Endovascular aneurysm repair: prevention and treatment of complications

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ABSTRACT

Objectives: This study was conducted to validate new computed tomography (CT)-applied software used to determine endograft limb position and apposition after endovascular aneurysm repair (EVAR).

Methods: Twenty-four patients who underwent elective EVAR were retrospectively selected. A type IB endoleak occurred in 12 patients during follow-up; they underwent distal extension. Twelve control patients without endoleak were matched on time of follow-up for the late follow-up CT scan of the endoleak group (ie, CT scan before detection of the type IB endoleak). Vascular Imaging Analysis prototype software (Endovascular Diagnostics, Utrecht, The Netherlands) was adapted to calculate the distal apposition zone. Six parameters were defined: fabric distance, shortest apposition length, endograft diameter, iliac seal surface (ISS), iliac endograft apposition surface (IEAS), and percentage of iliac surface coverage (IEAS/ISS×100). Measurements were performed on preoperative, first postoperative, and late follow-up CT scans. Endograft limbs with type IB endoleaks were compared to the control endograft limbs. Interobserver variability was assessed with the intraclass correlation coefficient (ICC).

Results: Thirty-six limbs were included: 15 in the endoleak group (3 patients had bilateral type IB endoleaks) and 21 in the control group (3 limbs were excluded because of primary endograft extensions to the external iliac arteries). CT follow-up was not significantly different between the endoleak and control groups (30 months [interquartile range (IQR), 18-58 months] vs 36 months [IQR, 21-59] months, P=.843). Interobserver agreement was good-to-excellent for all parameters (ICC, 0.879-0.985). Preoperative anatomy and endograft dimensions on first follow-up CT scan did not differ significantly between the groups. When late CT angiography was compared with first postoperative CT scan, endograft dimensions had significantly changed in the endoleak group; importantly, apposition was significantly decreased, and fabric distance was significantly increased. Difference in changes in endograft dimensions was significant between the groups.

Conclusions: New CT-applied software was introduced to visualize apposition and positional changes of endograft limbs during follow-up. The software demonstrated good-to-excellent interobserver agreement and enabled accurate analysis of post-EVAR endograft dimensions. Significant changes in apposition and position were observed with the software on late CT imaging before the CT scan where the diagnosis of type IB endoleaks was set.
INTRODUCTION

Abdominal aortic aneurysms (AAAs) are frequently treated by endovascular means.¹,² Follow-up after endovascular aortic repair (EVAR) is regularly performed with computed tomography angiography (CTA) scans.¹ Because of hemodynamic forces acting on the endograft, subtle changes in the position of the endograft may occur that can lead to post-EVAR complications such as migration or endoleak. Type I endoleaks are associated with a continued risk of aneurysm rupture after EVAR.²,³ A variety of studies have been performed on the loss of proximal apposition of the endograft. However, less attention has been paid to distal endograft fixation, even though a type IB endoleak may also repressurize the aneurysm and increase the risk of rupture.⁴-⁸ Accurately quantifying and visualizing the endograft position and apposition during follow-up is essential to prevent late seal failures. Identifying small changes in position of the endograft, such as tilting, migration, dilatation of common iliac artery (CIA), and thereby, also full expansion of the endograft limb, is challenging with standard CT imaging. The in-house developed CT-applied Vascular Imaging Analysis (VIA) prototype software (Endovascular Diagnostics, Utrecht, The Netherlands) can determine apposition and the three-dimensional (3D) position of the endograft during follow-up.⁹ The software has been validated to detect (subtle) changes in proximal abdominal aortic endograft position and apposition⁹-¹¹ and enabled demonstration of progressive changes in endograft position in the aortic neck before complications became obvious with standard CT imaging.¹⁰ The same methodology can be implemented for iliac endograft limb position and apposition. Hence, the purpose of this study was to validate the new CT-applied software focusing on endograft limb position and apposition, and changes herein during post-EVAR follow-up.

METHODS

Patient selection
Twelve elective EVAR patients were identified in the hospital’s database who had received revision surgery for a type IB endoleak, and who had at least a pre-EVAR CTA scan, a one-month CTA scan, and a late post-EVAR CTA scan on which the endoleak was not detected, prior to the CTA scan that showed the type IB endoleak. Three patients had bilateral type IB endoleaks. The CT scan before detection of the type IB endoleak was defined as the late follow-up CT scan in the endoleak group. All endograft limbs that later developed a type IB endoleak were analyzed. The contralateral limb was not included in the final analysis.
Twelve control patients were selected without type IA or type IB endoleaks, who had at least two post-EVAR CT scans and a similar interval between the primary EVAR procedure and the late follow-up CT scan of the endoleak group. Both endograft limbs were included for the control group, except from endograft limbs with primary extensions to the external iliac artery (EIA). The CT scan before the detection of the type IB endoleak in the endoleak group was compared with the late follow-up CT scan of the control patients.

The endograft limbs that required a distal revision procedure for a type IB endoleak were compared to the endograft limbs of the control group. Investigational review board approval was obtained, with exemption from patient consent for review of anonymized CT datasets.

**Measurement protocol**

Measurements were performed on the preoperative CT scan and the first and late postoperative CT scans. The endograft limbs of the first postoperative and late follow-up CT scans were compared between the two groups. All CT scans were part of regular EVAR follow-up, and radiologists assessed the scans according to a standardized protocol. Only to illustrate the two patient cases, measurements were also performed on the final CT scan that reported the type IB endoleak. CTA images were acquired on a 256-slice CT scanner with the following scan parameters: tube voltage, 120 kV; distance between slices, 0.75 mm; pitch, 0.9 mm; and collimation, 128 × 0.625 mm. Preoperative, first, and late postoperative CT images had a median slice thickness of, respectively, 2.0 mm (interquartile range [IQR], 1.5-3.2 mm), 1.5 mm (IQR, 1.5-3.0 mm), and 1.5 mm (IQR, 1.5-1.5 mm). CTs were acquired in the arterial phase, using bolus triggering with a threshold of 100 Hounsfield units.

The 3Mensio 9.0 SP1 vascular workstation (Pie Medical, Maastricht, The Netherlands) was used for the measurements. A center lumen line was semiautomatically drawn through the lumen of the aorta and iliac arteries. 3D coordinate markers were placed on the renal artery orifices (to define the baseline) and on the aortic and iliac bifurcations. The iliac bifurcation markers were placed just proximal to the orifice of the internal iliac artery (Figure 1, blue dots). On postoperative CT scans, markers were placed on the distal end of the fabric of the implanted iliac endograft limbs to identify the endograft limb position and visualize possible endograft limb retraction. A marker was also placed at the distal and proximal location where the endograft limb lost circumferential apposition with the CIA (Figure 1A, red and orange dots). Similar to a previous study by Bastos Gonçalves et al., the average outer wall CIA diameter was measured at a fixed distance of 10 mm proximal to the distal end of the endograft fabric on the postoperative CT scan.
VIA prototype software\textsuperscript{9-11} that was primarily developed to calculate the proximal endograft apposition within the infrarenal neck was adapted to calculate the iliac apposition zones. The VIA prototype software uses 3D coordinates of anatomical landmarks, the edges of the endograft fabric, the centerline and a mesh of the lumen, which are exported from the 3Mensio vascular workstation. The software then calculates and visualizes in 3D the apposition surface area, minimal length of apposition and fabric distances over the curve of the aorta and CIAs, and average diameter of the distal fabric edge (Figure 4.2).

**Definitions and visualization**

The following postoperative iliac endograft parameters were defined:

1. iliac seal surface (ISS)—surface area available for sealing in the CIA, defined as the area between the orifice of the common iliac artery and iliac bifurcation (Figure 4.1A);
2. iliac endograft apposition surface (IEAS)—the actual apposition of the endograft limb in the CIA (Figure 4.1A);
3. iliac surface coverage (ISC)—the percentage of the ISS that was covered by the endograft limb (IEAS/ISS × 100%);
4. fabric distance (FD)—the distance over the curve of the CIA between the most distal end of the endograft limb and the iliac bifurcation (Figure 4.1B);
5. shortest apposition length (SAL)—the shortest distance between the proximal and distal part of the endograft limb where there is circumferential seal (Figure 4.1B); and
6. endograft diameter (ED)—the average inner diameter over the plane perpendicular to the center lumen line through the distal end of the endograft limb (Figure 4.1B). With the ED, the percentage of endograft limb expansion (as a percentage of the original diameter) was calculated.

All endograft limbs were measured with the VIA prototype software to visualize the endograft limb position and apposition during follow-up.
Figure 4.1. Schematic depiction of an infrarenal abdominal aorta aneurysm with endograft and iliac apposition surface. A center lumen line was drawn through the lumen of the aorta and iliac arteries. Three-dimensional coordinate markers were placed on the renal artery orifices to define the baseline, and aortic and iliac bifurcations (blue dots). (A) The iliac seal surface (ISS)—surface area available for sealing in the common iliac artery (CIA), was defined as the area between the aortic and iliac bifurcation (green area); and iliac endograft apposition surface (IEAS)—the actual apposition of the endograft limb in the CIA (yellow area). The iliac surface coverage (ISC) was defined as IEAS/ISS × 100. (B) Shortest apposition length (SAL)—the shortest distance between the proximal (orange dots) and distal (red dots) part of the endograft limb where there is circumferential seal; and endograft diameter (ED)—average diameter of the distal end of the endograft limb; fabric distance (FD)—distance between the iliac bifurcation and the most distal end of the endograft limb. EIA = external iliac artery, IIA = internal iliac artery.
Figure 4.2. Overview of pre- and post-EVAR CT analysis in VIA prototype software. 3D coordinates of anatomical landmarks, the edges of the endograft fabric, the centerline and a mesh of the aortic lumen are exported from a vascular workstation. Apposition surface areas (yellow), shortest apposition lengths, fabric distances, and fabric edge diameters are calculated automatically from these 3D coordinates. Changes in apposition, fabric distance, or endograft expansion are displayed in the software for consecutive CT scans. In this example, the decrease of apposition surface (solid line) and shortest length of apposition (dotted line) are displayed for the distal left limb. Proximal apposition was stable, while distal apposition decreased in both limbs.

**Variability analysis**

To analyze the interobserver variability, two independent, experienced observers (S.G., R.S.) performed the measurements on the first postoperative CT scan. Both observers performed the centerline reconstructions and measurements. Variability of aortic morphology parameters have been previously described and demonstrated excellent agreement.\(^{13}\) Hence, this study only analyzed the variability regarding the previously defined iliac parameters (ie, ISS, IEAS, ISC, SAL, ED, and FD).

**Statistical analysis**

Statistical analyses were performed with SPSS 24 software (IBM Corp, Armonk, NY, USA). \(P\) values were considered significant when two-tailed \(\alpha\) was < 0.05. Normality of the data was tested. Because most of the data were non-normally distributed, data are presented as median (IQR). Differences in continuous variables between the endoleak and control groups were tested with the Mann-Whitney U test for nonparametric data.
Differences between first and late follow-up CTA were analyzed with the Wilcoxon signed-rank test. Differences in endografts were assessed with the Pearson $\chi^2$ test. The intraclass correlation coefficient (ICC) was used to determine the interobserver agreement. The ICC was tested with a two-way mixed model by absolute agreement and is expressed with the 95% confidence interval (CI). ICC values >0.8 were considered a good agreement. The repeatability coefficient (RC) was defined as 1.96 times the standard deviation (SD) of the difference between the paired measurements.

RESULTS

Fifteen endograft limbs with a type IB endoleak, and 21 endograft limbs without primary extensions of patients without an endoleak were selected. Baseline (anatomical) characteristics of the endograft limbs are reported in Table 4.1. The following endografts were deployed in the endoleak group: 7 Endurant (Medtronic, Minneapolis, MN, USA), 1 Talent (Medtronic, Minneapolis, MN, USA), 2 Zenith (Cook, Bloomington, IN, USA), and 2 AFX (Endologix, Irvine, CA, USA). Two types of endograft were used in the control group: 11 Endurant and 1 Zenith. The endografts used were not significantly different between the groups ($P = .238$).

Table 4.1. Baseline (anatomical) characteristics of the endograft limbs between the endoleak and control groups

<table>
<thead>
<tr>
<th>Variable$^a$</th>
<th>Endoleak (n=15)</th>
<th>Controls (n=21)</th>
<th>$P$ value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Days between CT scan and EVAR $^*$</td>
<td>55 [28–65]</td>
<td>41 [22–96]</td>
<td>.932</td>
</tr>
<tr>
<td>Iliac diameter (mm)</td>
<td>17 [15–23]</td>
<td>16 [14–18]</td>
<td>.170</td>
</tr>
<tr>
<td>Iliac length (mm)$^b$</td>
<td>47 [41–62]</td>
<td>57 [42–81]</td>
<td>.279</td>
</tr>
<tr>
<td>Oversizing (%)</td>
<td>0 [-12 to 10]</td>
<td>1 [-5 to 13]</td>
<td>.340</td>
</tr>
<tr>
<td>Maximum AAA diameter (mm)$^*$</td>
<td>65 [53–71]</td>
<td>62 [54–72]</td>
<td>.644</td>
</tr>
<tr>
<td>Endografts, No.$^*$</td>
<td>7</td>
<td>11</td>
<td>.238</td>
</tr>
<tr>
<td>Endurant</td>
<td>7</td>
<td>11</td>
<td></td>
</tr>
<tr>
<td>Zenith</td>
<td>2</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Talent</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>AFX</td>
<td>2</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

AAA, abdominal aortic aneurysm; CT, computed tomography; EVAR, endovascular aneurysm repair.

$^a$Continuous data are reported as the median [interquartile range].

$^b$Between the patients from each group (endoleak group: 12, controls: 12)

$^c$Length from orifice of common iliac artery to iliac bifurcation
The endoleak group comprised 15 studied endograft limbs; three patients had bilateral type IB endoleaks. The control group comprised 21 studied endograft limbs; three endograft limbs with primary EIA extensions were excluded. Preoperative median outer wall CIA diameter was 16.8 mm (IQR, 14.6–22.8 mm) vs 15.6 mm (IQR, 13.9–18.4 mm) in the endoleak and control groups, respectively ($P = .170$). The endograft limb size was a median of 16 mm (IQR, 16–20 mm) in the endoleak group and 16 mm (IQR, 13–20 mm) in the control group ($P = .340$). Median endograft limb oversizing was 0% (IQR, -12% to 10%) and 1% (IQR, -5% to 13%) in the endoleak and control groups, respectively ($P = .340$). Maximum AAA diameter was a median of 64.8 mm (IQR, 53.4–71.4 mm) vs 61.7 mm (IQR, 54.1–71.7 mm) in the endoleak vs control groups, respectively ($P = .644$).

**Variability analysis**

Interobserver variability was analyzed for all included endograft limbs (Table 4.2). There was a good agreement for the ED (ICC, 0.879), and the remaining variables demonstrated an excellent agreement (ICC, 0.959–0.985). The average difference between the observers for the ISS and IEAS was 121 mm$^2$, with an RC of 541 mm$^2$, and 142 mm$^2$ with an RC of 529 mm$^2$, respectively. When this is expressed as the percentage of the mean calculated value, the mean difference is within 5.0% for the ISS and 10.6% for the IEAS; 95% of the variability of both surfaces was within 22.5% to 39%, respectively. SAL, ED, and FD were calculated with a mean interobserver differences of 1.2, 1.3, and −0.1 mm and RCs of 9.0, 5.4, and 7.7 mm, respectively. Of these variables, 95% of the variability in calculating these distances was within 0.4% to 7.8%.

| Table 4.2. Interobserver variability for the apposition and seal parameters of the endograft limbs (n=36) |
|-----------------|----------|----------|----------|-----------------|----------|
| Variable        | Mean$^a$ | Diff.$^b$ | RC       | ICC (95% CI)   | $P$ value |
| ISS (mm$^2$)    | 2409     | 121      | 541      | 0.985 (0.970–0.992) | <.001    |
| IEAS(mm$^2$)    | 1549     | 142      | 529      | 0.976 (0.953–0.988) | <.001    |
| ISC (%)         | 55.6     | 2.9      | 15.1     | 0.964 (0.930–0.982) | <.001    |
| SAL (mm)        | 19.5     | 1.2      | 9.0      | 0.968 (0.937–0.984) | <.001    |
| ED (mm)         | 16.8     | 1.3      | 5.4      | 0.879 (0.763–0.938) | <.001    |
| FD (mm)         | 16.4     | -0.1     | 7.7      | 0.959 (0.920–0.979) | <.001    |

CI, confidence interval; ED, endograft diameter; FD, fabric distance; ICC, intraclass correlation coefficient; IEAS, iliac endograft apposition surface; ISC, iliac surface coverage; ISS, iliac seal surface; RC, repeatability coefficient; SAL, shortest apposition length.

$^a$Mean value measured by two observers

$^b$Mean difference between paired measurements
Table 4.3. Endograft limb dimensions between the endoleak and control groups on first postoperative CT scan

<table>
<thead>
<tr>
<th>Variable</th>
<th>Endoleak (n=15)</th>
<th>Controls (n=21)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follow-up [days]*</td>
<td>43 [28–50]</td>
<td>36 [29–43]</td>
<td>.887</td>
</tr>
<tr>
<td>Maximum AAA diameter (mm)*</td>
<td>63 [54–70]</td>
<td>62 [56–74]</td>
<td>1.0</td>
</tr>
<tr>
<td>Iliac diameter (mm)</td>
<td>17 [16–22]</td>
<td>16 [15–19]</td>
<td>.136</td>
</tr>
<tr>
<td>Endograft limb expansion (%)</td>
<td>100 [100–100]</td>
<td>100 [86–100]</td>
<td>.141</td>
</tr>
<tr>
<td>FD (mm)</td>
<td>17 [8–22]</td>
<td>13 [8–24]</td>
<td>.665</td>
</tr>
<tr>
<td>Apposition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISC (%)</td>
<td>52 [43–69]</td>
<td>64 [49–72]</td>
<td>.642</td>
</tr>
</tbody>
</table>

AAA, abdominal aortic aneurysm; FD, fabric distance; ISC, iliac surface coverage; SAL, shortest apposition length.
*Between the patients from each group (endoleak group: 12, controls: 12)
aData are presented as median [interquartile range].

Comparison between the endoleak and control groups

The endograft limb dimensions of the first postoperative CT scans are reported in Table 4.3. The duration from EVAR to the first follow-up CTA was not significantly different between the groups. On the first post-EVAR CTA, 80% of the endograft limbs were fully expanded in the endoleak group, and 57% were fully expanded in the control group. A similar part of the CIA was covered in both groups, and the SAL was comparable.

The late follow-up endograft parameters are reported in Table 4.4, and the differences between the late and first follow-up CT scan are reported in Table 4.5. The interval between EVAR and late follow-up CT imaging was 30 months (IQR, 18-58 months) vs 36 months (IQR, 21-59 months), which was not significantly different (P = .843).

The iliac diameter increased to 21.7 mm (IQR, 18.7-27.0 mm) in the endoleak group and to 17.5 mm [IQR, 15.8-21.0 mm] in the control group, which was significantly different between the groups (P = .012). At late follow-up CTA, 93% of endograft limbs in the endoleak group and 86% in the control group were expanded to their maximum (fabric) diameter. Aortic aneurysm sac regression (>0 mm) was observed in 25% of the patients with type IB endoleaks and in 67% of control group patients. Aortic aneurysm growth (>5 mm) was observed in 75% versus 0% for the endoleak and control group, respectively. Proximal displacement of the endograft limb was observed in both groups when compared with the first CT imaging. There was a significant difference in FD between the endoleak and control groups (28 mm [IQR, 11-41 mm] vs 18 mm [IQR, 7-27 mm], P = .048). A significant difference between the ISC of both groups (5% [0%-15%] vs 49% [37%-64%]) was found on late CT imaging (P < .001). The ISC was significantly decreased in the endoleak group, which was also reflected by the reduction in SAL.
Table 4.4. Endograft limb dimensions between the endoleak and control groups on the late postoperative CT scan*\textsuperscript{a,b}

<table>
<thead>
<tr>
<th>Variable</th>
<th>Endoleak (n=15)</th>
<th>Controls (n=21)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Follow-up (months)*</td>
<td>30 [18–58]</td>
<td>36 [21–59]</td>
<td>.843</td>
</tr>
<tr>
<td>Maximum AAA diameter (mm)*</td>
<td>78 [66–87]</td>
<td>55 [48–67]</td>
<td>.003</td>
</tr>
<tr>
<td>Iliac diameter (mm)</td>
<td>22 [19–27]</td>
<td>18 [16–21]</td>
<td>.012</td>
</tr>
<tr>
<td>Endograft limb expansion (%)</td>
<td>100 [100–100]</td>
<td>100 [88–100]</td>
<td>.537</td>
</tr>
<tr>
<td>Apposition</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISC (%)</td>
<td>5 [0–15]</td>
<td>49 [37–64]</td>
<td>&lt;.001</td>
</tr>
<tr>
<td>SAL (mm)</td>
<td>1 [0–3]</td>
<td>15 [10–24]</td>
<td>&lt;.001</td>
</tr>
</tbody>
</table>

AAA, abdominal aortic aneurysm; FD, fabric distance; ISC, iliac surface coverage; SAL, shortest apposition length.

*Between the patients from each group (endoleak group: 12, controls: 12)
*Data are represented as median [interquartile range].
*bFor the endoleak group the late CT scan is the scan before the presence of the endoleak. For the control group the CTA that was matched.

The difference in AAA change during follow-up was significant; the AAA diameter increased in the endoleak group, whereas a decrease in diameter was observed in the control group. The median increase in iliac diameter was larger in the endoleak group than in the control group (3 mm [IQR, 2–7 mm] vs 1 mm [IQR, 1–3 mm], P = .006). A median FD change of 6 mm [IQR, 2–11 mm] vs 3 mm [IQR, −1 to 4 mm] was observed in the endoleak and control groups, respectively (P = .026). In addition, apposition coverage and length demonstrated significant changes during follow-up in the endoleak group (ISC: −42% [IQR, −57% to −25%], P = .002; SAL: −10 [IQR, −19% to −6%], P = .001), which was significantly different from the differences observed during follow-up of the control group (ISC: −5% [IQR, −11% to 3%], P < .001; SAL: −3 mm [IQR, −6 to 1 mm], P = .003).

In the long run (following the late follow-up CT imaging included in this study), two patients of the control group died, three had not yet received follow-up since the late CT scan and the remaining seven patients did not have reported complications at the distal sealing zones after a median of 17 months (IQR, 15–21 months).

Two case examples

Figure 4.3A-D shows a patient who was electively treated for an AAA of 56 mm with an Endurant endoprosthesis with right and left endograft limb diameter of 16 mm. Effective proximal and distal seal were reported at 50 days (Figure 4.3B), with, respectively, 73% and 62% coverage of the right and left CIA, and full expansion of both endograft limbs. At 61 months, a type IA endoleak was suspected on CTA because of
an increase in AAA diameter to 65 mm, which was confirmed by subsequent digital subtraction angiography. During reintervention, the proximal seal was successfully extended with a 36-mm aortic cuff (Endurant). At 64 months (Figure 4.3C), the right iliac diameter had increased to 22 mm, which resulted in a major decrease in IEAS and SAL. The FD increased from 14 mm to 17 mm (i.e., the endograft limb retracted 3 mm); there was no sign of an endoleak. At 77 months (Figure 4.3D), the aneurysm sac diameter had grown progressively to 78 mm, and a type IB endoleak was detected. The IEAS was down to 8%, and the SAL had decreased to 0 mm. In addition, the limb was retracted by 7 mm compared with the first postoperative scan.

A second patient was treated for a symptomatic AAA of 123 mm. An Endurant endoprosthesis with right and left limb diameter of 16 mm (Figure 4.4A-D) was deployed. Both AICs were 16 mm, resulting in full expansion of the endograft limbs on the first postoperative CT scan (Figure 4.4B). For the left endograft limb, the ISC was 60% with adequate proximal and distal seal. At 31 months (Figure 4.4C), the FD had increased to 36 mm, thus the endograft limb was retracted by 22 mm. Consequently, the SAL, IEAS, and ISC had decreased significantly, but no endoleak was detected. At 59 months (Figure 4.4D), the limb retracted further by 12 mm, resulting in a confirmed type IB endoleak.

Table 4.5. Change in endograft limb dimensions between the late and first postoperative CT scan of the endoleak and control groups ab

<table>
<thead>
<tr>
<th>Variable</th>
<th>Endoleak (n=15)</th>
<th>Controls (n=21)</th>
<th>P valuec</th>
<th>P valuec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum AAA diameter (mm)*</td>
<td>13 [0–18]</td>
<td>.045</td>
<td>−9 [−13 to 1]</td>
<td>.034</td>
</tr>
<tr>
<td>Iliac diameter (mm)</td>
<td>3 [2–7]</td>
<td>.001</td>
<td>1 [1–3]</td>
<td>.001</td>
</tr>
<tr>
<td>Endograft limb expansion (%)</td>
<td>0 [0–0]</td>
<td>.109</td>
<td>0 [0–13]</td>
<td>.008</td>
</tr>
<tr>
<td>FD (mm)</td>
<td>6 [2–11]</td>
<td>.001</td>
<td>3 [−1 to 4]</td>
<td>.068</td>
</tr>
<tr>
<td>Apposition</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ISC (%)</td>
<td>−42 [−57 to −25]</td>
<td>.002</td>
<td>−5 [−11 to 3]</td>
<td>.063</td>
</tr>
<tr>
<td>SAL (mm)</td>
<td>−10 [−19 to −6]</td>
<td>.001</td>
<td>−3 [−6 to 1]</td>
<td>.014</td>
</tr>
</tbody>
</table>

AAA, abdominal aortic aneurysm; FD, fabric distance; ISC, iliac surface coverage; SAL, shortest apposition length.

*Between the patients from each group (endoleak group: 12, controls: 12)
abData are represented as median [interquartile range].
cP value for difference between late and first postoperative CT scan.
Figure 4.3. Left endograft limb position and apposition in a CIA during follow-up. (A) Preoperative CT scan with ISS. (B) First postoperative CT scan showing the initial apposition. (C) Late CT follow-up on which the type IB endoleak had not yet been identified. Notice the grey area, which is the area where the endograft limb does not have circumferential apposition with the arterial wall. A significant loss of seal is present because of an increase in CIA diameter. (D) CT scan before the reintervention for a type IB endoleak. There appears to be some surface coverage, however that is only on one side of the AIC. Therefore, the SAL is 0 mm, and there is no apposition of the endograft limb. AB, Aortic bifurcation; CIA, common iliac artery; FD, fabric distance; IB, iliac bifurcation; IEAS, iliac endograft apposition surface; ISC, iliac surface coverage; SAL, shortest apposition length. aExpansion is measured at the location of the iliac diameter measurements.

Figure 4.4. Endograft limb position and apposition of a retracting limb. (A) Preoperative CT scan with ISS. (B) First postoperative CT scan showing the initial apposition. Endograft limb expansion is already on 100%. (C) Late CT follow-up on which the type IB endoleak had not yet been identified. Notice that the endograft limb markers (yellow line) has shifted upwards towards the aneurysm sac (ie, the endograft limb is retracting). This is more clearly represented by the increasing FD. Moreover, the endograft limb does not have apposition with the arterial wall (the small grey area) due to the angle of the endograft limb with the CIA. A significant loss of seal is present because of the retraction of the endograft limb. (D) CT scan before the reintervention. The ISC has decreased to 4%, the SAL is merely 2 mm, and the FD increases further. The apposition length is 0 mm (red arrow), and a type IB endoleak is present. AB, Aortic bifurcation; CIA, common iliac artery; FD, fabric distance; IB, iliac bifurcation; IEAS, iliac endograft apposition surface; ISC, iliac surface coverage; SAL, shortest apposition length. aExpansion is measured at the location of the iliac diameter measurements.
DISCUSSION

This study validated CT-applied software for the quantification of expansion, position, and apposition of endograft limbs in the CIA. Interobserver agreement was high for all parameter measurements, with variability similar to measurements in the infrarenal aortic neck.\textsuperscript{13,14}

Adequate distal fixation and seal of the endograft limb in the CIA is essential to prevent type IB endoleak. Seal may be compromised by dilatation of the CIA or by limb retraction.\textsuperscript{4,6-8,12,15-18} Expansion of the endograft limb within the CIA, displacement of the endograft limb, as well as the resulting loss of apposition, can be precisely quantified and visualized with the VIA prototype software.

Full endograft limb expansion was observed in all patients in the complication group and in most of the control group, which was the result of almost no oversizing of the endograft limbs compared with the preoperative CIA diameter (Table 4.1). Oversizing of the endograft limbs by 10\% to 15\% could reduce the risk of type IB endoleak because the radial force will create more stability and seal in the distal landing zone.\textsuperscript{8,12,19} Excessive oversizing may, however, increase the risk of CIA dilatation and fabric infolding.\textsuperscript{12,20} Progressive dilatation of the iliac diameter beyond the endograft limb diameter can lead to detachment of the endograft limb and seal failure. Longer seal zones may better endure progressive dilatation and may protect against seal failure.

It is important to note that there are differences in sealing mechanisms between the limbs of different endograft types. For example, the apposition of a Zenith endograft limb may be smaller than that of an Endurant endograft limb. This study investigates the differences within a patient during follow-up; the first follow-up CT scan of a patient acts as the patient's control scan to compare the apposition with during follow-up. Change in apposition of each patient during follow-up is very relevant. However, the apposition zones of different endograft limbs cannot be directly compared to each other and a one on one comparison should only be performed for the same endograft types.

Significant positional changes were observed on the CT scan before detection of the type IB endoleak. The distance between the fabric and the origin of the hypogastric artery increased significantly for both groups, but the increase in the endoleak group was double the increase in the control group. If endograft limbs in the control group continue to displace, type IB endoleak may also develop in these patients during later follow-up. Therefore, this study is limited regarding the duration on follow-up, and type IB endoleaks may even occur in the control group. Currently, all patients are under strict duplex ultrasound follow-up.

In this study, the seal is represented by a percentage, because it is both intuitive as well as well-comparable within a patient. It also demonstrates the apposition of the
CIA that could have been utilized. Maybe this percentage of coverage can serve as a risk factor for late complications; a larger clinical study will be performed to identify risk factors for late type IB endoleaks. Longer distal seal zones (>15 mm), coverage of at least 70% of the iliac seal zone, and deployment of the endograft limb within 10 mm of the hypogastric artery protect against proximal migration of the endograft limb and type IB endoleak.\textsuperscript{4,6,8,12,21} In this study, however, no significant changes were observed between the endoleak and the control group for seal zone length, CIA coverage, and deployment accuracy on the first postoperative CT scan. This suggests that the 1-month CT scan is good for identifying acute failures (which were not included in this study) and for defining a postoperative baseline for the endograft dimensions. A second postoperative CT scan is essential for detecting changes from this baseline that may precede later seal failure.

An increase in the CIA diameter beyond the endograft limb diameter and retraction of the endograft limb results in loss of apposition, which could be clearly quantified and visualized with the VIA prototype software. Contrary to the control patients, apposition was largely lost in all patients in the endoleak group before the endoleak could be detected. Endograft limb extension to the hypogastric artery could be considered based on loss of apposition, before urgent repair of a repressurized aneurysm is required; however, no clear cutoff values can yet be provided for when to intervene before a clear type IB endoleak is visible.

Hostile iliac anatomy may increase the risk of apposition loss, particularly due to limb retraction. Although hostile anatomy has been investigated extensively in the infrarenal aortic neck and has been associated with endograft migration and type IA endoleak,\textsuperscript{22} a clear definition of hostile iliac seal zone criteria is lacking.\textsuperscript{23,24} Hostile CIA criteria that are associated with distal complications, such as type IB endoleak and limb occlusion, may provide a better understanding of long-term EVAR patency. The AAA volume was not measured in this study. While unfavorable anatomy and implanted devices may influence the risk for type IB endoleak,\textsuperscript{8,12} this study was not designed to find predisposing factors that increase the risk for distal seal failure.

**Limitations**

This study is retrospective with small numbers of patients. A large clinical study with a larger group of patients is needed to identify relevant cutoff values that indicate later seal failure and patients who require preventive reinterventions.

The VIA prototype software is still an investigational product and not yet licensed for clinical use. The dedicated post-EVAR analysis requires about 7 minutes of extra time to draw a centerline and to retrieve and process the coordinates. Similar to preoperative sizing measurements in a vascular workstation, accuracy of dedicated
post-EVAR analysis is limited by the quality of the CT scan and sufficient contrast in the limbs.

**CONCLUSION**

New CT-applied software was introduced to visualize apposition and positional changes of aortic endograft limbs during follow-up. The software demonstrated good-to-excellent interobserver agreement and enabled accurate analysis of post-EVAR endograft limb dimensions. Significant changes in apposition and position were observed on late CT imaging before the CT scan where the diagnosis of type IB endoleaks was set. A larger prospective patient study comparing groups with and without late distal complications is needed to demonstrate whether it can predict type IB endoleaks on a large scale.
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PART II

Outcomes of Endovascular Abdominal Aneurysm Repair (EVAR) in Complex Anatomies