Diffusion-weighted MR imaging of the normal pancreas: Reproducibility and variations of apparent diffusion coefficient measurement at 1.5- and 3.0-Tesla

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**KEYWORDS**

Diffusion-weighted MRI; MR imaging; Apparent diffusion coefficient; Pancreas; Reproducibility assessment

**Abstract**

**Purpose:** To evaluate reproducibility and variations in apparent diffusion coefficient (ADC) measurement in normal pancreatic parenchyma at 1.5- and 3.0-Tesla and determine if differences may exist between the four pancreatic segments.

**Materials and methods:** Diffusion-weighted MR imaging of the pancreas was performed at 1.5-Tesla in 20 patients and at 3.0-Tesla in another 20 patients strictly matched for gender and age using the same b values (0, 400 and 800 s/mm\(^2\)). Two independent observers placed regions of interest within the four pancreatic segments to measure ADC at both fields. Intra- and inter-observer agreement in ADC measurement was assessed using Bland-Altman analysis and comparison between ADC values obtained at both fields using non-parametrical tests.

**Results:** There were no significant differences in ADC between repeated measurements and between ADC obtained at 1.5-Tesla and those at 3.0-Tesla. The 95% limits of intra-observer

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Diffusion-weighted magnetic resonance imaging (DWI) with quantitative measurement of apparent diffusion coefficient (ADC) values has a well-established role in the detection and characterization of a variety of abdominal abnormalities [1–7]. Regarding pancreatic disease, several researchers have demonstrated that DWI with ADC measurement is helpful to detect and further characterize focal pancreatic lesions [8–11] and diffuse pancreatic conditions [12,13]. However, before ADC measurement can be considered as a robust and discriminating tool, the range of ADC values within the normal pancreas as well as their reproducibility should be investigated. In addition, a potential limitation of DWI is that reproducibility in ADC measurement may be affected by the field strength [1].

Several studies have investigated the reproducibility of ADC measurement of many intra-abdominal organs and they found marked variations at both 1.5- and 3.0-Tesla (T) [5,14,15]. By contrast, data reporting the reproducibility of ADC measurement of the pancreas are scarce. A recent study found no significant differences in ADC values of the pancreas between ADC values obtained at 1.5-T and those obtained at 3.0-T [16]. However, this study did not investigate the intra- and inter-observer variability in ADC measurement at each field strength [16]. Another study found no significant differences in ADC measurement of the normal pancreas at 3.0-T but did not make a comparison with results obtained at 1.5-T [15]. Because of limited available results in the literature and possible influence of the field strength on the resulting ADC value and its reproducibility in measurement, a study that addresses these concerns should be done.

Accordingly, we performed this study with two goals in mind. First, we tried to analyze intra- and inter-observer variability in ADC measurement of the pancreas at 1.5- and 3.0-T. Second, we wished to assess possible variations in ADC values among the different pancreatic segments in patients without pancreatic disease.

Materials and methods

Patients

This retrospective, single-center study was approved by our institutional review board and informed consent was waived. From January 2011 through January 2012, our MR imaging database was retrospectively queried to identify all cases of patients referred for abdominal MR imaging at 3.0-T. Patients were selected when they had MR imaging of the abdomen at 3.0-T for conditions unrelated to the pancreas, no visible pancreatic disease and no pancreatic atrophy with fatty replacement at MR imaging, and a DWI examination that entirely covered the pancreas. After review of clinical files, patients with body mass index greater than 25 kg/m^{2}, diabetes, exocrine or endocrine pancreatic dysfunction, cystic fibrosis, chronic hepatic disease, hepatic steatosis, prior history of cancer or systemic chemotherapy were excluded. All selected patients had normal results of laboratory blood tests including serum lipase and glucose levels.

Twenty patients (10 males and 10 females) with a mean age of 47.7 years ± 14.5 years (SD) (range: 19–78 years) who underwent abdominal MR imaging examination at 3.0-T including pancreatic study fulfilled the inclusion criteria. They were further strictly matched for gender and age to 20 patients (10 males and 10 females) with a mean age of 47.7 years ± 14.5 years (SD) (range: 19–78 years) who had abdominal MR imaging examination at 1.5-T during the same period and fulfilled the same inclusion and exclusion criteria.

MR examination protocol

All patients underwent MR imaging examination of the abdomen using a 1.5-T system (Magnetom Avanto, Siemens Healthcare, Erlangen, Germany, running software Syngo MR B15) or a 3.0-T system (Magnetom Verio, Siemens Healthcare, running software Syngo MR B13). High-resolution free-breathing T2-weighted fast spin-echo sequence with respiratory triggering using prospective acquisition correction and three-dimensional volumetric interpolated breath-hold gradient-echo (3D VIBE) sequence before and after intravenous administration of a gadolinium-chelate sequence were obtained in all patients in addition to DWI sequence.

All imaging examinations obtained at 1.5-T were performed using one anterior torso phased-array coil and one posterior phased-array coil with nine channels each. All imaging examinations obtained at 3.0-T were performed using one anterior torso phased-array coil and one posterior phased-array coil with 16 channels each. Patients were imaged in supine position.

DWI was performed with a fat-suppressed single-shot spin-echo echo-planar diffusion-weighted technique in the axial plane with 10 gradient factors (b values = 0, 10, 20, 30, 50, 80, 100, 200, 400 and 800 sec/mm^2) within the same acquisition. The diffusion gradients were applied in three orthogonal directions along the three main axes of the magnet bore. The single-shot EPI readout was preceded by a diffusion-sensitizing block consisting of two 180\degree radiofrequency pulses. Parallel imaging with generalized autocalibrating partially parallel acquisition (GRAPPA) was used with an acceleration factor (or reduction factor) of 2.
All DWI examinations were performed with fat suppression that consisted in a spectral-fat saturation technique. DWI was obtained using a respiratory-triggered acquisition and prior to gadolinium-chelate administration in all patients. DWI protocols used at both fields are described in Table 1.

**Image analysis**

The ADC maps were obtained from the source data using a commercially available workstation (MMWP with the Syngo Software, Siemens Healthcare). ADC values were calculated with three b values, including the $b = 0$, 400 and 800 values sec/mm$^2$, using a mono-exponential fitting algorithm on the basis of ln (SI) as a function of b value, where SI is the signal intensity of the pancreatic segment. Because the $b = 0$ value was included for ADC calculation, the resulting ADC was the ADC total and we did not separate perfusion and true diffusion effects [16].

Two independent observers (one fourth-year resident in radiology, further referred to as reader 1, and one radiologist with 21 years of experience in interpreting abdominal MR images, further referred to as reader 2) placed regions of interest (ROIs) on each pancreatic segment on the diffusion-weighted images obtained with $b = 0$sec/mm$^2$ (Fig. 1). Special care was given to avoid pancreatic vessels, pancreatic ducts and artifacts in ROI placement. Circular ROIs with a minimum size of 100 pixels were placed on each of the four pancreatic segments by each observer. However, ROI sizes varied according to axial dimensions of the pancreatic segment being analyzed. The ROIs were transferred from the $b_0$ images to the ADC maps. ADCs were measured three times by each observer and the three measurements were averaged for each pancreatic segment on DWI examinations obtained at 1.5-T. The same approach was made for ADC measurements at 3.0-T. For the evaluation of intra-observer variability, reader 1 made ADC calculations twice during two different sessions that were separated by a 3-week interval to avoid any recall bias.

The four pancreatic segments were defined as follows: the head was defined as the pancreatic segment located between the superior mesenteric vein and the gastroduodenal artery, that lies to the right of the superior mesenteric artery; the neck (or isthmus) was the thin section between the head and the body of the gland that lies anterior to the confluence of the superior mesenteric vein and splenic vein, which groove its posterior aspect; the body was defined as the longest portion of the pancreas, extending from the neck and passing to the tail, lying to the left of the superior mesenteric vessels; the tail was defined as the final portion of the left pancreas, that lies anterior to the left kidney adjacent to the splenic hilum [17].

**Statistical analysis**

Results of ADC measurements for each pancreatic segment were expressed as medians, first quartiles (q1), third quartiles (q3) and ranges. Intra- and inter-observer agreement in ADC measurements at 1.5- and 3.0-T was determined as mean absolute difference (bias) and 95% confidence interval of the mean difference (limits of agreement) according to the method of Bland and Altman [18] and expressed as percentages of median ADC values. The results of reader 1 were used for assessment of intra-observer variability. Pairwise comparisons of the ADC values obtained by the two observers were made using the Wilcoxon signed rank test; for this comparison, the results of the first ADC measurements of Reader 1 were used. For each pancreatic segment, ADC

<table>
<thead>
<tr>
<th>Table 1</th>
<th>MR Imaging acquisition parameters for two diffusion-weighted sequences obtained at 1.5- and 3.0-Tesla.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Field strength</td>
<td>1.5-Tesla</td>
</tr>
<tr>
<td>MR unit</td>
<td>Magnetom Avanto VB15</td>
</tr>
<tr>
<td>Receiver channels</td>
<td>18</td>
</tr>
<tr>
<td>Gradient strength (mT/m)/maximal gradient slope (T/m/sec)</td>
<td>45/200</td>
</tr>
<tr>
<td>EPI technique</td>
<td>Fat-suppressed single-shot spin-echo echo-planar imaging</td>
</tr>
<tr>
<td>Gradient factors</td>
<td>$b$ values = 0, 10, 20, 30, 50, 80, 100, 200, 400 and 800sec/mm$^2$</td>
</tr>
<tr>
<td>TR (msec)/TE (msec)</td>
<td>1300/52</td>
</tr>
<tr>
<td>Echo spacing (msec)</td>
<td>0.83</td>
</tr>
<tr>
<td>Receiver bandwidth (Hz/pixel)</td>
<td>1.347</td>
</tr>
<tr>
<td>Acquisition time (sec)</td>
<td>300</td>
</tr>
<tr>
<td>Number of axial sections</td>
<td>26</td>
</tr>
<tr>
<td>Echo-planar imaging factor</td>
<td>104</td>
</tr>
<tr>
<td>Respiratory triggering</td>
<td>Yes</td>
</tr>
<tr>
<td>Number of signal averages</td>
<td>2</td>
</tr>
<tr>
<td>Field of view (mm)</td>
<td>340</td>
</tr>
<tr>
<td>Voxel size (mm$^3$)</td>
<td>$2.5 \times 2.5 \times 7$</td>
</tr>
<tr>
<td>Matrix size</td>
<td>$104 \times 128$</td>
</tr>
<tr>
<td>Section thickness (mm)</td>
<td>7</td>
</tr>
<tr>
<td>Intersection gap (mm)</td>
<td>0</td>
</tr>
</tbody>
</table>

TR: repetition time; TE: echo time; EPI: echo-planar imaging; T: Tesla.
values obtained at 1.5-T were compared to those obtained at 3.0-T using the Mann-Whitney test; the results of the first ADC measurements of reader 1 were used for this comparison. ADC values obtained at 1.5-T were compared between segments with the Kruskal-Wallis test for overall comparison and the Wilcoxon signed rank test was used when overall comparison was significant. The same comparison was made with ADC values obtained at 3.0-T.

R version 2.8 (R Foundation, http://www.r-project.org/) was used for statistical analysis. All statistical tests were two-tailed and statistical significance was considered at \( P < 0.05 \).

**Results**

**Intra-observer variability**

The ADC values calculated for the four pancreatic segments during the two repeated measurements of reader 1 at 1.5-T and at 3.0-T are shown in Tables 2 and 3. No significant differences in ADC measurements were found for each of the four pancreatic segments being considered at 1.5-T and 3.0-T.

At 1.5-T, the mean absolute difference (bias) and 95% confidence intervals of the mean difference (limits of agreement) for the head, neck, body and tail were 

\[-0.001 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.013 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.014 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.219 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.008 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.143 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.162 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.192 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.028 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.148 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.203 \times 10^{-3} \text{ mm}^2/\text{s} \]  

respectively. The 95% limits of agreement between ADC values obtained on repeated DWI examinations by the reader 1 were 1% of the mean ADC value for the head, 11% for the neck, 6.7% for the body and 24.2% for the tail. Graphic illustration of these data with Bland-Altman plots is displayed in Fig. 3.

At 3.0-T, the mean absolute difference (bias) and 95% confidence intervals of the mean difference (limits of agreement) for the head, neck, body and tail were 

\[-0.001 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.139 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.137 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.219 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.008 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.143 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.162 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.192 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.028 \times 10^{-3} \text{ mm}^2/\text{s} \]  
\[-0.148 \times 10^{-3} \text{ mm}^2/\text{s} \]

\[-0.203 \times 10^{-3} \text{ mm}^2/\text{s} \]  

respectively. The 95% limits of agreement between ADC values obtained on repeated DWI examinations by the reader 1 were 1% of the mean ADC value for the head, 11% for the neck, 6.7% for the body and 24.2% for the tail. Graphic illustration of these data with Bland-Altman plots is displayed in Fig. 3.

<table>
<thead>
<tr>
<th></th>
<th>First measurement</th>
<th>Second measurement</th>
<th>( P ) value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Head</strong></td>
<td>1.239</td>
<td>1.268</td>
<td>0.7510</td>
</tr>
<tr>
<td></td>
<td>(1.155; 1.455)</td>
<td>(1.125; 1.414)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.802—1.819]</td>
<td>[0.735—1.844]</td>
<td></td>
</tr>
<tr>
<td><strong>Neck</strong></td>
<td>1.311</td>
<td>1.286</td>
<td>0.2043</td>
</tr>
<tr>
<td></td>
<td>(1.107—1.480)</td>
<td>(1.107—1.447)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.725—1.660]</td>
<td>[0.799—1.575]</td>
<td></td>
</tr>
<tr>
<td><strong>Body</strong></td>
<td>1.171</td>
<td>1.175</td>
<td>0.6012</td>
</tr>
<tr>
<td></td>
<td>(1.064; 1.315)</td>
<td>(1.034; 1.353)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.757—1.617]</td>
<td>[0.734—1.523]</td>
<td></td>
</tr>
<tr>
<td><strong>Tail</strong></td>
<td>1.018</td>
<td>.993</td>
<td>0.3317</td>
</tr>
<tr>
<td></td>
<td>(0.946; 1.256)</td>
<td>(0.930; 1.226)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>[0.749—1.663]</td>
<td>[0.785—1.599]</td>
<td></td>
</tr>
</tbody>
</table>

Data are expressed as medians, numbers in parentheses are first quartiles (q1) and third quartiles (q3), numbers in brackets are ranges. Comparisons were made using the Wilcoxon signed rank test.
Figure 2. Intra-observer reproducibility of apparent diffusion coefficient (ADC) measurement ($\times 10^{-3} \text{mm}^2/\text{s}$) at 1.5-T for the four pancreatic segments. Bland-Altman plots of difference of ADC measurements (y-axis) against mean ADC measurement (x-axis), with mean absolute difference (bias) (continuous line) and 95% confidence interval of the mean difference (limits of agreement) (dashed lines).

Figure 3. Intra-observer reproducibility of apparent diffusion coefficient (ADC) measurement ($\times 10^{-3} \text{mm}^2/\text{s}$) at 3.0-T for the four pancreatic segments. Bland-Altman plots of difference of ADC measurements (y-axis) against mean ADC measurement (x-axis), with mean absolute difference (bias) (continuous line) and 95% confidence interval of the mean difference (limits of agreement) (dashed lines).
Table 3  Apparent diffusion coefficient (ADC) values (× 10−3 mm2/s) obtained at 3.0-Tesla from the four pancreatic segments during repeated measurements by the same reader (reader1, intra-observer comparison).

<table>
<thead>
<tr>
<th>Segment</th>
<th>First measurement (q1)</th>
<th>First measurement (q3)</th>
<th>Second measurement (q1)</th>
<th>Second measurement (q3)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>1.286 [0.909—1.883]</td>
<td>1.145 [0.842—1.887]</td>
<td>1.292 [0.842—1.887]</td>
<td>1.154 [0.842—1.887]</td>
<td>0.9702</td>
</tr>
<tr>
<td>Neck</td>
<td>1.300 [0.746—1.643]</td>
<td>1.115—1.454</td>
<td>1.322 [0.725—1.660]</td>
<td>1.071—1.480</td>
<td>0.7369</td>
</tr>
<tr>
<td>Body</td>
<td>1.222 [0.852—1.719]</td>
<td>1.006; 1.374</td>
<td>1.165 [0.792—1.607]</td>
<td>1.005; 1.376</td>
<td>0.6950</td>
</tr>
<tr>
<td>Tail</td>
<td>1.202 [0.936; 1.323]</td>
<td>0.936; 1.323</td>
<td>1.150 [0.798—1.451]</td>
<td>0.966; 1.302</td>
<td>0.1304</td>
</tr>
</tbody>
</table>

Data are expressed as medians, numbers in parentheses are first quartiles (q1) and third quartiles (q3), numbers in brackets are ranges. Comparisons were made using the Wilcoxon signed rank test.

Inter-observer variability

The ADC values calculated for the four pancreatic segments by the two readers at 1.5-T and at 3.0-T are shown in Tables 4 and 5. No significant differences in ADC measurements were found for each of the four pancreatic segments being considered at 1.5- and 3.0-T.

Table 4  Apparent diffusion coefficient (ADC) values (× 10−3 mm2/s) obtained at 1.5-Tesla from the four pancreatic segments during measurements by two independent readers (inter-observer comparison).

<table>
<thead>
<tr>
<th>Segment</th>
<th>Reader 1 (q1)</th>
<th>Reader 1 (q3)</th>
<th>Reader 2 (q1)</th>
<th>Reader 2 (q3)</th>
<th>P value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head</td>
<td>1.239 [0.802—1.819]</td>
<td>1.149 [0.808—1.829]</td>
<td>1.228 [0.808—1.829]</td>
<td>1.145 [0.808—1.829]</td>
<td>0.2702</td>
</tr>
<tr>
<td>Neck</td>
<td>1.311 [0.725—1.660]</td>
<td>1.073—1.477</td>
<td>1.256 [0.728—1.607]</td>
<td>1.071—1.480</td>
<td>0.0739</td>
</tr>
<tr>
<td>Body</td>
<td>1.171 [0.757—1.617]</td>
<td>1.060; 1.337</td>
<td>1.170 [0.758—1.609]</td>
<td>1.060; 1.337</td>
<td>0.5879</td>
</tr>
<tr>
<td>Tail</td>
<td>1.018 [0.749—1.663]</td>
<td>0.949; 1.259</td>
<td>1.015 [0.779—1.641]</td>
<td>0.949; 1.259</td>
<td>0.6547</td>
</tr>
</tbody>
</table>

Data are expressed as medians, numbers in parentheses are first quartiles (q1) and third quartiles (q3), numbers in brackets are ranges. Comparisons were made using the Wilcoxon signed rank test.

At 1.5-T, the mean absolute difference (bias) and 95% confidence intervals of the mean difference (limits of agreement) for the head, neck, body and tail were 0.018 × 10−3 mm2/s [−0.110 × 10−3—0.146 × 10−3], 0.018 × 10−3 mm2/s [−0.09 × 10−3—0.106 × 10−3], −0.005 × 10−3 mm2/s [−0.084 × 10−3—0.074 × 10−3] and 0.003 × 10−3 mm2/s [−0.015 × 10−3—0.019 × 10−3], respectively. The 95% limits of agreement between ADC values obtained by the two readers were 13.8% of the mean ADC value for the head, 14% for the neck, 4.2% for the body and 1.9% for the tail. Graphic illustration of these data with Bland-Altman plots is shown in Fig. 4.

At 3.0-T, the mean absolute difference (bias) and 95% confidence intervals of the mean difference (limits of agreement) for the head, neck, body and tail were −0.001 × 10−3 mm2/s [−0.148 × 10−3—0.146 × 10−3], −0.001 × 10−3 mm2/s [−0.021 × 10−3—0.019 × 10−3] and 0.026 × 10−3 mm2/s [−0.020 × 10−3—0.025 × 10−3], respectively. The 95% limits of agreement between ADC values obtained by the two readers were 8% of the mean ADC value for the head, 8% for the neck, 25% for the body and 22.5% for the tail. Graphic illustration of these data with Bland-Altman plots is shown in Fig. 5.

Comparison of apparent diffusion coefficient values at 1.5- and 3.0-T

For each pancreatic segment, ADC values obtained at 1.5-T were similar to those obtained at 3.0-T (head: 1.239 × 10−3 mm2/s vs. 1.286 × 10−3 mm2/s, P=0.8666; neck: 1.311 × 10−3 mm2/s vs. 1.300 × 10−3 mm2/s, P=0.9405; body: 1.171 × 10−3 mm2/s vs. 1.222 × 10−3 mm2/s, P=0.6542; tail: 1.018 × 10−3 mm2/s vs. 1.202 × 10−3 mm2/s, P=0.1169) (Tables 4 and 5) (Fig. 6).
Figure 4. Inter-observer reproducibility of apparent diffusion coefficient (ADC) measurement ($\times 10^{-3}$ mm$^2$/s) at 1.5-T for the four pancreatic segments. Bland-Altman plots of difference of ADC measurements (y-axis) against mean ADC measurement (x-axis), with mean absolute difference (bias) (continuous line) and 95% confidence interval of the mean difference (limits of agreement) (dashed lines).

Figure 5. Inter-observer reproducibility of apparent diffusion coefficient (ADC) measurement ($\times 10^{-3}$ mm$^2$/s) at 3.0-T for the four pancreatic segments. Bland-Altman plots of difference of ADC measurements (y-axis) against mean ADC measurement (x-axis), with mean absolute difference (bias) (continuous line) and 95% confidence interval of the mean difference (limits of agreement) (dashed lines).
Discussion

The results of our study show that ADC measurements within the four pancreatic segments are reproducible on both an intra- and inter-observer basis. Our data may serve as a reference with respect to the limits of error in ADC measurement for future studies involving DWI of the pancreas. It may be reasonably hypothesized that this will be increasingly done to help detect and characterize pancreatic abnormalities.

We have evaluated the reproducibility of ADC measurement on both an intra- and inter-observer basis. The 95% limits of agreement between ADC values obtained on repeated measurements ranged from 1% to 24.2% for intra-observer variability and from 4.2% to 25% for inter-observer variability. These results did not substantially differ at 1.5-T and 3.0-T. However, we identified the pancreatic tail as the segment that showed the greatest range of variations in reproducibility of ADC measurement.

Recent studies have evaluated the value of ADC measurement for discriminating between malignant and benign pancreatic conditions and other have determined to what extent ADC measurements help grade the severity of chronic pancreatitis [10–12]. In this regard, some authors found

**Table 6** $P$ values of paired comparisons of apparent diffusion coefficient (ADC) values obtained from the four pancreatic segments at 1.5- and 3.0-Tesla.

<table>
<thead>
<tr>
<th></th>
<th>1.5-Tesla</th>
<th>3.0-Tesla</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head vs. neck</td>
<td>0.925</td>
<td>0.99</td>
</tr>
<tr>
<td>Head vs. body</td>
<td>0.430</td>
<td>0.51</td>
</tr>
<tr>
<td>Head vs. tail</td>
<td>0.039</td>
<td>0.41</td>
</tr>
<tr>
<td>Neck vs. body</td>
<td>0.430</td>
<td>0.69</td>
</tr>
<tr>
<td>Neck vs. tail</td>
<td>0.053</td>
<td>0.51</td>
</tr>
<tr>
<td>Body vs. tail</td>
<td>0.430</td>
<td>0.92</td>
</tr>
</tbody>
</table>

Comparisons were made using the Wilcoxon signed rank test.

At 1.5-T, a significant difference in ADC values was found between the four pancreatic segments ($P = 0.014$) (Fig. 7). This was due to a lower median ADC value at the pancreatic tail by comparison with the head (Table 6). Conversely, at 3.0-T, no significant differences in ADC values were found between the different pancreatic segments ($P = 0.16$).
that pancreatic tumors have ADC values significantly lower than that of normal pancreatic parenchyma [11]. However, these studies did not take into account the limits of margin error for determining the cut-off values that helped discriminate between the different conditions being compared. Our study shows that ADC measurement of the normal pancreatic parenchyma is subjected to variations so that absolute differences in ADC values should be interpreted with caution.

Previous studies have reported ADC values of the normal pancreas using parallel imaging at 1.5- and 3.0-T and marked variations were found among studies. Using a free-breathing technique without respiratory triggering and that included $b_0$ for ADC calculation ($0 \text{ s/mm}^2 \leq b \leq 800 \text{ s/mm}^2$), Rosenkrantz et al. found mean ADC values of $1.26 \times 10^{-3} \text{ mm}^2/\text{s}$ at 1.5-T and of $1.39 \times 10^{-3} \text{ mm}^2/\text{s}$ at 3.0-T for normal pancreatic parenchyma, which are close to the ADC values we found [16]. Conversely, using a breath-hold technique at 1.5-T with two $b$ values of 50- and 500-mm$^2$/s, Wiggermann et al. found a very low mean ADC value of $0.17 \times 10^{-3} \text{ mm}^2/\text{s}$ [10]. Using a free-breathing technique at 1.5-T and three $b$ values of 0-, 500- and 1000-mm$^2$/s, another group of researchers found ADC values ranging from $1.59 \times 10^{-3} \text{ mm}^2/\text{s}$ to $1.68 \times 10^{-3} \text{ mm}^2/\text{s}$ for normal pancreatic parenchyma, with no significant differences between the three pancreatic segments (head, body and tail) [19]. It has been assumed that variations in ADC values may be the results of differences in patient population, imaging sequences, inclusion or not of specific $b$ values for ADC calculation, or other technical parameters [19,20]. In accordance with Dale et al., we did not find any difference in pancreatic ADC value between ADC values obtained at 1.5-T and those obtained at 3.0-T [21]. In addition, our results were within the ranges of those reported by these researchers [21].

Calculation of ADC values may be influenced by the inclusion of low $b$ values as explained by the intravoxel incoherent motion (IVIM) theory [22,23]. For a given ROI, we obtained a total ADC value that consisted in the added results of diffusion and microperfusion effects. The effect of microperfusion on the resulting total ADC is more prominent using low $b$ values [24].

In our study, we found that the pancreas showed homogeneous distribution of ADC values among the four segments at 3.0-T. This is consistent with the results of Braithwaite et al. [15]. Conversely, we found significant differences between segments at 1.5-T, due to a lower ADC value of the tail by comparison with the other three segments. A similar result was found by Yoshikawa et al. who found lower ADC value for the pancreatic tail ($1.65 \times 10^{-3} \text{ mm}^2/\text{s} \pm .34$) by comparison with the head ($1.82 \times 10^{-3} \text{ mm}^2/\text{s} \pm .40$) and the body ($1.81 \times 10^{-3} \text{ mm}^2/\text{s} \pm .41$) [25]. Yoshikawa et al. have advocated possible differences in surrounding tissues as a cause for lower ADC values at the pancreatic tail at 1.5-T [25]. However, there is currently no plausible cause that may explain the difference for ADC values of the tail between 1.5- and 3.0-T.

A few studies have investigated the degree of reproducibility of ADC measurement in the pancreas. The high degrees of reproducibility may be due in part to the fact that, except for the tail, the pancreas is not affected by respiratory motion. Conversely, a variability of 20% in ADC exists when measurements are obtained from abdominal organs that are subjected to diaphragmatic movements during respiration such as the left lobe of the liver [16].

Our study has several limitations. One is that the results of ADC values we obtained may not reflect the variability of ADC values that can be encountered in a more general population because patients with fatty replacement of pancreatic tissue or pancreatic atrophy were excluded or because of the specific age category of our population [26–28]. We agree that different values might have been obtained with a less restricted patient population. However, the goal of our study was to assess reproducibility of ADC measurement of the normal pancreas. A second limitation is that DWI examinations at 1.5-T and 3.0-T were obtained on two different groups of patients thus potentially introducing a bias for further comparison. We agree that a comparison of ADC values obtained at 1.5- and 3.0-T on the same group of patients would have produced a more meaningful study. However, our two groups of patients were built with patients who were strictly matched for age and gender and patients with a body mass index greater than 25 kg/m$^2$ were excluded. In addition, none of them had pancreatic disease, thus limiting this potential bias. A third limitation is that we used 10 $b$ factors for DWI but only 3 $b$ values were obtained for ADC calculation so that we only calculated ADC total. We agree that further studies should be done to address this concern and that the IVIM model should be applied to evaluate the reproducibility of perfusion fraction (f) and that of the perfusion free diffusion parameter (D) in the normal pancreatic parenchyma [29,30]. Similarly, further studies should be done to investigate at what extent the number of $b$ values may affect the reproducibility of ADC measurement [1,5].

Conclusion

In conclusion, we found that ADC measurement of the normal pancreatic parenchyma conveys acceptable degrees of intra- and inter-observer variability. However, the 95% upper and lower limits of agreement are subjected to variations that may act as confounders when using ADC values as discriminating tool. This should be kept in mind when ADC measurement is used for characterizing pancreatic disease or grading the severity of chronic pancreatitis.

**KEY POINTS**

1. Pancreatic ADC measurement conveys high degrees of intra- and inter-observer reproducibility.
2. Pancreatic segments have similar ADC values at 1.5- and 3.0-Tesla.
3. The 95% limits of intra-observer agreement of ADC measurement are 2.3%–22.7% at 1.5-Tesla and 1%–24.2% at 3.0-Tesla.
4. The 95% limits of inter-observer agreement of ADC measurement are 1.9%–14% at 1.5-Tesla and 8%–25% at 3.0-Tesla.

Disclosure of interest

The authors declare that they have no conflicts of interest concerning this article.
References


