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Carotid Bifurcation Position and Branching Angle in Patients with Atherosclerotic Carotid Disease

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A B S T R A C T

Carotid artery bifurcation (CB) is the preferred site for development of atherosclerosis (AS) in extracranial cerebral arteries; internal carotid artery stenosis is the most common cause of ischemic stroke. The frequent atherosclerotic disease of CB may best be explained by the hemodynamic influence of complex blood flow that results from the unique geometry of the bifurcation. Few papers analyze all possible geometric structural characteristics of this bifurcation. While performing many carotid endarterectomies, we noticed that a certain correlation between CB height in the neck and its angle existed, that a larger angle is accompanied with increased frequency of elongation and kinking and that CB shape influences distribution of atherosclerosis. The purpose of this paper is to quantify and evaluate these clinical observations. Radiogrametric analysis of 154 bi-plane orthogonal aortic arch arteriograms of patients with symptomatic atherosclerotic carotid artery disease was performed and a total of 289 CBs were analyzed. The CB height in relation to cervical spine segments was measured and real angles of each bifurcation were calculated. A positive linear correlation between CB height and angle exists: the CB angle increases / decreases 3,34° for each third of the cervical vertebral body height or intervertebral space height. The CB is positioned a little higher on the left side. The proximal border of the atherosclerotic process is found at the level of intersection of the axes of the common carotid artery branches in 92.6% of examined CBs. In lower CBs (with smaller angles) the proximal border was located in the last segment of the common carotid artery, while in high bifurcations (wider angles) the proximal border of the AS process is more distally in the blood flow, in the beginning of the internal carotid artery, and the process was more extensive. High CBs are more suitable for eversion endarterectomy while normal and low CBs are more suitable for open (classic) carotid endarterectomy. The influence of the geometric risk factor demands further investigation.

Key words: *carotid bifurcation, morphometry, carotid artery, stenosis, atherosclerosis, atherogenesis, carotid endarterectomy, arteriography*

Introduction

Carotid artery stenosis, as defined as a >50% reduction in vessel diameter, is a frequent vascular disorder affecting approximately 0.5% of people in their 50s and about 10% of those over age 80[1,2]. The ipsilateral stroke risk for people with internal carotid artery (ICA) stenosis of greater than 50% is 2–5% per year[3–6]. Stroke in itself represents one of the leading causes of death in most western countries, as well as in Croatia, where it is the leading cause of death and disability[7]. The high incidence of stroke related disability represents an enormous socioeconomic problem in all communities.

The frequent atherosclerotic disease of the carotid artery bifurcation (CB) (up to 75% of all extracranial cerebral arteries) is best explained with the hemodynamic influence of the complex blood flow properties caused by the unique geometry of this bifurcation[8,9]. Current knowledge on quantitative correlations between carotid artery bifurcation geometry, hemodynamics and distribution of atherosclerosis remains incomplete in spite of great interest of clinicians and biofluidmechanicians.

The carotid bulbus may for example be comprehended hemodynamically as a natural axially non-symmetric aneurysm[10]. Its lateral border, opposite to the blood flow divider, is the site of the earliest depositions in the atherosclerotic process[11]. Surgical repair of the hemodynamically unfavorable influence of the bulbus is best achieved with carotid endarterectomy (CEA) accompanied with a not-too-wide patching which uniformly widens the postbulbar segment of internal carotid artery.

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Carotid endarterectomy, being a method of surgical treatment of advanced carotid stenosis, is one of the most commonly performed vascular procedures. Approximately 200 CEA procedures are performed each year at the Department of Surgery at »Sestre Milosrdnice« University Hospital in Zagreb. During these procedures, we have noticed that CB height is variable in different patients and that a certain correlation between the bifurcation height in the neck and the carotid bifurcation angle exist. Furthermore, a relationship between the CB shape and distribution of the atherosclerotic process has also been noted. The purpose of this paper is to quantify and evaluate these clinical observations.

Patients and Methods

One hundred and fifty-four bi-plane orthogonal aortic arch arteriograms (Figure 1 and 2) of patients with symptomatic atherosclerotic carotid disease were obtained preoperatively. The gender and age distribution of the patients was as follows: 116 (75,32%) were male, the average age was 57.2 years (range: 24–76); 38 (24.68%) were female of an average age of 58.4 years (range: 27–79). It was possible to investigate 289 carotid bifurcations; the remaining 19 carotid bifurcations could not be evaluated due to either bifurcation occlusion caused by advanced atherosclerotic disease or insufficient radiographic imaging.

Radiogrametric analysis (RGM) of these angiograms was performed. Radiogrametry is a quantitative method of establishing reliable angular and linear dimensions of structures shown on the radiogram; in this case the studied arteries were the carotid arteries visualized

Fig. 1. Aortic arch angiogram (uniplane).

Fig. 2. Angiogram of a common carotid artery with a high bifurcation, internal and external carotid arteries. Stenosis of the internal carotid artery (arrows).

with biplane orthogonal arteriography of the aortic arch[12]. The two orthogonal projections (1 and 2) were interpreted as orthogonal projections in the coordinate system x-y-z, which is shown in Figure 3.

A modification of the Balasubramanians method[13] and an original solution in analytic geometry for calculating true angular dimensions of the carotid bifurcation were developed. The following formula by Marković[14] was used to calculate the bifurcation angle Ω from data obtained from the biplane angiograms:

$$\Omega = arc\cos \frac{tg\alpha \cdot tg\beta + 1 + tg\delta \cdot tg\gamma}{\sqrt{tg^2\alpha + 1 + tg^2\gamma} \cdot \sqrt{tg^2\beta + 1 + tg^2\delta}}$$

Figure 4 shows schematically the relevant angles (α, β, γ, δ) on the orthogonal projections of the carotid bifurcation that were used in the previous formula.

The height of the bifurcation in relation to the cervical spine segment was determined on angiograms for each studied carotid bifurcation. The CB height was determined at the intersection level of axes of the carotid artery branches (internal end external carotid arteries). A simplified relative measurement system for the bifurcation height was used[12]. Each cervical vertebral body was assigned three measurement units and each intervertebral space one unit. Point »1« is the lower surface of the body of the 6th cervical vertebra, the height level of the lowest CBs in our series. Point »15« is the superior surface of the 3rd cervical vertebra, the level of the highest CBs that we found (Figure 5).

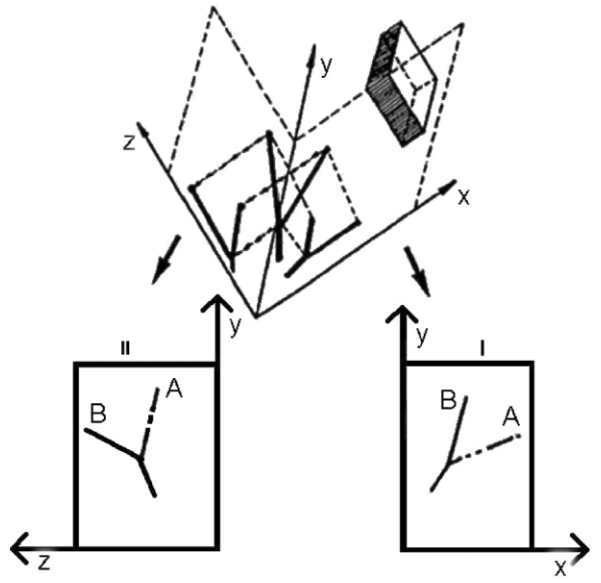

Fig. 3. Geometric interpretation of biplane orthogonal projections of one carotid bifurcation. Upper part: drawing of one carotid bifurcation and its projection onto the y–z and y–x plane. Lower part: the resulting x-ray image of the bifurcation. It is noticeable that the angles of one bifurcation are different in each projection.

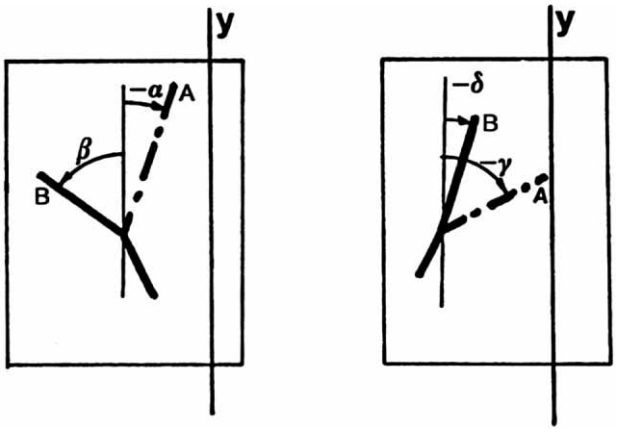

Fig. 4. The principle of determination the carotid bifurcation angle from two orthogonal projections.

Results

The average carotid bifurcation angle of all 289 examined CBs was 40.5° (SD=17.14) and the average height was 9.01 (SD 2.96). The CBs were most commonly found at the level of the middle third of the 4th cervical vertebra body (63 bifurcations, 21.79%) where the average bifurcation angle was 38.9°. Figure 5 shows the frequency of the carotid bifurcation height in relation to each of previously described height levels relative to cervical spine segments.

The height of the carotid bifurcation was further classified according to the frequency of the findings,

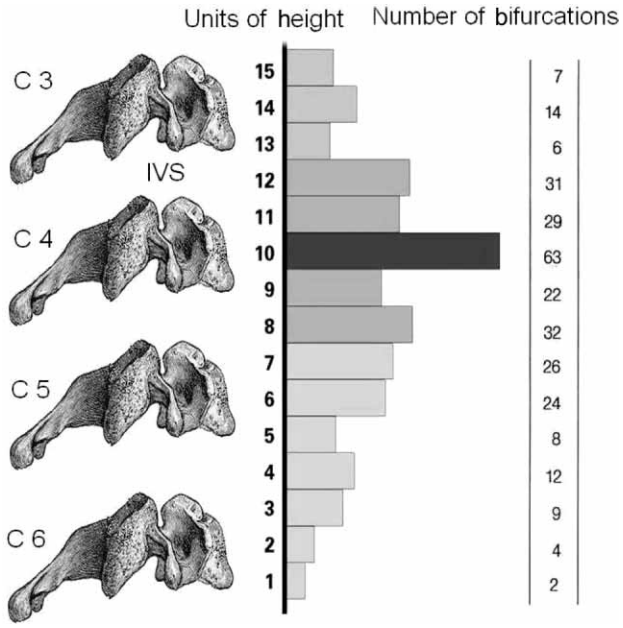

Fig. 5. Frequency histogram and schematic representation of various carotid bifurcation positions in studied subjects in relation to cervical vertebral column. (Left: schematic representation of cervical vertebrae 3–6. Middle: Frequency histogram of patients with respective bifurcation height in relation to cervical vertebral column expressed in Units of height. Right: Number of patients with respective carotid bifurcation height)

Gauss' distribution and anatomically as normal (or rather: the most common), high or low (Table 1). The cut-off points of these groups were set as follows: Low CBs were at height levels 1–7, »normal« from 8 to 12 and high bifurcations from 13–15. Normal bifurcations were most commonly found to be located at the level of middle third of the 4th cervical vertebra. Low bifurcations were usually at the level of 5th and 6th cervical vertebra, whereas high bifurcations were usually found at the level of superior 2/3 of C3 (Figure 5). The position of these high bifurcations was associated with a more difficult surgical approach for endarterectomy. These high bifurcations were also associated with an increased bifurcation angle, as well as with increased frequency of elongation or frank kinking. Kinking was found in 3,2% of all 289 CBs; during surgery, after dissecting the ICA it was found in 25% of patients with high CB.

The CB heights were compared in regard to the side of the body. The average CB height on the left side was found to be 9.15 (SD=3.1) and 8.99 (SD=3.0) on the right side. These differences were statistically significant on t-test paired observations (t diff.=2.15, $p<0.05$) but minimal. The average left CB height was found to be just above the lower third of the C4 body and this height was practically reached on the right side.

The carotid bifurcation height was found to be closely related to the bifurcation angle. It is evident that a positive linear correlation between the height (in relation to cervical vertebral column segment) and carotid

TABLE 1
NUMBER OF PATIENTS WITH EACH ASSIGNED BIFURCATION HEIGHT IN THE NECK AND THE CLASSIFICATION OF LOW, NORMAL AND HIGH BIFURCATIONS

Bifurcation height	Number of bifurcations	Height classification
1	2	Low bifurcation
2	4	
3	9	
4	12	
5	8	
6	24	
7	26	
8	32	Normal bifurcation
9	22	
10	63	
11	29	
12	31	
13	6	High bifurcation
14	14	
15	7	

TABLE 2
RELATIONSHIP BETWEEN THE HEIGHT OF THE CAROTID BIFURCATION IN THE NECK AND ITS BRANCHING ANGLE

Units of height	Average bifurcation angle (°)	SD
1	22.10	6.7
2	24.30	11.2
3	27.40	5.0
4	24.10	4.9
5	39.00	18.3
6	29.10	8.9
7	33.80	10.7
8	36.30	13.7
9	39.80	8.5
10	38.90	11.2
11	39.60	9.4
12	54.40	18.6
13	47.80	16.1
14	76.90	16.2
15	63.90	23.9

bifurcation angular size exists (Table 2, Figure 6). These findings were found on both sides: the correlation coefficient between CB height and CB angles on the left side was 0.549 and 0.623 on the right side. Both of these coefficients were statistically highly significant ($p<0.01$). The bifurcation angle decreases/increases averagely 3.34° for each intervertebral space or 1/3 of vertebral body height (Figure 6).

Another very interesting finding was that the atherosclerotic process was more pronounced on the lateral wall of the CB and internal carotid artery. The proximal border of this lateral atherosclerosis was found to be at the level of the geometrically defined intersection of the

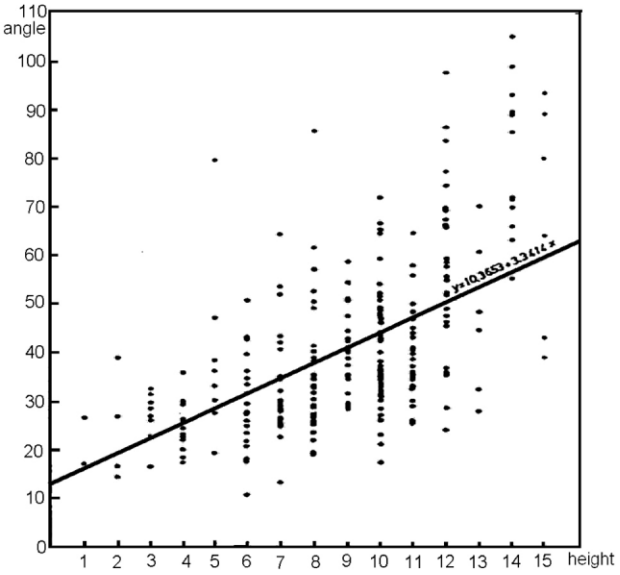

Fig. 6. Relationship between the height and the angle of carotid bifurcation. Positive linear correlation is found.; the correlation coefficient is 0.58 which is statistically significant at the level of r=0.01. The carotid bifurcation angle increase rate for each bifurcation height measurement unit is averagely 3.34°.

axes of the carotid artery branches in 92.6% of examined CBs. This corresponds to the levels we used to define the height of the CB.

Discussion

The North American Symptomatic Carotid Endarterectomy Trial (NASCET) showed that CEA is beneficial in symptomatic patients with ICA stenosis of greater than 70%[15]. The NASCET demonstrated a 65% reduction in the relative risk of ipsilateral stroke with CEA in symptomatic patients and a 17% reduction in absolute risk after two years. As a result, CEA for symptomatic patients with high-grade carotid artery stenosis has become widely accepted in clinical practice. The European Carotid Surgery Trial (ECST) assessed the risks and benefits of carotid endarterectomy in terms of stroke prevention in patients with recently symptomatic carotid stenosis[16]. It was found that CEA is indicated for most patients with a recent non-disabling carotid-territory ischemic event when the symptomatic stenosis is greater than about 80%. Age and sex should also be taken into account in decisions on whether to operate. The ECST showed that the frequency of a major stroke or death at 3 years was 14.9% for the surgery group, as opposed to 26.5% for the control group, resulting in an absolute benefit from surgery of 11.6%.

The outcome in asymptomatic patients is not as statistically evident and significant as in the symptomatic group and the indication for surgery was until recently controversial for asymptomatic patients. The Asymptomatic Carotid Atherosclerosis Study (ACAS) addressed this issue and provided evidence that asymptomatic

patients with high-grade stenosis (60% or greater) also benefit from surgical rather than medical management alone[4]. Furthermore, carotid endarterectomy was found to be cost-effective when compared with other commonly accepted health care practices; surgery does not appear cost-effective in very elderly patients, in settings where the operative stroke risk is high, or in patients with very low stroke risk without surgery[17]. The Asymptomatic Carotid Surgery Trial (ACST) very recently confirmed that immediate carotid endarterectomy upon finding a carotid diameter reduction about 70% or more on ultrasound in asymptomatic patients younger than 75 years of age halved the net 5-year stroke risk from about 12% to about 6%[18]. The 10-year benefits are not yet known.

We performed radiogrametric analysis of arteriograms of CBs in 154 patients: it is possible to distinguish three types of adult human carotid bifurcations in respect to the height in the neck: the »normal«, high and low bifurcation. Vascular geometry represents an important risk factor in atherogenesis[8,9]; therefore it must also have an implication on the choice of surgical technique in the treatment of carotid artery disease. During surgery, normal and low bifurcations were more easily repaired than high bifurcations. These high bifurcations proved to be less favorable to operate upon, as the approach to the internal carotid artery was difficult because of the close relationship with the hypoglossal nerve and vagus nerve in the extremely limited space between the mandibular angle and the mastoid process. Another interesting finding was that high carotid bifurcations were associated with an increased frequency of ICA elongation and frank kinking. Furthermore, in about 25% of the patients with ICA elongation, after dissection of the vessels and its freeing from surrounding tissues, this ICA elongation turned into kinking. A significant ICA kinking in itself can be associated with transitory ischemic attacks[19] and is associated with concomitant atherosclerosis in 40%, which continues from the lateral atherosclerotic process[20]. Surgically, it is wiser to correct such anomalous anatomies by reducing the bifurcation angle and shortening the elongated ICA in order to prevent the development of atherosclerotic process on a longer arterial segment. This may be performed with the procedure of resection, eversion endarterectomy and oblique neoanastomosis of the internal carotid artery.

Concerning the investigated sample, one might argue that these findings are not generalisable. The negative aspect of arteriography of the aortic arch with visualization of the carotid bifurcation anatomy is its highly invasiveness. It cannot be used for screening in a healthy population that might perhaps have a different anatomy of the CB from the one found in patients with carotid artery disease and it is not indicated for initial diagnostic workup for patients with CB disease. With the enormous advances in noninvasive ultrasonographic imaging, duplex scanning has become the standard and only diagnostic procedure necessary to decide if a patient requires a carotid endarterectomy and only in a small number of examinees may duplex scanning give unclear findings that require further investigation with an arteriography.

The quantitative relationship between CB geometry and distribution of atherosclerotic plaques has recently been investigated by Goubergrits, et al. and Beiles. In the paper by Goubergrits, et al. [21] it is stated that the diameter of the carotid bulbus is a highly significant geometric risk factor for the most advanced lesions (fibrous or severe plaques) on the ICA and that there is no correlation between the branching angle and atherosclerosis. On the other hand, Beiles[22] investigated the relationship between the CB height (measured from the sternoclavicular joint during CEA) and the extent of disease in the ICA. A statistically significant negative correlation was found between the extent of disease in the ICA and the bifurcation height, i.e. a low CB correlates with a longer extent of disease in the ICA. These two studies do not correlate in total with our clinical observations and experience with CEA. We agree with the notion that the carotid bulbus diameter is important for the initial beginning of atherogenesis and the intensity of the atherosclerotic process in the ICA (in concord with Poiseuille's law), which is the reason we advocate the correction of this unfavorable geometric risk factor of atherosclerosis with open endarterectomy and closure of the arteriotomy with patch angioplasty. In our investigations, we found that the normal and low CBs had a smaller branching angle of the carotid artery. If the atherosclerotic process in the ICA in these bifurcations has a longer extent, as it is stated by Beiles and if we find this pathology, which is seldom, we prefer open endarterectomy with patch angioplasty.

In our research, we found that the atherosclerotic process was more pronounced on the lateral wall of the CB and internal carotid artery and more variable than the process on the medial side of the artery. The proximal border of this lateral atherosclerosis was found to be at the level of the geometrically defined intersection of the axes of the carotid artery branches in 92.6% of bifurcations. This corresponds to the levels we used to define the height of the CB. In other words, lower bifurcations (which have a smaller angle) had a more proximal border of the atherosclerotic process on the lateral wall, beginning in the last segment of the common carotid artery in the bifurcation. Higher bifurcations have higher angles of bifurcation; they also had higher proximal borders of the atherosclerotic process- these high CBs had the beginning of the atherosclerotic process in the proximal internal carotid artery, i.e. more distally in the blood flow. Similarly, the extent of the atherosclerotic process is more distal with these high bifurcations, affecting the postbulbar segment, and in some cases extending as high up as the cranium base. Furthermore, we found elongation and kinking of the ICA associated more commonly with high bifurcations, which had wider branching angles and are more suitable for eversion CEA. In high bifurcations, the elongation of ICA with

curves or true kinking may also influence the extent of atherosclerosis on a longer segment of this artery, which we often find during surgery. This makes the anatomically unfavorable approach even more difficult for open CEA but more suitable for eversion endarterectomy. It may be speculated that duration of the atherosclerotic process and presence of a smaller or larger number of classic risk factors of atherosclerosis also significantly influences the progression and distribution of atherosclerotic disease on CBs. It is evident that the influence of the geometric factor demands further investigation whereas the individual intraoperative finding dictates the choice of carotid endarterectomy technique.

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POLOŽAJ KAROTIDNE BIFURKACIJE I KUT RAČVANJA U BOLESNIKA S ATEROSKLEROTSKOM KAROTIDNOM BOLEŠĆU

SAŽETAK

Bifurkacija karotidne arterije (KB) je preferento mjesto razvoja ateroskleroze (AS) na ekstrakranijskim cerebralnim arterijama, a stenoza unutarnje karotidne arterije najčešći je uzrok ishemijskog moždanog udara. Učestala aterosklerotska bolest na KB najbolje se može objasniti hemodinamskim utjecajem kompleksnog krvnog protoka kojeg uvjetuje jedinstvena geometrija te bifurkacije. Malo ima radova koji analiziraju sve moguće geometrijske oblikovne karakteristike te bifurkacije. Izvodeći veliki broj karotidnih endarterektomija zapazili smo da postoji izvjesna korelacija visine KB na vratu i veličine njenog kuta, da je uz veći kut češća elongacija i »kinking» i da različit oblik na neki način utječe i na distribuciju ateroskleroze. Cilj ovog rada bio je kvantificirati i procijeniti ove kliničke opservacije. Radiogrametrijskom analizom proučeno je 154 ortogonalnih biplanarnih arteriograma luka aorte bolesnika sa simptomatskom aterosklerotskom karotidnom bolešću i analizirano je ukupno 289 KB. Izmjerene su visine KB u odnosu na segment vratne kralježnice i izračunati su realni pripadajući kutovi svake bifurkacije. Nađena je pozitivna linearna korelacija visine i veličine kuta KB. Kut bifurkacije pada/raste prosječno za 3.34° sa svakom trećinom visine trupa vratnog kralješka, odnosno s visinom intervertebralnog prostora. KB je smještena nešto više na lijevoj strani. Proksimalna granica aterosklerotskog procesa je pronađena na križanju osi ogranaka zajedničke karotidne arterije u 92.6% ispitanih KB. Kod niskih KB (s manjim kutom grananja) ova proksimalna granica smještena je u završnom segmentu zajedničke karotidne arterije, dok je kod visokih bifurkacija proksimalna granica AS procesa distalnije u krvotoku, na početku unutarnje karotidne arterije. Visoke KB pogodnije su za everzijsku, a normalno položene i niske za otvorenu (klasičnu) karotidnu endarterektomiju. Utjecaj geometrijskog faktora rizika zahtjeva daljnje istraživanje.