Improving the image quality of contrast-enhanced MR angiography by automated image registration: A prospective study in peripheral arterial disease of the lower extremities

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Authors: J. Menke; Goettingen/DE
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Purpose

Peripheral arterial disease (PAD) of the lower extremities is mediated by arterial steno-occlusions, has a high prevalence in the elderly, and can reduce the quality of life substantially [1,2]. The diagnosis is primarily based on clinical findings [1,2]. Additional angiography may be required for differential diagnosis and for anatomical assessment of steno-occlusions before treatment [1].

Catheter-based digital subtraction angiography (DSA) is the gold standard of diagnostic imaging in PAD [1]. In DSA, an unenhanced mask image is digitally subtracted from one or more subsequent contrast-enhanced images. This subtracts especially the x-ray-absorbing bones, while keeping the contrast-enhanced arteries. If the patient has slightly moved their legs between acquisition of the mask image and of the contrast-enhanced image, then the quality of the subtraction image can be improved by manual image registration ("pixel shift"), where the mask image is digitally moved vertically and/or horizontally to compensate the leg movement.

This prospective study investigated whether such image registration can also improve the quality of contrast-enhanced magnetic resonance angiography (MRA) in patients with suspected or known PAD of the lower extremities [3].
Methods and Materials

Patients and MRAs:

Over a study period of 3 years, 407 leg MRAs of patients with PAD symptoms were prospectively enrolled. Three MRAs were excluded (1 with insufficient arterial contrast and 2 with technical artifacts). In the included 404 MRAs, 5 upper legs and 27 lower legs were excluded from further analysis because of leg amputation or complete arterial occlusion. In the 404 MRAs the clinical Fontaine stages were: 7% PAD ruled out, 10% stage 1, 54% stage 2, 22% stage 3, and 7% stage 4. Patient age ranged from 36 to 92 (median 68) years and body weight from 35 to 130 (median 80) kg. The female-to-male ratio was about 1:3.

Image registration:

The contrast-enhanced three-dimensional image volumes were automatically registered to their non-enhanced counterparts by using a proprietary C++ program that incorporates the freely available automated image registration software package AIR 5.2.5 (Woods RP, AIR 5.2.5, http://bishopw.loni.ucla.edu/AIR5/) [4]. The computation time for automated image registration was evaluated and refers to calculation on a personal computer with a 2.4 GHz Pentium Quad processor and 1.5 GB internal memory.

Analysis of image quality:

The standard non-registered MRAs were compared to automatically linear, affine and warp registered MRAs by four image quality parameters, including the vessel detection probability (VDP) in maximum intensity projection (MIP) images and different contrast-to-noise ratios (CNR) [3]. These parameters have been described in detail by Sun et al [5]. The different registration types were compared by analysis of variance with the significance level set at P<0.05.
Results

Illustrative case:

Fig. 1 shows an illustrative case where the standard non-registered MRA is compared to the linear-registered MRA. The left lower leg gained most from linear registration. This left lower leg had shifted about 2.5 millimeters between acquisition of the non-enhanced and the contrast-enhanced MRA sequence. In the other body regions the body shift was less than 1 millimeter. Their non-registered image quality was good without need for image registration.
Fig. 1: Standard non-registered MRA versus linear-registered MRA (example). This figure shows coronal MIP images of a leg MRA in a 66-year-old man with PAD (Fontaine stage 2B) without image registration (A) and with linear image registration (B). Linear registration improved the image quality in the left lower leg considerably (9 seconds calculation time). In this patient the treatment was conservative, considering the Fontaine stage, the rich profundal collaterisation of the superficial femoral artery occlusions, and because of several comorbidities. 


Fig. 2 compares the registration types in the left lower leg. Linear registration required 9 seconds, affine registration 15 seconds, and warp registration 155 seconds. Without registration the vessel detection probability (VDP) was 25%. VDP became 98% with linear registration, 99% with affine registration, and 100% with warp registration. The other image quality parameters improved similarly with image registration.

Fig. 2: Comparison of different registration types (example). Coronal MIP images of the left lower leg of Figure 1: (A) No image registration; (B) linear registration; (C) affine registration; (D) warp registration. Panel (E) shows the non-registered left lower leg in a follow-up MRA one year later. In (E) the left lower leg had shifted only 0.2 millimeters without need for image registration.

Registration times:

Image registration of a whole MRA required on average less than a minute with linear or affine registration, but about 14 minutes with warp registration. Focused registration (such as registration of the left lower leg in Fig.2) required accordingly less time.

<table>
<thead>
<tr>
<th></th>
<th>Count</th>
<th>Linear registration,</th>
<th>Affine registration,</th>
<th>Warp registration,</th>
<th>Time ratio warp / linear</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pelvis</td>
<td>404</td>
<td>19.0 (3.8) sec</td>
<td>20.0 (6.1) sec</td>
<td>6.0 (2.8) min</td>
<td>18.9 (8.4)</td>
</tr>
<tr>
<td>Upper legs</td>
<td>799</td>
<td>7.7 (2.5) sec</td>
<td>8.1 (2.8) sec</td>
<td>2.1 (1.1) min</td>
<td>16.2 (8.2)</td>
</tr>
<tr>
<td>Lower legs</td>
<td>784</td>
<td>7.1 (1.7) sec</td>
<td>7.2 (1.9) sec</td>
<td>1.9 (1.1) min</td>
<td>16.5 (7.2)</td>
</tr>
<tr>
<td>Whole MRA</td>
<td>404</td>
<td>47.9 (8.2) sec</td>
<td>49.8 (10.6) sec</td>
<td>13.8 (4.1) min</td>
<td>17.3 (4.3)</td>
</tr>
</tbody>
</table>

Table 1: Registration times in the different body regions. This table summarizes the average (SD) computation times for linear, affine and warp registration of the whole MRA and of selected body regions. The time ratio in the right column shows how many linear registrations could be performed instead of computing one warp registration.


Body shift:

The average (±SD) body shift between acquisition of the non-enhanced and of the contrast-enhanced MR sequence was 0.9 (±0.8) mm in the pelvis, 0.8 (±0.5) mm in the upper legs, and 0.6 (±0.6) mm in the lower legs. Most cases showed a body shift of less than 1 mm (Table 2). A body shift of 1 mm or more was found in 19% of pelvises, 19% of upper legs, and 12% of lower legs. Only a minority shifted 2 mm or more (pelvis 5%, upper legs 3%, lower legs 3%).
Table 2: Body shift in the different vascular body regions, stratified into 4 body shift classes.

<table>
<thead>
<tr>
<th>body shift class</th>
<th>body shift, mm</th>
<th>pelvis, n</th>
<th>upper legs, n</th>
<th>lower legs, n</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0 – 0.9 mm</td>
<td>327</td>
<td>650</td>
<td>693</td>
</tr>
<tr>
<td>2</td>
<td>1 – 1.9 mm</td>
<td>55</td>
<td>125</td>
<td>64</td>
</tr>
<tr>
<td>3</td>
<td>2 – 2.9 mm</td>
<td>14</td>
<td>20</td>
<td>18</td>
</tr>
<tr>
<td>4</td>
<td>≥ 3 mm</td>
<td>8</td>
<td>4</td>
<td>9</td>
</tr>
<tr>
<td>total</td>
<td>404</td>
<td>799</td>
<td>784</td>
<td></td>
</tr>
</tbody>
</table>


Analysis of image quality:

In the analysis of variance all studied image quality parameters showed similar trends [3]. Generally, registration improved the MRA quality significantly (P < 0.05). The 12% of lower legs with a body shift of 1 mm or more (body shift classes 2-4 in Table 2 and Fig.3) showed the highest gain in image quality when using linear registration instead of no registration, with an average VDP gain of 20-49%. Warp registration improved the image quality slightly further.
Fig. 3: Gain in MRA image quality when using image registration. This figure shows the average gain in the image quality parameter VDP (vessel detection probability) when using (A) linear registration instead of no registration, or (B) warp registration instead of linear registration. The body shift classes are defined in Table 2. Especially in the lower legs the highest gain is achieved when using linear registration instead of no registration (panel A). Warp registration can improve the image quality slightly further (panel B), but at the expense of a much longer computation time.

Conclusion

DSA is the imaging gold standard in patients with suspected or known PAD of the lower extremities, but is invasive [1]. In the clinical setting MRA and computed tomographic angiography have become noninvasive diagnostic alternatives to DSA.

In DSA, pixel shift is a well-known manual image registration for improving image quality in patients who moved during angiography. Similarly, automated image registration can improve the image quality of lower extremity MRA, as shown in this study.

The effect of image registration was highest in the lower legs. This may be explained by the relatively small size of the tibiofibular arteries (2-3 mm diameter) where, for example, a 2-mm body shift has a stronger visual effect than in the larger-sized pelvic arteries (9-11 mm diameter).

In a clinical setting linear image registration could be sufficient, since it is fast and effective. Also, it is most similar to the well-known pixel shift of DSA. Furthermore, this is a robust algorithm that does not deform the images; it just rotates and shifts them [6].

While automated image registration is useful in MRA of the lower extremities, this need not apply in other body regions, as shown in MRA of the carotid arteries [4].

In summary, in patients with suspected or known PAD, automated image registration can improve the MRA image quality especially in the lower legs, which is comparable to the effect of pixel shift in DSA [3].


Personal Information

Jan Menke
Diagnostic Radiology, University Hospital, 37075 Goettingen, Germany
Menke-J@T-Online.de