Comparison of assessment techniques for CT scanner spatial resolution measurement

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Why assess spatial resolution?

• Ability to visualise small objects governed by the spatial resolution of an imaging system
• CT generally prioritises depiction of low contrast features
  – Able to see attenuation differences of approx 1%
  – Typical spatial resolution of ~6-8 lp/cm
• Some CT applications demand high spatial resolution
  – Bone and lung imaging in particular
  – CT scanner typically has limiting spatial res. of 12-20+ lp/cm
• Need to be able to assess suitability for imaging task
Resolution measures

- Limiting visual resolution
  - Given in lp/cm, cycles/cm or detail size in mm
- Modulation transfer function
  - Percentage transfer of spatial information from object to image over range of frequencies

![Graph showing MTF (Modulation Transfer Function) with frequency on the x-axis and MTF (%) on the y-axis. The graph shows that low frequency has nearly 100% transfer, while higher frequency has nearly 0% transfer.]

Low frequency: nearly 100% transfer
Higher frequency: nearly 0% transfer
Methods for measurement (1)

- Subjective techniques
  - Limiting resolution using line pairs etc.
  - Commonly used, but have limited accuracy and repeatability
Methods for measurement (2)

- **Objective techniques**
  - Indirect method using line pairs
    - Droege and Morin, can be measured at scanner console
  - Point sources e.g. metal wires and beads
    - Point spread function measured
  - ‘Edge’ method, currently used by ImPACT
    - CT number change of Teflon edge in water measured
• Measure CT# and SD of background (bg) and max CT#
• \( M_0 \) = Mean of bg and max CT#
• \( N \) = Mean noise
  = \( \sqrt{bg^2 + \text{max CT#}^2} \) SD
• Measure SD of each bar pattern

\[
MTF(f) = \frac{\sqrt{2}}{4\pi} \frac{\sqrt{SD(f) - N}}{M_0}
\]
Point sources

- Wire or bead on uniform background
  - Recon with small field of view, FT(PSF) -> MTF
Edge method

- Edge spread function measured
  - Angled edge oversamples ESF
Edge method (2)

- Differentiate ESF -> PSF
  - FT(PSF) -> MTF

![Graph showing CT number vs position and MTF vs frequency](image)
Results compared

- Results for the same scanner using a routine filter, showing each analysis method
Issues with bead, wire and edge

- Phantom alignment for edge and wire
- Noise in MTFs
- Bead and wire contrast – noise in MTFs
- Background subtraction for wire and edge
- Asymmetric edge spread functions
- Overshoot of PSF with edge method
Phantom alignment

- Wire and edge phantoms need alignment along z-axis
  - Misaligned phantoms blur point or edge
  - Following results show effect of tilting gantry by up to 3°

<table>
<thead>
<tr>
<th>Angle</th>
<th>MTF_{50}</th>
<th>MTF_{10}</th>
<th>MTF_{2}</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>6.2</td>
<td>8.7</td>
<td>10.0</td>
</tr>
<tr>
<td>0.5°</td>
<td>6.2</td>
<td>8.9</td>
<td>10.3</td>
</tr>
<tr>
<td>1°</td>
<td>6.1</td>
<td>8.8</td>
<td>10.1</td>
</tr>
<tr>
<td>1.5°</td>
<td>6.1</td>
<td>8.7</td>
<td>10.1</td>
</tr>
<tr>
<td>2°</td>
<td>6.3</td>
<td>8.9</td>
<td>10.2</td>
</tr>
<tr>
<td>3°</td>
<td>6.1</td>
<td>8.6</td>
<td>9.9</td>
</tr>
</tbody>
</table>
Noise in MTFs

- Edge method gives noisier MTFs than direct PSF methods
  - Differentiated ESF is noisier than direct PSF measurements
  - Worse for sharp filters
- Can be reduced using multiple images
Bead and wire contrast – noise in MTFs

- Wire contrast independent of slice width
- Bead contrast depends on slice width
- Ideally want high contrast without saturating CT# range
  - Best way to consistently achieve this is with a wire
Background subtraction for wire and edge

- MTF is normalised to value at 0 frequency (DC value)
  - Correct background subtraction is important. Following example uses different methods, giving b/g values 86-90 HU
Asymmetric ESFs

- Edge spread function theoretically differentiates to give PSF
  - In practice, the ESF is not symmetric due to non-linear effects (e.g. beam hardening, bone artefact reduction)
Under/overshoot

- Undershoot in PSF from ‘edge enhancing’ algorithms different for edge and point methods
  - More undershoot seen in edge PSF → overshoot in MTF
  - Needs further investigation
Conclusions

• An objective method for resolution assessment is essential
• Point techniques seem to produce better results than edge
  – Less noise in MTF
  – Less prone to other problems
• Bead and wires each have their advantages
  – Beads have simpler alignment
  – Wires offer constant contrast
• ImPACT will assess resolution in future with a new 0.1 mm wire phantom (100 mm Ø, 60mm long cylinder, ~60 HU)
<table>
<thead>
<tr>
<th>Method</th>
<th>Pros</th>
<th>Cons</th>
</tr>
</thead>
<tbody>
<tr>
<td>Droege and Morin</td>
<td>Can be assessed at console</td>
<td>Poor accuracy</td>
</tr>
<tr>
<td>Edge</td>
<td>Multiple images per rotation</td>
<td>Noisy MTF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Potential asymmetric ESF</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Careful alignment required</td>
</tr>
<tr>
<td>Bead</td>
<td>Can assess x, y and z resolution.</td>
<td>Contrast a function of slice width</td>
</tr>
<tr>
<td></td>
<td>No alignment required</td>
<td></td>
</tr>
<tr>
<td>Wire</td>
<td>Constant contrast</td>
<td>More careful alignment needed</td>
</tr>
<tr>
<td></td>
<td>Multiple images per rotation</td>
<td></td>
</tr>
</tbody>
</table>
Correction for finite point size

- Wire and bead methods use a theoretical delta impulse
  - In fact this has a finite size (in our phantoms 0.18 – 0.28 mm)
- Small correction is made to MTF curves due to this
  - $\text{MTF}_{\text{measured}} = \text{MTF}_{\text{system}} \times \text{MTF}_{\text{point}}$
  - Bessel function for a wire, more complicated for bead