Three-dimensional Computed Tomographic Reconstruction of the Carotid Artery: Identifying High Bifurcation

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WHAT THIS PAPER ADDS
The distance of carotid bifurcation from the base of skull is a potentially useful measurement that has not been previously described. This measurement has been compared with several other methods of quantifying carotid bifurcation height. It is demonstrated that bifurcations within 5 cm of the mastoid process are likely to be in the highest quartile of carotid bifurcations. This measurement could alert vascular surgeons to carotid endarterectomy cases that are more likely to be technically challenging.

Objective: To investigate variability in the level of bifurcation relative to other anatomical landmarks on computed tomography (CT) and to develop an objective and reproducible technique for identifying patients with a high carotid bifurcation who might therefore be at greater risk of operative complications.

Methods: This was a retrospective cross-sectional, imaging study. A series of 86 nonselected consecutive CT carotid angiograms (172 arteries) were analysed. Using three-dimensional reconstructive software, the curved length (CL) of the internal carotid artery (ICA) and the straight-line distance (SLD) from the bifurcation to the base of skull was measured for 140 carotid arteries. The tortuosity index (TI) of each ICA was calculated by dividing CL by SLD. The relationship of the bifurcation to eight anatomical landmarks in the neck was assessed in order to identify a landmark that could act as a surrogate marker of high carotid bifurcation. The landmarks examined were the angle of mandible, greater horn of hyoid, body of hyoid, upper margin of thyroid cartilage, cervical vertebrae, mastoid process, sternoclavicular joint, and sternal notch.

Results: The median curved length of the ICA was 80.4 mm (range 58.0–129.0 mm). The median distance of bifurcation from the base of skull was 72.7 mm (range 58.1–98.1 mm). There was excellent interobserver agreement in measuring SLD, with an intraclass correlation coefficient of 0.993 (p = .00). The median tortuosity index was 1.12 (range 1.01–1.64). Distance from the mastoid process had the greatest correlation with high bifurcation; Pearson’s correlation coefficient of 0.894 (two-tailed p = .00). Bifurcations within 5 cm of the mastoid process are likely to be in the highest quartile (82.9% sensitive, 80.1% specific).

Conclusions: Measuring the distance of carotid bifurcation from the base of the skull (SLD), a measure previously not well defined, may be useful in predicting difficult neck dissection and endarterectomy. A distance from mastoid of ≤ 5 cm may also alert the surgeon to potential difficulties.

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Article history: Received 6 March 2014, Accepted 10 October 2014, Available online 15 November 2014
Keywords: Carotid bifurcation height, Carotid endarterectomy, CT carotid angiogram

INTRODUCTION
The carotid bifurcation is classically described as lying at the level of the superior border of thyroid cartilage, in line with the C3—C4 intervertebral space.1–3 Studies examining the clinical anatomy of the carotid arteries have shown a high rate of variation from the “normal” position.1,2

A study of cranial nerve injury in patients who underwent carotid endarterectomy (CEA) in the European Carotid Surgery Trial demonstrated an incidence of 5.1%, with hypoglossal nerve injury being the most common.4 A higher incidence of cranial nerve injury has been demonstrated in patients with a high carotid bifurcation.1,5–8

At present there is no standardised method of measuring the bifurcation position, relative to the base of skull, preoperatively. An accurate predictor of a high bifurcation may be beneficial in planning surgery and predicting technical challenges. Adjunctive measures that may be considered include nasotracheal intubation, division of the digastric muscle, resection of the styloid process, anterior subluxation of the mandible, or endovascular stenting.5,9,10

This study aims to examine the anatomy of the carotid arteries using three-dimensional (3D) reconstruction computed tomography (CT) analysis, and to define the...
degree of anatomical variation in a clinically relevant patient cohort. The study aims to define a method for clinicians to identify those patients in whom a high bifurcation is present, allowing for prediction of intraoperative technical challenges.

MATERIALS AND METHODS

Study design

This was a retrospective, cross-sectional imaging study carried out on archived 0.65-mm slice CT angiograms in Cork University Hospital. The main indication for CT carotid angiogram at the institution was the work-up of confirmed or suspected carotid atheromatous disease, making findings from this database of images more applicable to the population of patients in whom CEA is being considered. Thin-slice CT ensured optimal accuracy for the purposes of this study in precisely describing the anatomy of the carotid bifurcation. The measures of bifurcation height can easily be applied in clinical practice to the more widely utilised 3-mm slice CT scans.

A series of 86 nonselected consecutive CT angiograms from the Picture Archive Communication System archive in Cork University Hospital were analysed. Arteries demonstrating occlusion of the ICA were excluded from the study, as the vessel distal to the point of occlusion cannot be visualised sufficiently to allow the required variables to be measured. Twelve arteries were excluded owing to vessel occlusion. Angiograms were also excluded if patient posture deviated significantly from the anatomical position, such that our measured variables would be unduly altered. Anatomic positional exclusion criteria were lateral angulation of the skull >5 degrees, rotation >10 degrees, and flexion or extension >15 degrees. Ten angiograms (20 arteries) were excluded owing to abnormal posturing.

A total of 140 carotid arteries, from 76 patients, were included in the study. Seventy-six of the arteries were from men, 64 were from women. Seventy-two of the arteries were right carotid arteries, 68 were left carotid arteries. Median patient age was 68.0 years (range 20.0–90.0 years).

The incidence and degree of carotid artery disease described in radiologists’ reports for the included cases were analysed in order to assess the applicability of the study findings to our patient population of interest. Of the 76 CT angiograms included in the study, 60 demonstrated carotid artery disease. Fifty-five of these patients had bilateral disease. Thirty patients had either moderate or severe disease (50–100% stenosis), with 12 patients having one completely occluded ICA. Only 16 patients were free from arterial disease. These included patients with trauma or with suspected acute dissection.

For each artery, centre-line vessel analysis, multiplanar reconstruction, and 3D reconstruction of the radiological images were performed, using a dedicated 3D vascular workstation (TeraRecon, Santa Monica, CA, USA). The study was granted ethical approval by the clinical research ethics committee of the Cork teaching hospitals.

Study measures

For each case, patient age and sex were recorded. Aside from these demographics, 12 variables were measured for each carotid system. These variables are described below as four separate groups of variables. The four groups of variables are summarised in Table 1. Aside from the three “artery characteristics”, the remaining nine variables studied are a variety of methods for describing carotid bifurcation height. This list of nine measures was compiled following a literature search of articles discussing carotid bifurcation height, and each of these measures was compared to assess their accuracy in identifying those bifurcations which are close to the base of skull.

Artery characteristics. This group included the curved length (CL) of the internal carotid artery (ICA); the straight-line distance (SLD) of the carotid bifurcation from the base of skull; and the tortuosity index (TI) of the ICA. For all measurements, the point of carotid bifurcation was taken as the most cranial point of communication between the internal and external carotid arteries.

3D reconstruction software is capable of measuring the CL of artery spanning between two markers, placed at the carotid bifurcation and the point of entry through the base of skull, respectively. This produced the measure of CL of the ICA.

While commercially available software can measure the length of the curved centre line between the two markers, it is not capable of joining these two markers with a single straight line. This limitation is owing to the fact that both markers lie in separate coronal, sagittal, and transverse planes. In both multiplanar and 3D reconstruction, measurement lines can only be drawn within a single plane of view. Therefore, single-planar measurements had to be

| Table 1. The 12 measured variables summarised in their four distinct groups. |
| Artery characteristics |
| 1 Curved length of internal carotid artery |
| 2 Straight-line distance of carotid bifurcation from base of skull |
| 3 Tortuosity index of internal carotid artery |
| Qualitative variables |
| Whether the carotid bifurcation lies above/at/below the: |
| 4 Angle of mandible |
| 5 Greater horn of hyoid |
| 6 Body of hyoid |
| 7 Upper margin of thyroid cartilage |
| Semiquantitative variables |
| 8 Vertebral level |
| Quantitative variables |
| Distance of carotid bifurcation from: |
| 9 Mastoid process |
| 10 Angle of mandible |
| 11 Sterno-clavicular joint |
| 12 Sternal notch |
combined so as to generate the SLD we wished to measure. The method of combining measurements for calculation of SLD was designed to provide accurate and reproducible results, while remaining simple to perform, to allow for ease of use in the clinical setting.

This was achieved by first viewing the image in the anterior 3D view. A measurement line was drawn from the blue marker, denoting the point of entry through the base of skull, down to the point in that same plane that corresponded with the red marker, denoting the point of carotid bifurcation (Fig. 1). By then changing to a lateral view (Fig. 2), it can be seen, in fact, that the caudal end of this measurement line (X) lies directly anterior to the marker denoting the point of bifurcation. From this lateral view, a second measurement line can be drawn (Y) to join the caudal end of the first measurement line to the true point of bifurcation of the common carotid artery. This creates a right-angled triangle, the hypotenuse of which is the SLD of the bifurcation from the base of skull (Fig. 2).

Thus, the SLD, from the point of carotid bifurcation to the point of entry through the base of skull, can be calculated using Pythagoras’ theorem (i.e., \( SLD = \sqrt{X^2 + Y^2} \)), where \( X \) and \( Y \) are the measurements described above). Interobserver variability was looked for in the measurement of SLD by calculating the intraclass correlation coefficient (ICC) for a subset of 24 arteries for which SLD was measured by two independent observers.

Once the CL and SLD were obtained, the TI was calculated by dividing CL by SLD (i.e., \( TI = CL/SLD \)).

Qualitative variables. The second group of variables explored the position of the carotid bifurcation qualitatively in relation to four other landmarks in the neck: the angle of mandible, the greater horn of hyoid bone, the body of hyoid bone, and the superior margin of lamina of thyroid cartilage. In relation to each of these four structures, the carotid bifurcation was recorded as lying above, at, or below.

Semi-quantitative variables. The third group contained only one variable—a semiquantitative measure of the height of carotid bifurcation, which categorizes bifurcations according to the vertebral level at which they occur. For precision, each vertebra is subdivided into three levels (upper, middle, and lower thirds), with each intervertebral space classified as another level equivalent in size to one third of a vertebral body.

Quantitative variables. The fourth group of variables measured quantitatively the distance of carotid bifurcation from four bony landmarks in the neck: the mastoid process, apex of angle of mandible, sterno-clavicular joint, and sternal notch. Each of the four measurements was best visualised using 3D reconstruction. The lateral view was used to measure the distance from the mastoid process and the distance from the angle of mandible. The anterior view was used to measure the distance from the sterno-clavicular joint and the distance from the sternal notch. As the angle of mandible is not a well-defined point from which to measure, this figure was measured correct to the nearest 5 mm.

Figure 1. First step for measuring the straight-line distance. A line is drawn in the anterior three-dimensional view from the marker placed at the point of entry of internal carotid artery through the base of skull (blue) to the marker placed at the carotid bifurcation (red).
Data analysis

In order to assess the reliability of each of the methods of quantifying carotid bifurcation height, it was necessary to define high carotid bifurcation. The bifurcations were divided into three groups according to the SLD from the base of skull. Group 1 was the shortest quartile (i.e., the “high bifurcations”), group 2 was the middle 50% (i.e., the “normal bifurcations”), and group 3 was the longest quartile (i.e., the “low bifurcations”). Each of the measures of carotid bifurcation height was then assessed for reliability in identifying group 1 bifurcations.

In evaluation of the four qualitative variables, each of the four landmarks was assessed in terms of its sensitivity and specificity in predicting high carotid bifurcation (i.e., those bifurcations classed as group 1). For each landmark, the sensitivity and specificity was calculated twice: first to assess if “above” the landmark could be used as the predictor of high bifurcation; and, second, to assess if “at or above” the landmark could be used as the predictor of high bifurcation. Spearman’s correlation coefficient was then used to quantify the correlation of each of the four qualitative variables with SLD quartile group, allowing for objective comparison of reliability with the semi-quantitative and quantitative variable groups.

Spearman’s correlation coefficient was used to assess the degree of correlation of the vertebral level of carotid bifurcation, as well as each of the four quantitative variables, with the SLD quartile group. While Pearson’s correlation coefficient could accurately demonstrate a higher degree of correlation between the linear “quantitative variables” and the SLD quartile group, this tool could not be used to quantify the correlation between the ordinal “qualitative variables” and “semiqualitative variables”. Hence, Spearman’s correlation coefficient was used throughout to allow for comparison of the degree of correlation between all of our groups of variables.

RESULTS

Artery characteristics

The median CL of the ICA was 81.8 ± 11.4 mm (range 58.0–129.0 mm). The median SLD was 72.1 ± 9.6 mm (range 48.0–98.1 mm). A t test demonstrated no difference in SLD between the right and left sides (t = −.35 [p = .73]). There was excellent interobserver agreement in measuring SLD, with an ICC of 0.99 (p = .00). Median TI was 1.15 ± 0.13 (range 1.01–1.64). A short SLD demonstrated moderate correlation with tortuosity (Pearson’s correlation coefficient = −.42 [p = .00]). t tests demonstrated statistically significant variation in the mean CL between men and women, with values of 86.0 mm and 81.8 mm, respectively (p = .03). There was no sex difference in SLD, which is being used as the standard measure of carotid bifurcation height for the purposes of this study. There was also no difference in TI between men and women.
There was no correlation between age and CL, but there was statistically significant inverse correlation between age and SLD (Pearson’s correlation coefficient = -.234 \([p = .01]\)). There was also statistically significant positive correlation between increasing age and tortuosity of the ICA (Pearson’s correlation coefficient = .313 \([p = .00]\)).

**Qualitative variables**

In relation to the angle of mandible, 0.7% of bifurcations lay above, 3.6% lay at the same level, and 95.7% lay below. In relation to the greater horn of hyoid, 17.1% lay above, 21.4% at the same level, and 61.4% below. In relation to the body of hyoid, 62.9% lay above, 26.4% at the same level, and 10.7% below. In relation to the superior margin of the thyroid cartilage, 79.3% lay above, 16.4% at the same level, and 4.3% below.

The sensitivities and specificities of each anatomical landmark for predicting high carotid bifurcations are outlined in Table 2. Correlation between SLD quartile group and each of the four anatomical landmarks is summarised in Table 3.

**Semiquantitative variables**

In relation to the vertebral level of carotid bifurcation, the level at which the greatest number of bifurcations occurred was the middle third of C4 (17.9% of bifurcations; \(n = 25\)). The median vertebral level at which carotid bifurcation occurred was the upper third of C4, while the range of vertebral levels seen was from the lower third of C2 down to the upper third of C6. Fig. 3 illustrates the distribution of carotid bifurcations according to their vertebral level.

There was moderate correlation between vertebral level and SLD quartile group, as outlined in Table 3.

**Quantitative variables**

The median distance of the carotid bifurcation from the mastoid process was 57.8 mm (range 31.9–87.7 mm). The median distance from the angle of mandible was 25.0 mm (range 0.0–60.0 mm). Median distance from the sterno-clavicular joint was 81.1 mm (range 36.6–128.0 mm). Median distance from the sternal notch was 97.9 mm (range 49.6–141.0 mm).

Correlation between SLD quartile group and each of the four quantitative measures is summarised in Table 3.

Of the four "quantitative variables" assessed, the distance of the carotid bifurcation from the mastoid process had the highest correlation with SLD quartile group (Spearman's correlation coefficient = .823). On inspection of the dataset, a bifurcation lying 5 cm from the mastoid process was seen to correspond approximately with the cut-off point for the highest quartile of bifurcations. With this observation in mind, bifurcations lying within 5 cm of the mastoid process were examined. The sensitivity and specificity of this marker (≤5 cm from the mastoid process) in predicting a group 1 bifurcation (i.e., a "high bifurcation" or

**Table 2.** Sensitivities and specificities of the four landmarks, in terms of their ability to detect those bifurcations lying in group 1 (i.e., the highest quartile).

<table>
<thead>
<tr>
<th>Anatomical landmark</th>
<th>Sensitivity (%)</th>
<th>Specificity (%)&lt;sup&gt;a&lt;/sup&gt;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Angle of mandible&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Above 0&lt;sup&gt;b&lt;/sup&gt;</td>
<td>Above 14.3&lt;sup&gt;d&lt;/sup&gt;</td>
</tr>
<tr>
<td></td>
<td>At/above 37.1</td>
<td>At/above 65.7</td>
</tr>
<tr>
<td>Greater horn of hyoid</td>
<td>Above 97.1</td>
<td>Above 100.0</td>
</tr>
</tbody>
</table>

<sup>a</sup> As 25.0% of the all bifurcations lie in the upper quartile, a specificity close to 25.0% has no real specificity at all.

<sup>b</sup> Only two bifurcations lay above the angle of mandible and only two bifurcations lay at the level of the angle of mandible (see text).

**Table 3.** Correlation of each of the measures of carotid bifurcation height with SLD quartile groups.

<table>
<thead>
<tr>
<th>Anatomical relationship with:</th>
<th>Spearman’s significance correlation coefficient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Greater horn of hyoid bone</td>
<td>.40  .00</td>
</tr>
<tr>
<td>Body of hyoid bone</td>
<td>.38  .00</td>
</tr>
<tr>
<td>Upper margin of thyroid cartilage</td>
<td>.36  .00</td>
</tr>
<tr>
<td>Vertebral level</td>
<td>.73  .00</td>
</tr>
<tr>
<td>Distance of carotid bifurcation from:</td>
<td>.82  .00</td>
</tr>
<tr>
<td>Angle of mandible</td>
<td>.70  .00</td>
</tr>
<tr>
<td>Sterno-clavicular joint</td>
<td>-.15 .07</td>
</tr>
<tr>
<td>Sternal notch</td>
<td>-.18 .04</td>
</tr>
</tbody>
</table>

Note. Correlation calculated using Spearman’s correlation coefficient. Correlation is significant at the 0.01 level (two-tailed).

![Figure 3. Bar chart demonstrating the prevalence of bifurcations occurring at each of the vertebral levels defined in this study.](image-url)
a bifurcation lying in the highest quartile) was calculated. Of the 35 bifurcations lying in the highest quartile (group 1), 29 were within 5 cm of the mastoid process, giving this marker a sensitivity of 82.9%. Of the 36 bifurcations lying within 5 cm of the mastoid process, 29 were group 1 bifurcations (i.e., “high bifurcations” according to SLD), giving this marker a specificity of 80.1%.

DISCUSSION
In this study a new measure of carotid bifurcation height has been described, which has been referred to throughout as the SLD of the bifurcation from the base of skull. Although SLD has not been described previously, it was used throughout this study as the standard to which each of the other measures has been compared. This approach was taken as no other measure of carotid bifurcation height is of proven value, and, compared with the other measures discussed, SLD better quantifies the space the surgeon has to work with when performing CEA. Additionally, the base of skull is a more consistent landmark, with many of the other landmarks being capable of movement, or displaying significant anatomical variation between individuals. We demonstrated almost perfect interobserver agreement in the measurement of SLD. The images were assessed by a consultant vascular surgeon and a junior doctor. The variation in experience and training between the two observers shows that there is no steep learning curve for interpreting the images in the manner outlined, and the measurements can be taken reliably by nonradiologist doctors. The techniques outlined can confidently be applied to normal arteries, as well as to diseased arteries. The population that may present for carotid artery surgery (including those who have sustained penetrating neck trauma) is well represented in this study.

Information regarding the carotid bifurcation height and tortuosity of the ICA should be routinely included in the preoperative work-up of patients considered for CEA, as this information is relevant to the operating surgeon for predicting more complex endarterectomies with greater risk of complication. While current software does not have the capacity to calculate the SLD of the bifurcation from the base of skull, this is a feature that could, potentially, be incorporated by the manufacturer in an updated version.

It is acknowledged that high carotid bifurcation is only one of a number of anatomical features that contribute to difficult neck dissection and endarterectomy. Compared with other features, however, such as shortness of the neck, thickness of the neck, and stiffness of the vertebral column (preventing optimum positioning on the table), bifurcation height should be easily definable and is the most occult of these anatomical features, evident only on imaging studies.

Of the four “qualitative variables” assessed, “at or above the greater horn of hyoid” had the greatest correlation with SLD quartile group (Spearman’s correlation coefficient = .402). This marker’s sensitivity and specificity in detecting high bifurcations were 65.7% and 42.6%, respectively.

The vertebral level of carotid bifurcation had a higher correlation with the SLD quartile group than did any of the qualitative variables (Spearman’s correlation coefficient = .731). However, the correlation was still relatively low, so vertebral level would not make for a reliable measure of carotid bifurcation height.

Distance from the mastoid process had the greatest correlation with SLD, of any of the postulated measures of carotid bifurcation height (Spearman’s correlation coefficient = .823). Additionally, bifurcations ≤5 cm from the mastoid process were seen to predict group 1 (high) bifurcations with a sensitivity of 82.9% and a specificity of 80.1%.

The absence of intraoperative clinical correlation with the objective CT-based measurements of carotid artery anatomy is a potential weakness of the analysis, and further prospective research in patients undergoing CEA is required to determine the clinical relevance of high carotid bifurcation as defined by this study.

As mentioned, 10 angiograms (20 arteries) were excluded from the study owing to abnormal posturing. The positional exclusion criteria were relatively stringent so that the results of this study would not be influenced by the abnormal posture of a few patients. In clinical practice, the actual impact of these abnormal postures on any measurements taken would be minimal.

In conclusion, this article proposes to define high carotid bifurcation as one whose distance from the base of skull is lower than the twenty-fifth centile. A scientific method for measuring this distance from the base of skull on 3D reconstruction of CT carotid angiograms has been described. Nine previously described methods of measuring bifurcation height, as identified in a literature search of clinical and anatomical studies, have been compared with the conclusion that distance from mastoid process is the most clinically relevant and reliable of these previously described measures. 3D CTA reconstruction is a useful tool in the preoperative work-up of patients considered for CEA, and routine reporting of distance of bifurcation from the base of skull would add value to this test.

FUNDING
None.

CONFLICT OF INTEREST
None.

REFERENCES


