Artifacts in CT

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Definition

- Artifacts
  - Artificial structures, which deviate from reality, in images
  - Artificially made (Latin: arte factum)
  - Visualization in images as a result of the systematic discrepancy b/w CT# & true atten. coeff.

- What is imaged correctly or artificially produced?
  - Experience
  - Knowledge of the system’s artifact behavior & understanding physics behind it

- Ideality
  - High dose & high photon counts
  - Monochromatic x-ray beam
  - Infinite detector resolution & perfect detectors
  - No motion
  - No scatter
Why in CT?

- CT is \textit{vulnerable} to artifacts
  - Image reconstruction assumes that the measurements are \textit{consistent}
  - (Filtered) backprojection with \textit{inconsistent} measurements results in artifacts

- Artifacts are most pronounced close to the site of their origin, but they can affect the image at greater distances from this site by the physical nature of CT

Monochromatic; homogeneous

\[ I(u) = I(0)e^{-\mu_s} \]

Monochromatic; heterogeneous

\[ I(u) = I(0)e^{-\int_s \mu(s)ds} \]

Polychromatic; heterogeneous

\[ I(u) = \int_{0}^{E_{\text{max}}} I_0(E)e^{-\int_s \mu(E,s)ds} dE \]

\[ p(u) = -\ln \frac{I(u)}{I(0)} = \int_s \mu(s)ds \]
Artifact appearance (Types)

- **Streaking**
  - Inconsistency in a single measurement

- **Shading**
  - Group of channels or views deviating gradually from the true measurement

- **Rings**
  - Errors in an individual detector malfunction (or calibration)

- **Distortion**
  - Helical reconstruction

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Important causes of CT artifacts

- Patient movement
- Beam hardening
- Scattered radiation
- Partial volume effects
- Metallic implants
- Sampling errors
- Patient exceeding the limits of the field of measurement (FOM)
### Category

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### Beam hardening

- Attenuation of a broad **polychromatic** x-ray spectrum
  - Energy, object type, projection direction
  - Variable increases in the mean energy of the spectrum
    - $\mu$ varies w/ the projection direction, raising inconsistent data
  - e.g. Houndsfield bar (‘hypodense’ dark zones/streaks) b/w the petrous bones
- What happens w/ a **monochromatic** x-ray beam?
- **Cupping artifacts**
  - Attenuation thru thick uniform region

- **Streaks & dark bands**
  - Shown b/w two dense objects in very heterogeneous regions
  - For two diff't directions, less hardened thru one of the objects than thru both objects
  - Usually bony regions & scans w/ a contrast medium
• **Correction**
  - **Filtering**
    - Pre-harden the beam before it passes thru the patient
    - Bowtie filter hardens the edges of the beam, which will pass thru the thinner parts of the patients
  - **Calibration**
    - Capping artifact due to overcorrection (mismatch b/w uniform phantom & patient anatomy)
    - Difficult to correct simultaneously for water, bone, & contrast medium
  - **Iterative correction algorithm**
    - Minimize blurring of the bone/soft tissue interface
    - Reduce the dark bands in nonhomogeneous regions

![Images of CT scans](image)

**Partial volume**

- **(2D) Transversal** partial volume effect
  - Blurring of the details at the object boundary due to the partial overlap of object structures on the detector elements
  - Nonlinear characteristics
    \[ \text{Measurement} - \ln(\alpha l(x_1) + (1 - \alpha)l(x_1)) < -\ln(\alpha l(x_1)) - \ln((1 - \alpha)l(x_1)) \text{ True atten.} \]
    - Underestimate the attenuation ⇒ **inconsistent** measurements for rays passed from object boundaries
  - Sometimes regarded as the sampling artifact

![Graphs and diagrams](image)
- (3D) **Longitudinal** or **axial** partial volume artifacts
  - Restricted slice thickness $\Delta z$

  ![CT-slices](image)

  ![axial reconstruction 1](image)
  ![axial reconstruction 2](image)

  ![Streak artifacts](image)

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**Photon starvation**

- **Streaking** artifacts in highly attenuating areas
  - Measurements of insufficient photons, resulting in very noisy projections
  - **Filtered** backprojection magnifies the noise, resulting in streaks in the image

- Correction
  - Tube current modulation
  - Adaptive filtering (software)
    - Smooth the noisy attenuation profile before recon

  ![Low mA](image)
  ![High mA](image)

  ![Noisy due to insufficient photon statistics](image)
Noisy sonogram (i.e. inconsistent measurement) gives rise to streaks

- FBP with inconsistent projection values due to scattered radiation results in streak artifacts
  - Scatter contribution to the measured intensity profile contains very little high-spatial frequencies
  - Attenuation of a particular beam is underestimated due to the scattered photons

Scatter

Mobile CT scanner Philips Tomoscan M
Undersampling

- Misregistration of information relating to sharp edges & small objects
- View aliasing
  - Fine stripes radiating from the edge of (but a distance from) a dense structure
  - Due to not enough view samples (i.e. the number of projections) per rotation

Ray aliasing

- Stripes & ringing close to the structure sharp edges
  - Badly approximated sharp edge in a projection
  - High-frequency damped oscillation around the edge
  - Backprojection along the line tangent to the edge in the image (aliasing artifacts)
- Due to not enough detector samples (i.e. the number of detector elements) per projection
  - Quarter-detector shift
  - Flying focal spot
Metal artifacts

- **Polychromatic** x-ray beam-hardening effect due to metals
  - \[ PE \propto \frac{Z^4}{E^3} \]
  - Incomplete attenuation profiles
  - Overranging in sinogram
- (Plus) Higher SPR, causing a lower SNR in the metal shadow
- (Plus) Partial volume effect (due to sharp-edged metal implant objects)
- (Plus) Aliasing
- (Plus) FBP
  - Inconsistencies in the integral attenuation values appear along the respective x-ray path of the backprojection under the diverse angles

- Limitation of the *interpolation* correction
  - Remove streaking distant from the metal
  - Remain a loss of detail around metal-tissue interface (regions of diagnostic interest)

- Statistical reconstruction
  - System matrix that models the physical x-ray absorption process
    - Each row represents a *weighted* single x-ray beam running through the measurement volume
  - A priori knowledge of the statistical distribution of photon counts
Motion artifacts

- Misregistration artifacts
- (2D) Streaks, blurring (shading), and ghost images in FBP due to inconsistencies in the raw data

- Streaks b/w high contrast edges & x-ray tube position
- (3D) Mismatch of the size and position of objects in consecutive slices

Truncation

- Incomplete projections
- Incomplete information relating to the field of measurement (FOM) & streaking or shading artifacts

The patient's arms down but outside the scanning field: Their presence in some views during scanning leads to severe streaking artifacts
Electronic artifacts

- Circular ring artifacts due to a detector channel failure (defective/miscalibrated channels)
  - Outside the tangent circle: defective image due to reconstruction artifacts
  - Inside the tangent circle: almost artifact-free
- **Noise**
  - Poisson noise due to the statistical error of low photon counts
  - Random thin bright & dark streaks along the direction of greatest attenuation
  - $\sigma_{\text{Poisson}} \propto \sqrt{1/(\Delta z \times \text{mAs})}$, but tradeoff b/w noise & resolution

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**Pelvic CT**

**Head CT**

**Modified W/L setting**

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**60 mA, 120 kVp, $\Delta z = 5 \text{ mm}$**

**440 mA (x7.3 higher dose & x2.7 less noise)**
Model-based iterative reconstruction

- Find the most probable image given:
  - Relationship b/w the image & the projection data
  - Prior distribution images (often assuming smoother images are more probable)

- Optimization problem
  - With noisy projection data, there is a wide range of different images that are consistent w/ the measured projection data
  - Prior distribution of images directs the iterative reconstruction to pick a smoother image out of the range of possible images

- Key role of MBIR is to attempt to generate a smooth image while preserving edges
  - Tradeoff b/w smoothness & edge-preservation

- Noise & image quality are decoupled:
  - As the dose is reduced, the noise increases only slightly, but resolution worsens!
  - New artifacts may be introduced at very low dose levels; different noise texture from the FBP
    - Called a "plastic" appearance
Cone-beam effect

- Similar to the artifacts by longitudinal partial volume
- More pronounced for the outer detector rows
- Worse with increasing cone angle

More about beam hardening & scatter

- **Beam hardening** & scatter are different mechanisms that both produce dark streaks between two high attenuation objects, such as metal, bone, & contrast medium
- They can also produce dark streaks along the long axis of a single high attenuation object
- For highly attenuated x-ray beams, beam hardening & scatter both cause more photons to be detected than expected, resulting in dark streaks along the lines of greatest attenuation
- **High-pass filter** (in FBP) exaggerates differences between adjacent detector elements, producing bright streaks in other directions
- **DE-CT** can reduce beam hardening, but not scatter
Flat-panel CBCT

- Dedicated applications
  - Intervention, maxillofacial exams, breast, small-animal imaging
- Characterized by a demand for high spatial resolution
- Limitations
  - Low frame rates
  - Small FOM ($\phi < 25$ cm)
  - Inhomogeneities in periphery
  - Low dose efficiency (i.e. DQE) & dynamic range of flat-panel detectors
  - Poor soft-tissue contrast (& other image qualities)

- CBCT with an FPD with the performance of isotropic spatial resolution (0.14 mm)

  Spherical tumor phantom with a radius of 2 mm

  Focal spot of 0.4 mm; pixel pitch of 0.184 mm
- Typical-parameter comparison

<table>
<thead>
<tr>
<th></th>
<th>MDCT</th>
<th>CBCT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tube voltage</td>
<td>80–140 kVp</td>
<td>50–125 kVp</td>
</tr>
<tr>
<td>Tube current</td>
<td>10–1000 mA</td>
<td>10–1000 mA</td>
</tr>
<tr>
<td>X-ray power</td>
<td>20–120 kW</td>
<td>10–80 kW</td>
</tr>
<tr>
<td>Focal-spot size</td>
<td>0.6–1.2 mm</td>
<td>0.3–0.8 mm</td>
</tr>
<tr>
<td>Rotation time</td>
<td>0.27–1 s</td>
<td>5–20 s</td>
</tr>
<tr>
<td>Detector elements</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in fan direction</td>
<td>512–1024</td>
<td>512–2500</td>
</tr>
<tr>
<td>in z-direction</td>
<td>64</td>
<td>512–2500</td>
</tr>
<tr>
<td>Field of measurement</td>
<td></td>
<td></td>
</tr>
<tr>
<td>in fan direction</td>
<td>500 mm</td>
<td>100–250 mm</td>
</tr>
<tr>
<td>in z-direction</td>
<td>40 mm</td>
<td>100–250 mm</td>
</tr>
<tr>
<td>Min. slice thickness</td>
<td>0.5–0.7 mm</td>
<td>0.1–0.3 mm</td>
</tr>
<tr>
<td>Scintillator/Thickness</td>
<td>Gd₂O₂S/1.0–1.4 mm</td>
<td>CsI:Tl/0.4–0.8 mm</td>
</tr>
<tr>
<td>Data rate</td>
<td>≤ 1,000 MB/s</td>
<td>≤ 60 MB/s</td>
</tr>
<tr>
<td>Projection rate</td>
<td>1,000–5,000 fps</td>
<td>5–80 fps</td>
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</table>

- Is it true that the dose used in dental CBCT is lower than clinical CT?

**Homogeneity test**

**Low-contrast resolution test**

**Spatial resolution test**
- Metal artifact reduction w/ the improvement of low-contrast visibility close to the implant.

**Interventional imaging**

**Intraoperative imaging**

- Scatter
- Truncation
- Misalignment
- Short-scan approach using a smaller detector w/ offset to the isocenter
  - Central region: $2\pi$ scan
  - Peripheral region: $\pi + \phi$
  - Ring artifact due to the abrupt transition b/w the two regions

- Cone-beam divergence
  - Aliasing (undersampling) artifact as appeared as line patterns

Line patterns diverging from the center towards the periphery
MBIR

Image = arg max \( L(p, Ax) - \beta R(x) \)

Statistical, ML: \( L(p, Ax) = \ln p(x) \)
Data fidelity, LS or WLS: \( L(p, Ax) = \|Ax - p\|^2 \)

\[ R(x) = \sum_j \sum_k \psi(x_j - x_k) \]

Penalty strength
Penalty or prior ('regularization')
Measured projections

FBP Siemens SAFIRE