In the last few years, several new imaging modalities for the evaluation of arterial vessels have been introduced. These include Color Doppler Ultrasound (CDU), spiral Computed Tomography (CT) and Magnetic Resonance Imaging [1-5]. The non-invasive character of these techniques represents a major advantage when compared with intra-arterial Digital Subtraction Angiography (DSA). These techniques are redefining the goals of DSA or “catheter based” angiography, with increasing emphasis being placed on its use in interventional procedures alone.

Nevertheless, although in a less conspicuous way, DSA has been updated and refined, so that the new angio systems now offer performance and application tools which, until a few years ago, would have been inconceivable.

One of the most interesting of these options is the ability to perform “rotational angiography” (RA), in which the C-arm assembly carrying the X-ray tube and image intensifier rotates around the vessel under examination during a selective intra-arterial injection of contrast agent. This technique, which is already widely applied in neuroradiology, offers interesting perspectives in other arterial regions such as the carotid arteries and the peripheral arteries.

In addition, the use of this type of acquisition, in conjunction with a workstation that is able to create three-dimensional (3D) reconstructions and virtual angioscopy displays, gives a three-dimensional impression of the morphology of various lesions. This opens up new and extremely intriguing perspectives, particularly with respect to the possibilities for endovascular treatment.

A further development of the 3D reconstruction technique is a tool that adds visualization of the atherosclerotic burden and endovacular prosthesis (i.e. calcified plaque and stents) to the 3D display of the vessel.

The diagnostic accuracy of two-dimensional intra-arterial digital subtraction angiography with the “rotational” tool in the evaluation of the carotid arteries has already been demonstrated by various authors [6-8] but, up until now, there has not been enough data on the possibility of three-dimensional angiography in this region.

To our knowledge the only experiences of 3D angiography are mainly focused on intracranial arteries [9-12], while only few preliminary papers have been devoted to extracranial vessels [13-15].

The cases detailed in this article display the possible applications of 3D angiography in examinations of the carotid arteries. The technique has the advantage of giving an extremely accurate impression of the three-dimensional relationships of the vessels.

The article describes our experience over a period of one year. The results presented have been obtained in cooperation with the Clinical Science members of the Cardio/Vascular Department, Philips Medical Systems.

**Examination technique**

Over the last 12 months, fifty patients underwent DSA of the supra-aortic vessels. In all cases rotational acquisition was performed. All patients had been referred for DSA evaluation on the basis of findings at Doppler sonography, which served as a screening method (degree of stenosis ≥ 70% or inconclusive results). In all cases the whole data set was transferred to the 3D RA workstation which produces the 3D reconstructions.
The examinations were performed on the new Integris Allura system (Philips Medical Systems, Best, the Netherlands).

The Integris Allura is specifically designed for angiography and interventional radiology, and has a special program for rotational angiography acquisitions. The program allows two rotational movements of the C-arm: “propeller” (550/s, 2400 movement range; 25 frames/s) and “roll” (300/s, 1800 movement range; 12.5 frames/s).

The first was used to evaluate the carotid arteries, while the second was used to evaluate the region of the iliac arteries.

In all the cases, the examinations were performed using a non-ionic contrast agent at a concentration of 350 mgI/ml (Iomeron, Bracco, Milan, Italy). The standard procedure was based on using a retrograde common femoral arterial approach to place a pigtail high-flow catheter in the aortic arch, in order to assure visualization of the origin of both common carotid and subclavian arteries. The pigtail catheter was replaced by a selective catheter (Simmons 1 or 2 or Headhunter) for catheterization of both common carotid arteries.

In order to obtain a satisfactory vessel opacification rate during the rotational acquisition period, a flow of 4-5 ml/s was employed for a total of 20-25 ml of contrast agent. The injection flow settings were set in accordance with the vessel size and flow characteristics, determined with a test bolus: in the case of large vessels a flow of 5 ml/s and a volume of 25 ml was chosen. In five patients the injection parameters between 60 ml at 15 ml/s and 80 ml at 20 ml/s.

The image acquisition procedure comprises the following steps:
• Position the C-arm cranial to the longitudinal axis of the tabletop
• Position the anatomy to be examined in the system isocenter; in the case of the carotid arteries, they should be positioned approximately in the center of the fluorescent field in both AP and LL projections
• Select the automatic rotation acquisition protocol and set the propeller-movement limits (start and end point of the scan)
• Perform a non-contrast (calcification detection run) followed by the rotational angiography run with contrast.

The injection of contrast media was performed with an automatic power injector (Medrad Mark 5), set to start the injection 1 second prior to the start of the rotational acquisition.

The rotation angle was set to a range of -120° to +120°. The rotation was performed in 4 seconds during which 100 frames were acquired. Two series of 100 images were taken, the first without contrast agent (calcification detection run), the second after the contrast injection. No temporary or permanent effects related to the intra-arterial procedure or to the use of contrast media were observed.

The two sets of two-dimensional images were transferred to the workstation. The transfer of data, including the reconstruction, requires approximately 75 seconds. The reconstruction process is based on the Feldkamp back-projection method, allowing display of the vessel geometry in three dimensions. Accurate reconstruction requires an understanding of the projection data and acquisition system characteristics. The latter require a two-fold image correction: pincushion and S-distortion correction, and geometric correction. The pincushion and S-distortion correction are required due to the curved shape of the image intensifier input screen and the influence of the environmental magnetic field. The geometric correction is used to correct any imperfections in the scan caused by a non-ideal circular trajectory. The final reconstructed data set is considered to be free of distortion.

3D reconstructions can be displayed with four different visualization techniques: MIP (maximum intensity projection), SUM, SSD (surface shaded display) and VR (volume rendering). The last two are applied as standard. Besides the 3D arterial visualization, the workstation is capable of vessel diameter measurements and virtual endoluminal display. The latter provides an inside view of the vessel, used for the virtual lumen inspection.

The additional post-processing software allows superimposition of the two runs (with and without contrast agent) by means of motion compensation software. This software is used to correct deficiencies caused by patient motion between the two runs and by vessel pulsation. The final reconstruction shows a vessel reconstruction where the relationship between the residual vessel lumen and the corresponding calcification is clearly visible. Endovascular devices can also be visualized and superimposed on the vessel portions.

The “calcification detection” data set is based on a rotational scan during which low kV settings are used in order to decrease the X-ray penetration rate and increase calcification visualization. During the native scan, the hyperdense calcification is not visible to the naked eye.
After the correction has been performed and the reconstruction is completed, the 3D reconstruction reveals a clear image of the hyperdense calcification. The calcification detection run is followed by the contrast run, which provides a 3D reconstruction of the residual vessel lumen. A combination of both runs provides a clear impression of the calcification location in relation to the residual lumen. The smallest resolution achievable is 32 microns. It is important to mention that even an initial data set provides satisfactory calcification detection, and usually no sub-reconstructions are required. If any additional geometrical assessment is desired, a sub-reconstruction is made and the measurement tool is used to perform the measurements of e.g. plaque thickness or residual lumen diameter.

Results

The results achieved are demonstrated by the following examples.

Case 1

A 74 year old male. Color Doppler imaging showed bilateral calcified plaque in the carotid
bifurcation, which made it difficult to assess the true degree of stenosis. Rotational angiography was therefore performed, with selective injection in both common carotid arteries.

In this example all the different types of reconstruction are shown. The subtracted angiogram of the RA of the right carotid artery (Figure 1a) shows only a mild stenosis of the proximal tract of the internal carotid artery. After transfer of the volume data set to the 3D console, different reconstructions can be obtained. The first image shown (Figure 1b) is a volume-rendered image obtained before the selective contrast injection; the calcified plaques on the right carotid bifurcation are clearly visible, together with the bony structures.

After contrast agent injection the 3D surface-shaded display (Figure 1c) shows the carotid artery and the bifurcation: there is good correlation with the angiogram shown in Figure 1a.

Figure 1d shows a newly available tool: 3D processing with matching of calcified plaques to the carotid arteries. Calcified plaque can be seen involving the proximal tract of the internal carotid artery. The cervical spine is also shown.
Figure 1e demonstrates the “cropping” function: this tool is able to remove all the bone structures at more than 4 mm distance from the artery, so that the arteries can be viewed from any required angle.

Another possible display function is the “cut plane” technique which permits removal of part of the reconstructed structures. Figure 1f shows a longitudinal cut plane along the axis of the bifurcation. The internal lumen of the carotid artery can be seen together with the protruding calcified plaque.

A more complex type of reconstruction gives the possibility of performing “virtual angioscopy”: after selection of the start and end point, the software automatically traces a tour inside the artery (Figure 1g).

Figure 1h shows the appearance of the carotid bifurcation in the virtual angioscopy trace.

Case 2
A 68 year old male. Color Doppler ultrasound showed right internal carotid artery stenosis. The best of the oblique projections obtained during the rotational acquisition shows a stenosis of 84% (Figure 2a). The 3D reconstruction clearly confirms the tight stenosis located at the origin of the internal carotid artery (Figure 2b).

In this case the 3D images were obtained with different angles of view. Superimposition of the calcified plaques shows how these calcifications appear to be distant from the lumen (Figure 2c,d) suggesting the presence of a soft or fibrous component in the plaque. Figure 2e is a cut-plane view showing the eccentric distribution of the plaque.

Case 3
A 55 year old female. Color Doppler ultrasound showed bilateral carotid stenosis. The preliminary rotational angiography (Figures 3a,b) shows an aneurysmatic dilatation of the upper tract of the internal carotid artery. The 3D reconstruction (Figure 3c) clearly shows the outer appearance of the sac, while the cut plane technique (Figure 3d) shows the internal lumen as well. The large arrows in Figure 3e define the real diameter of the vessel in a 3D rendering.

Discussion
All the cases we have studied show good correlation with the two-dimensional images. An emerging advantage of rotational angiography and 3D rendering is the ability to depict hyperdense structures, such as the calcium in the atheromatous plaques. On the basis of this observation we set about developing software to match the calcified plaque to the carotid vessel. The results are shown in Figures 1d,e,f and 2c,d,e.

These two studies represent a new way of displaying the carotid arteries, with good demonstration of the stenosis and an extremely precise representation of the calcified component of the atheromatous plaque, which has never been obtained in conventional angiography before.

The limitation of 3D RA, as with conventional angiography, is the risk associated with the catheterization [16,17]. 3D angiography is obtained after rotational angiography, and is derived from the same acquisition, so it does not require any prolongation of the procedure time or additional risk. It only requires additional time on the 3D console.

We believe that 3D RA should be performed on selected cases after performing the preliminary AP and LL carotid artery study, or carotid RA.

Another field of application, as reported by other authors [13], is the sizing of stents: the 3D display makes it possible to perform measurements of the diameter of the carotid artery above and below the site of the stenosis (Figure 2e).

Comparison with other modalities
Spiral CT
Until now, only spiral CT has been able to provide 3D visualization of the carotid arteries. However, 3D processing in CT is rather time-consuming.

3D angiography only requires a short time (about 75 seconds) to transfer the data from the operator’s console to the 3D console. The images are displayed automatically, with only a minimum of operations by the user. Complex reconstructions, such as superimposition of calcified plaques or virtual angioscopy, are performed within seconds.

Color Doppler Ultrasound
Color Doppler Ultrasound (CDU) is less invasive than 3D RA, and is superior in the definition of plaque composition. However CDU still has multiple limitations due to the short tract of the carotid arteries evaluated, the presence of calcified plaques obscuring the lumen, and the level of experience required from the operator. Furthermore, recent papers stress the need to be very careful when basing the evaluation of the degree of stenosis on this technique alone [18, 19].
Figure 2. Right carotid artery bifurcation.

Figure 2a. Rotational angiography showing a high-grade (84 %) stenosis of the internal carotid artery (arrow).

Figure 2b. 3D surface-shaded display confirms the stenosis at the origin of the carotid artery.

Figures 2c, d. 3D renderings after applying the "calcified plaque" tool. The calcified component of the atheromatous plaque is eccentrically distributed. This aspect is clearly shown in the "cut plane" display.

Figure 2e. The "cut plane" view clearly shows the eccentric distribution of the plaque.

Figure 3. Aneurysm of the internal carotid artery at the cranio-cervical junction.

Figures 3a, b. Two frames of the rotational angiography show a focal enlargement of the upper tract of the internal carotid artery (arrow). Only a mild stenosis is visible at the origin of the vessel.

Figure 3c. The 3D surface-shaded display confirms the findings.

Figure 3d. An internal view of the aneurysm.

Figure 3e. Measurements of the diameter of the vessel lumen can be obtained by placing the arrows on the vessel walls.
Magnetic Resonance Angiography

Magnetic Resonance Angiography (MRA) is also an established technique in constant evolution, so the results are to some extent dependent on the experience of the operators and the system at their disposal. At times, this technique can also suffer from overestimation of stenosis caused by “flow void artifacts” which are particularly evident in high-grade stenosis [20]. However, a recent paper on the new elliptic centric contrast-enhanced MR angiography [21] reported very good sensitivity and specificity (sensitivity 97.1%; specificity 95.2%; likelihood ratio for a positive test result 20.4).

Conclusions

In conclusion we believe that, although X-ray angiography now plays a smaller role in the diagnosis of atheromatous carotid artery disease, it still maintains an important role in the preoperative management of carotid stenosis, and is of fundamental importance in endovascular treatment such as carotid stenting. The possibility of providing a 3D representation of the affected artery, before and after the procedure, appears to be extremely useful for the operator and very beneficial for the patient.

INTERMEZZO

A century of angiography

The world’s first angiogram was made a month after Roentgen’s original discovery when, in January 1896, Haschek and Lindenthal injected a mixture of chalk, cinnabar (mercuric sulfide) and vaseline into the blood vessels of the amputated hand of a cadaver. However, it was not until 1923 that the first angiogram was obtained in a living human being, when Berberich and Hirsch demonstrated the arterial supply to the thumb, using strontium bromide as the contrast agent.

Later, it was concluded that only iodine compounds offered the necessary combination of radiopacity and low toxicity.

For several decades, angiography was performed by direct injection through a needle inserted into a surgically exposed artery, but in 1953 Sven Ivar Seldinger introduced the modern technique in which a catheter is introduced percutaneously and passed over a guidewire, allowing the catheter tip to be precisely posicioned for selective injection.

The next major breakthrough was the invention of Digital Subtraction Angiography. The principle of subtraction had been proposed by Ziedses des Plantes as early as 1934, but had little practical application until the introduction of digital image processing, which paved the way for the introduction of digital subtraction, pioneered by Mistretta et al. in 1980.

The complexity of the vascular structures requires acquisition of the images in several projections to avoid the possibility of an abnormality being obscured by an overlying vessel.

Rotational angiography, introduced by Philips in 1995, acquires a complete series of projections while the imaging assembly rotates around the patient. As well as giving a choice of views, the complete data set can also be processed to provide accurate three-dimensional reconstructions.
References


