age and aneurysm initial volume presented clear patterns. Age correlated positively with stable or even a decrease in aneurysm volume, and negatively with its increase. Initial sack volume presented an opposite correlation: large volume correlated positively with sack volume increase. Aneurysm aspect ratio correlated positively with sack volume decrease and negatively with overall volume decrease. For stable behaviour, its correlations were not uniform. Cigarette smoking presented a negative correlation with sack volume decrease. Observed influence of hypertension on sack volume change was unclear. It presented a high positive correlation with stable behaviour and a strong negative correlation with VS. Branching zone location showed an opposite correlation. Bottleneck ratio and sidewall location correlated negatively with volume increase as well as, interestingly, with length of follow-up, this latter factor having a positive correlation with VI type detection.

Discussion

The presented analysis of unruptured intracranial aneurysm volume changes over time paints a rather complicated landscape of UIAs size changes.

As in many previous studies on this topic [14, 20–22], the most frequent UIAs were those presenting no sack volume changes, comprising almost 72% of cases. Volume increase occurred in 23% of UIAs, and a decrease was detected in the other 5%. Decreasing volume occurred only in sidewall and branching zone aneurysms, and mostly in women. The percentage of growing aneurysms was slightly higher than previously reported (10-18%) [23–26]. Female sex was determined to be a risk factor for aneurysm growth, similar to the report by Kubo et al. [27] and the ELAPSS score [20].

Our first brand new discovery was that a substantial amount of UIAs (almost 30%) presented various types of volume change over the course of the follow-up. This leads us to conclude that stable volume is not a permanent state.

The news is even worse when we realise that growth, especially abrupt growth as presented in this work by PI2 type, could be preceded by a long period of sack stabilisation. It is important that periods of stabilisation are significantly shorter for VD and VI aneurysms (median 1.1 and 2.3 years respectively) compared to the VS type (4.2 years).

Posterior circulation and PCom aneurysm, which have been thought to pose the highest risk of rupture [1–4], presented the highest percentage of stable behaviour (88% and 80% respectively). This finding contradicts the ELAPSS scale. In our opinion, this could be caused by bias due to the careful selection of patients for follow-up in both groups. It could also indicate that an aneurysm volume increase in not a *sine qua non* condition for rupture.

On the other hand, branching zone aneurysms presented the highest percentage of growth (28%). This finding is consistent with ELAPSS's higher risk of UIA growth for MCA bif aneurysms, as well as with other studies [28, 29].

In GLM model analysis, we have found that high AR is a strong and positive predictor of aneurysm volume decrease or overall stable volume in the V subgroup. Low values of this factor correlate positively with S, I and OI behaviour. Aspect ratio has been extensively analysed as a risk factor in aneurysm rupture, and its influence has been shown to be uncertain [30] or not linear [31]. Its influence on aneurysm growth was not stated or unclear [5]. Interestingly, hypertension correlated positively with S but negatively with VS. Hypertension is a well-known risk factor of aneurysm growth and rupture. The detected discrepancy could be explained by assuming that in the VS group blood pressure was not optimal opposite to S. This was not tested due to a lack of robust data.

In the presented data, higher age and smaller volume of the aneurysm seemed to prevent growth, which contradicts most recent studies [32].

Only seven (4.7%) surveilled aneurysms were treated, whereas actual significant growth was detected in 35 (23.5%) aneurysms (ratio 1:5). This discrepancy is caused by the criteria of growth used in our institution in daily practice i.e. a 25% increase of volume or an increase in one dimension of more than 1mm which are far less sensitive than the statistical analysis used in this study. Finally, six aneurysms were treated and one patient refused treatment and stayed in follow-up with no subarachnoid haemorrhage.

All these facts clearly demonstrate that not every aneurysm volume growth leads to rupture. This point was made by Rinkel in his work [33].

Limitations

Based on the single-centre, retrospective character of this study, several limitations have been identified. Patients with small intracranial aneurysms are more likely to be managed conservatively rather than to be referred for interventional treatment, creating a possible bias. Furthermore, referring physicians could be less comfortable with long-lasting imaging surveillance of aneurysms with higher bleeding risk (e.g. posterior fossa), which might have affected the location representation of intracranial aneurysms in the analysed material.

However, the aforementioned bias might be also be present in prospective studies to avoid exposing patients to an increased risk of subarachnoid haemorrhage. Furthermore, the diagnostic accuracy of aneurysm change detection gets lower as the aneurysm size decreases, and many of the surveilled intracranial aneurysms were considered small. Finally, based on the limited clinical data available, evaluation of established or suspected risk factors for rupture could not be performed. A large, multicentre, retrospective study would address most of these issues.

Clinical implications/future directions

This study demonstrates that followed-up intracranial aneurysms may change volume in a non-uniform way, and there are other than linear patterns of growth. These findings shed new light on the benefits of aneurysm surveillance and may affect future follow-up guidelines.

Article information

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References

1. Vlak MHm, Algra A, Brandenburg R, et al. Prevalence of unruptured intracranial aneurysms, with emphasis on sex, age, comorbidity, country, and time period: a systematic review and meta-analysis. Lancet Neurol. 2011; 10(7): 626–636, doi: 10.1016/S1474-4422(11)70109-0, indexed in Pubmed: 21641282.
2. Brown RD, Broderick JP, Brown RD, et al. Unruptured intracranial aneurysms: epidemiology, natural history, management options, and familial screening. Lancet Neurol. 2014; 13(4): 393–404, doi: 10.1016/S1474-4422(14)70015-8, indexed in Pubmed: 24646873.
3. Backes D, Vergouwen MDI, Tiel Groenestege AT, et al. PHASES score for prediction of intracranial aneurysm growth. stroke. 2015; 46(5): 1221–1226, doi: 10.1161/STROKEAHA.114.008198, indexed in Pubmed: 25757900.
4. Thompson B, Brown R, Amin-Hanjani S, et al. Guidelines for the management of patients with unruptured intracranial aneurysms. stroke. 2015; 46(8): 2368–2400, doi: 10.1161/str.0000000000000070.
5. Juvela S, Juvela S. Growth and rupture of unruptured intracranial aneurysms. J Neurosurg. 2018; 131(3): 843–851, doi: 10.3171/2018.4.JNS18687, indexed in Pubmed: 30215563.
6. Steiner T, Juvela S, Unterberg A, et al. European Stroke Organization. European Stroke Organization guidelines for the management of intracranial aneurysms and subarachnoid haemorrhage. Cerebrovasc Dis. 2013; 35(2): 93–112, doi: 10.1159/000346087, indexed in Pubmed: 23406828.
7. Bijlenga P, Gondar R, Schilling S, et al. The PHASES score for prediction of intracranial aneurysm growth. Blogging Stroke. 2015, doi: 10.1161/blog.20150324.200000.
8. Greving JP, Wermer MJH, Brown RD, et al. Development of the PHASES score for prediction of risk of rupture of intracranial aneurysms: a pooled analysis of six prospective cohort studies. Lancet Neurol. 2014; 13(1): 59–66, doi: 10.1016/S1474-4422(13)70263-1, indexed in Pubmed: 24290159.
9. Neulen A, Pantel T, König J, et al. Comparison of unruptured intracranial aneurysm treatment score and PHASES score in subarachnoid hemorrhage patients with multiple intracranial aneurysms. Front Neurol. 2021; 12: 616497, doi: 10.3389/fneur.2021.616497, indexed in Pubmed: 33897586.
10. Serrone J, Tackla R, Gozal Y, et al. Aneurysm growth and de novo aneurysms during aneurysm surveillance. Journal of Neurosurgery. 2016;

125(6): 1374–1382, doi: 10.3171/2015.12.jns151552, indexed in Pubmed: 26967775.
11. Juvela S, Poussa K, Porras M. Factors affecting formation and growth of intracranial aneurysms: a long-term follow-up study. Stroke. 2001; 32(2): 485–491, doi: 10.1161/01.str.32.2.485, indexed in Pubmed: 11157187.
12. Lee KS, Zhang JJY, Alalade AF, et al. Radiological surveillance of small unruptured intracranial aneurysms: a systematic review, meta-analysis, and meta-regression of 8428 aneurysms. Neurosurg Rev. 2021; 44(4): 2013–2023, doi: 10.1007/s10143-020-01420-1, indexed in Pubmed: 33094423.
13. Serrone JC, Tackla RD, Gozal YM, et al. Aneurysm growth and de novo aneurysms during aneurysm surveillance. J Neurosurg. 2016; 125(6): 1374–1382, doi: 10.3171/2015.12.JNS151552, indexed in Pubmed: 26967775.
14. Żyłkowski J, Kunert P, Jaworski M, et al. Changes of size and shape of small, unruptured intracranial aneurysms in repeated computed tomography angiography studies. Wideochir Inne Tech Maloinwazyjne. 2015; 10(2): 178–188, doi: 10.5114/wiitm.2015.52707, indexed in Pubmed: 26240617.
15. Koffijberg H, Buskens E, Algra A, et al. Growth rates of intracranial aneurysms: exploring constancy. J Neurosurg. 2008; 109(2): 176–185, doi: 10.3171/JNS/2008/109/8/0176, indexed in Pubmed: 18671627.
16. Chien A, Callender RA, Yokota H, et al. Unruptured intracranial aneurysm growth trajectory: occurrence and rate of enlargement in 520 longitudinally followed cases. J Neurosurg. 2019; 132(4): 1077–1087, doi: 10.3171/2018.11.JNS181814, indexed in Pubmed: 30835694.
17. Lindquist Liljeqvist M, Hultgren R, Gasser TC, et al. Volume growth of abdominal aortic aneurysms correlates with baseline volume and increasing finite element analysis-derived rupture risk. J Vasc Surg. 2016; 63(6): 1434–1442.e3, doi: 10.1016/j.jvs.2015.11.051, indexed in Pubmed: 27106248.
18. Żyłkowski J, Rosiak G, Spinczyk D. Semi-automatic measurements and description of the geometry of vascular tree based on Bézier spline curves: application to cerebral arteries. Biomed Eng Online. 2018; 17(1): 115, doi: 10.1186/s12938-018-0547-8, indexed in Pubmed: 30157865.
19. Żyłkowski J, Rosiak G, Rowiński O, et al. Age- and gender-dependent variability in the geometry of middle cerebral artery bifurcations. Journal of Anatomy. 2020; 238(3): 765–784, doi: 10.1111/joa.13338.
20. Backes D, Rinkel GJE, Greving JP, et al. ELAPSS score for prediction of risk of growth of unruptured intracranial aneurysms. Neurology. 2017; 88(17): 1600–1606, doi: 10.1212/WNL.0000000000003865, indexed in Pubmed: 28363976.
21. Brinjikji W, Pereira VM, Khumtong R, et al. PHASES and ELAPSS scores are associated with aneurysm growth: A study of 431 unruptured intracranial aneurysms. World Neurosurg. 2018; 114: e425–e432, doi: 10.1016/j.wneu.2018.03.003, indexed in Pubmed: 29530704.
22. Brinjikji W, Zhu YQ, Lanzino G, et al. Risk factors for growth of intracranial aneurysms: A systematic review and meta-analysis. AJNR Am J Neuroradiol. 2016; 37(4): 615–620, doi: 10.3174/ajnr.A4575, indexed in Pubmed: 26611992.
23. Backes D, Vergouwen MDI, Tiel Groenestege AT, et al. PHASES score for prediction of intracranial aneurysm growth. stroke. 2015; 46(5): 1221–1226, doi: 10.1161/STROKEAHA.114.008198, indexed in Pubmed: 25757900.
24. Burns JD, Huston J, Layton KF, et al. Intracranial aneurysm enlargement on serial magnetic resonance angiography: frequency and risk factors. Stroke. 2009; 40(2): 406–411, doi: 10.1161/STROKEAHA.108.519165, indexed in Pubmed: 19023101.
25. Matsubara S, Hadeishi H, Suzuki A, et al. Incidence and risk factors for the growth of unruptured cerebral aneurysms: observation using serial computerized tomography angiography. J Neurosurg. 2004; 101(6): 908–914, doi: 10.3171/jns.2004.101.6.0908, indexed in Pubmed: 15597749.
26. Chien A, Liang F, Sayre J, et al. Enlargement of small, asymptomatic, unruptured intracranial aneurysms in patients with no history of subarachnoid hemorrhage: the different factors related to the growth of single and multiple aneurysms. J Neurosurg. 2013; 119(1): 190–197, doi: 10.3171/2013.3.JNS121469, indexed in Pubmed: 23621603.
27. Kubo Y, Koji T, Kashimura H, et al. Female sex as a risk factor for the growth of asymptomatic unruptured cerebral saccular aneurysms in elderly patients. J Neurosurg. 2014; 121(3): 599–604, doi: 10.3171/2014.5.JNS132048, indexed in Pubmed: 24972124.
28. Detmer FJ, Chung BJ, Jimenez C, et al. Associations of hemodynamics, morphology, and patient characteristics with aneurysm rupture stratified by aneurysm location. Neuroradiology. 2019; 61(3): 275–284, doi: 10.1007/s00234-018-2135-9, indexed in Pubmed: 30456458.
29. Liu Q, Jiang P, Jiang Y, et al. Bifurcation configuration is an independent risk factor for aneurysm rupture irrespective of location. Front Neurol. 2019; 10: 844, doi: 10.3389/fneur.2019.00844, indexed in Pubmed: 31447764.
30. Lall RR, Eddleman CS, Bendok BR, et al. Unruptured intracranial aneurysms and the assessment of rupture risk based on anatomical and morphological factors: sifting through the sands of data. Neurosurg Focus. 2009; 26(5): E2, doi: 10.3171/2009.2.FOCUS0921, indexed in Pubmed: 19408998.
31. Yin JH, Su SX, Zhang X, et al. U-shaped association of aspect ratio and single intracranial aneurysm rupture in Chinese patients: A Cross-Sectional Study. Front Neurol. 2021; 12: 731129, doi: 10.3389/fneur.2021.731129, indexed in Pubmed: 34803880.
32. Etminan N, Rinkel GJ. Unruptured intracranial aneurysms: development, rupture and preventive management. Nat Rev Neurol. 2016; 12(12): 699–713, doi: 10.1038/nrneurol.2016.150, indexed in Pubmed: 27808265.
33. Rinkel GJE. Management of patients with unruptured intracranial aneurysms. Curr Opin Neurol. 2019; 32(1): 49–53, doi: 10.1097/WCO.0000000000000642, indexed in Pubmed: 30516639.