The Halo-Artifact in $^{68}\text{Ga}$-PSMA-PET/MR: Studies Using Phantom and Clinical Data

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Motivation

- **Prostate-specific membrane antigen (PSMA)**
  - PET targeting PSMA is used to detect recurrent prostate cancer

- **$^{68}$Ga-PSMA imaging**
  - Key application for hybrid PET/MR imaging?

- **Photopenic artifacts (‘halo’)**
  - May impair PET image quality
Aim

- Investigate the halo-artifact in $^{68}$Ga-PSMA PET/MR
  - performing phantom measurements.
  - evaluating clinical data.
- Deduce guidelines which help to avoid the occurrence of halo-artifacts.
- Provide workaround techniques effectively reducing the size of the halo-artifact.
Devices and Software

• Devices
  – Siemens Biograph mMR (model number 2008)
  – Siemens Biograph mCT (model number 1104)

• Software
  – Siemens e7tools offline software package
    » mMR: version VA20
    » mCT: version VG40

• Reconstruction
  – Ordinary-Poisson OSEM
    » Accounting for normalization, randoms, scatter, and attenuation
    » $N_{\text{iter}} = 3$
    » $N_{\text{sub}} = 21$
$^{18}$F-FDG vs. $^{68}$Ga-PSMA

**Without Scatter Correction**

- **$^{18}$F-FDG**
  - 248 MBq
  - 85 min p.i.

- **$^{68}$Ga-PSMA**
  - 144 MBq
  - 104 min p.i.
\( ^{18}\text{F-FDG} \) vs. \( ^{68}\text{Ga-PSMA} \)

With Scatter Correction

\( ^{18}\text{F-FDG} \)

- 248 MBq
- 85 min p.i.

\( ^{68}\text{Ga-PSMA} \)

- 144 MBq
- 104 min p.i.
Single Scatter Simulation (SSS)$^1$

- Scatter estimation is based on SSS
- **Relative** version
  - Estimated scatter is scaled to fit the ‘scatter tails’
- **Absolute** version
  - Estimated scatter is intrinsically scaled
- Default parameters
  - No prompt gamma correction (PGC) applied
  - Maximum scatter fraction MaxSF = 75 %
  - …

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Single Scatter Simulation (SSS)

Absolute vs. Relative SSS

Absolute SSS

Relative SSS

[kBq/mL]

0.0 0.6
Single Scatter Simulation (SSS)  
Prompt Gamma Correction (PGC)

• **Prompt gammas**
  - within coincidence timing window
  - may fall within energy acceptance window
  - may produce valid coincidence events
  - result in an approximately homogeneous background activity distribution

• **Prompt gamma correction**\(^1,2\)
  - Include estimation of prompt gamma distribution into scatter correction
  - Reduces scatter overestimation
  - Has been shown to reduce the halo around the kidneys in \(^{68}\text{Ga-PSMA-PET/CT}\)\(^2\)

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Single Scatter Simulation (SSS)

Maximum Scatter Fraction (MaxSF)

- MaxSF gives the maximum allowed scatter-to-primary ratio
- Default value: $\text{MaxSF} = 75\%$
- Typical scatter fraction in whole-body PET/MR scan: $\text{SF} \approx 30-50\%$

- Does decreasing MaxSF from 75% to 40% reduce the halo without introducing new artifacts?

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Phantom Experiments

• Dedicated pelvis phantom\(^1\)
  – Background: Plastic box filled with water (\(\approx 11\) L)
  – Bladder: Bladder insert filled with water (\(\approx 80\) mL)

• Data acquisition
  – \(10^7\) events acquired during each measurement
  – Attenuation and scatter correction based on CT-derived attenuation map (plastic box not visible in MR-based attenuation map)

Phantom Experiments

$^{68}$Ga vs. $^{18}$F-FDG

- $^{68}$Ga or $^{18}$F-FDG
- Administered activity
  - Bladder: 30.0 MBq
  - Background: 5.3 MBq
- Resulting organ-to-background ratio: OBR ≈ 800

- Scan with mMR and mCT
- Use absolute SSS
- No PGC
- MaxSF = 75%

![Image of $^{68}$Ga and $^{18}$F-FDG scans](Image)
Phantom Experiments

Reducing MaxSF

• $^{68}$Ga or $^{18}$F-FDG
• Administered activity
  – Bladder: 30.0 MBq
  – Background: 5.3 MBq
• Resulting organ-to-background ratio: $OBR \approx 800$

• Scan with mMR
• Use absolute SSS
• No PGC
Phantom Experiments

Dual Tracer Approach

- **Background:** $^{68}\text{Ga}$ (33 MBq, $T_{1/2} = 68$ min)
- **Bladder:** $^{18}\text{F-FDG}$ (23 MBq, $T_{1/2} = 110$ min)
- Allows for a time-dependent OBR
- OBR doubles every $\Delta t \approx 180$ min

MaxSF = 40 % MaxSF = 75 %

$\Delta t \approx 180$ min
Patient Data

- 25 $^{68}$Ga-PSMA PET/MR patients
  - Administered activity: $213 \pm 66$ MBq
  - Acquisition time: $119 \pm 44$ min p.i.
  - Arms down

- Scatter Correction (SC)
  - Relative or absolute single scatter simulation (SSS)
  - Maximum scatter fraction $\text{MaxSF} = 75$% or 40%
  - $^{68}$Ga Prompt Gamma Correction (PGC) off/on
    (for relative SSS only)
Patient Data

Results Patient 1

No SC

160 MBq
128 min p.i.
OBR ≈ 70

MaxSF = 75 %
MaxSF = 40 %

Abs SC
Rel SC
Rel SC and PGC

[kBq/mL]

0.0 2.0
**Patient Data**

**Results Patient 2**

No SC

144 MBq
104 min p.i.
OBR ≈ 700

Rel SC
Rel SC and PGC
Abs SC

MaxSF = 40 %  MaxSF = 75 %

[kBq/mL]

2.0
0.0
Patient Data

Results Patient 3

No SC

189 MBq
179 min p.i.
OBR ≈ 350

MaxSF = 40 %
MaxSF = 75 %

Rel SC

Rel SC and PGC

Abs SC

[kBq/mL]
Patient Data

Results

- 25 $^{68}$Ga-PSMA PET/MR patients
- Investigate halo around bladder
  - Halo present or not?

<table>
<thead>
<tr>
<th></th>
<th>no Halo</th>
<th>Halo</th>
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<tbody>
<tr>
<td>Relative SSS</td>
<td>5</td>
<td>20</td>
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<td>($\text{MaxSF} = 75%$)</td>
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<td>Absolute SSS</td>
<td>17</td>
<td>8</td>
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<td>Relative SSS</td>
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<td>4</td>
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<td>($\text{MaxSF} = 40%$)</td>
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<tr>
<td>Absolute SSS</td>
<td>24</td>
<td>1</td>
</tr>
<tr>
<td>($\text{MaxSF} = 40%$)</td>
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Summary

• Phantom experiments
  – Size of halo increases with increasing OBR.
  – No significant differences between PET/MR and PET/CT.
  – Prompt gammas do not seem to be the (main) reason for halo artifact.
  – Decreasing the maximum scatter fraction to MaxSF = 40 % reduces halo size and thus improves image quality.

• Patient Data
  – Halo-artifact may occur around bladder and/or kidneys.
  – Absolute SSS results in better image quality than relative SSS.
  – PGC does not reduce halo size in case of severe halo-artifacts.
  – Decreasing MaxSF from 75 % to 40 % improves image quality.
Conclusions

• To avoid the occurrence of halo-artifacts in $^{68}$Ga-PSMA-PET/MR, the patient
  – should be scanned as fast as possible after tracer injection.
  – should be asked to void the bladder prior to data acquisition.

• Reducing the maximum scatter fraction to $\text{MaxSF} = 40\%$ significantly reduces the halo size.

• Accurate quantitative $^{68}$Ga-PSMA PET/MR independent of the workflow mandates new scatter estimation techniques.
The 4th International Conference on Image Formation in X-Ray Computed Tomography

July 18 – July 22, 2016, Bamberg, Germany
www.ct-meeting.org

Conference Chair
Marc Kachelrieß, German Cancer Research Center (DKFZ), Heidelberg, Germany

Thank You!

This work was supported by the Helmholtz International Graduate School for Cancer Research, Heidelberg, Germany.
Parts of the reconstruction software RayConStruct-IR were provided by RayConStruct® GmbH, Nürnberg, Germany.
$^{18}$F-FDG vs. $^{68}$Ga-PSMA

Sinograms

$^{18}$F-FDG

Emission

Normalized Scatter Estimation

Emission – Scatter

$^{68}$Ga-PSMA

Counts

Negative values causing the halo-artifact
PET Image Reconstruction

• Ordinary-Poisson Ordered Subset Expectation Maximization (OP-OSEM)

• Update equation:

\[
\lambda_i^{(n+1)} = \lambda_i^{(n)} \frac{1}{\sum_{j \in J} a_j / N_j} \sum_{j \in J} M_{ij} \frac{p_j}{\sum_k M_{kj} \lambda_k^{(n)} + (N_j r_j + s_j) / a_j}
\]

- \( i \): Voxel index
- \( j \): LOR index
- \( n \): Iteration number
- \( M \): System matrix
- \( \lambda \): Image
- \( a \): Attenuation
- \( N \): Normalization
- \( r \): Randoms
- \( s \): Scatter
- \( J \): Subset
- \( p \): Emission data
Patient Data

Results Patient 4

No SC

283 MBq
180 min p.i.
OBR ≈ 600

MaxSF = 75 %
Rel SC

MaxSF = 40 %
Rel SC and PGC

Abs SC

[kBq/mL]

0.0
2.0