# Magnetic Particle Imaging Resolution needed for Magnetic Hyperthermia Treatment Planning: A Sensitivity Analysis

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#### **Supplementary Information:**

# Verification and Validation of the COMSOL Multiphysics solver for Magnetic Nanoparticle Hyperthermia:

The solver was verified and validated against the analytical and experimental solution given by Goldenberg et. al. and Andra et. al. [1,2]. The results show that the numerical solution agrees with the analytical and experimental results.



Figure S 1: Comparison between numerical, analytical and experimental results. The COMSOL Multiphysics yields results that agree to the experimental and analytical solution.

#### Calibration Curve for the Volumetric Heat Source from Magnetic Field:

The calibration curve for the volumetric heat source obtained from the magnetic field, mass of

MION, MPI imaging and concentration of MION is shown in Figure S 2.



Figure S 2: a. Calibration curve for the mean voxel value obtained from concentration of MION from the MPI scanner.

#### **Performance Metrics:**

The performance metrics for the sensitivity analysis of the voxel resolution for the three distributions, that is, uniform, Gaussian, and *in vivo*, for the SLP's 300-600 [W/g] are listed in Table S 1.

			LVD [voxel/mm]							
			4.06	3.34	2.71	1.99	1.18	0.81	0.54	0.36
		Α	0.75	1.02	1.37	1.70	2.07	2.18	2.28	2.36
	D1	В	2.93	4.14	5.78	7.23	8.54	9.00	9.28	9.60
	DI	С	3.59	5.15	7.79	10.02	12.13	12.81	13.26	13.34
		D	0.00	0.00	1.66	4.36	7.55	8.73	9.65	10.62
	D2	Α	0.80	1.06	1.39	1.70	2.01	2.11	2.14	2.26
300		В	1.80	2.39	3.15	3.87	4.62	4.85	4.93	5.21
[W/g]		С	2.14	2.97	4.11	5.24	6.48	6.87	7.01	7.49
		D	0.00	0.00	0.00	0.00	0.00	0.53	0.96	2.76
		Α	0.79	1.18	1.41	1.70	2.12	2.24	2.28	2.42
	D2	В	3.57	5.51	6.65	8.38	10.22	10.77	10.97	11.63
	D3	С	4.38	7.10	8.77	11.33	13.99	14.78	15.06	15.99
		D	0.00	0.67	1.99	4.24	7.03	7.95	8.27	9.30
		Α	0.98	1.34	1.86	2.40	3.03	3.23	3.40	3.54
	D1	В	3.87	5.55	8.02	10.29	12.40	13.12	13.58	14.06
	DI	С	4.90	7.44	11.29	14.78	18.02	19.06	19.77	20.45
		D	0.00	1.24	5.95	11.55	18.30	20.55	22.45	24.05
		Α	1.03	1.38	1.83	2.28	2.78	2.94	3.00	3.20
400	D1	В	2.32	3.13	4.20	5.27	6.48	6.87	7.01	7.50
[W/g]	D2	С	2.87	4.07	5.78	7.60	9.79	10.52	10.79	11.72
		D	0.00	0.00	0.00	3.18	12.13	14.75	15.80	19.15
		Α	1.03	1.40	1.92	2.45	3.07	3.26	3.34	3.58
	D2	В	4.72	6.59	9.19	11.78	14.48	15.29	15.58	16.54
	D3	С	5.99	8.68	12.52	16.20	19.98	21.12	21.53	22.88
		D	0.06	1.9	5.46	9.49	14.69	16.7	17.75	20.78
	D1	Α	1.21	1.69	2.45	3.28	4.32	4.66	4.96	5.21
		В	4.84	7.11	10.62	13.83	16.90	17.93	18.62	19.30
		С	6.30	9.87	14.87	20.05	24.64	26.10	27.17	28.12
		D	0.15	4.17	12.34	21.30	32.46	36.38	39.57	42.06
	D2	Α	1.26	1.71	2.32	2.98	3.80	4.09	4.20	4.59
500		В	2.85	3.90	5.37	6.96	8.93	9.59	9.84	10.7
[W/g]		С	3.65	5.28	7.77	10.69	14.45	15.69	16.15	17.73
		D	0.00	0.00	3.86	15.40	27.31	31.73	33.07	39.22
	D2	Α	1.27	1.77	2.50	3.31	4.28	4.60	4.72	5.15
		В	5.94	8.45	12.00	15.47	19.12	20.23	20.63	21.99
	05	С	7.73	11.43	16.51	21.38	26.54	28.15	28.74	30.75
		D	1.16	4.35	9.93	17.30	28.12	32.22	33.68	39.99
		Α	1.45	2.09	3.16	4.42	6.06	6.64	7.15	7.58
	D1	В	5.86	8.86	13.52	17.81	22.00	23.41	24.40	25.35
		С	7.84	12.24	19.61	25.83	31.94	33.94	35.47	36.04
		D	1.54	7.94	20.06	33.64	49.97	55.83	61.84	66.67
	D2	Α	1.49	2.05	2.88	3.88	5.35	5.92	6.15	7.03
600		В	3.39	4.72	6.73	9.11	12.27	13.39	13.81	15.39
[W/g]		С	4.48	6.65	10.25	14.80	20.55	22.56	23.33	26.20
		D	0.00	0.04	13.73	28.49	52.88	65.12	68.45	78.07
	D3	Α	1.53	2.18	3.20	4.38	5.96	6.55	6.78	7.67
		В	7.24	10.47	15.01	19.47	24.36	25.94	26.53	28.60
	00	С	9.27	13.83	20.02	26.20	33.39	35.80	36.72	40.02
		D	2.69	7.44	15.93	29.54	53.78	65.43	68.23	77.28

Table S 1: Metrics for the sensitivity analysis of voxel resolution

A: Average  $\Delta T$  [°C] B: Maximum  $\Delta T$  [°C] C: Maximum change in temperature at 1250 [s] (after heating cycle). D: Thermal dose at 1500 [s] (at end of the simulation).

#### **Regression Parameter for the Logarithmic Curve Fitting:**

		Maximum ∆T [°C]		Average ∆T [°C]		Thermal dose [%]	
	SLF [W/g]	Α	В	Α	В	Α	В
	300	2.81	6.15	0.68	1.5	4.87	3.73
D1	400	4.34	8.7	1.1	2.12	10.83	9.47
זע	500	6.18	11.63	1.74	2.91	18.47	17.51
	600	8.33	14.93	2.67	3.95	28.23	27.95
	300	1.43	3.39	0.61	1.49	0.76	0.29
D2	400	2.18	4.64	0.91	2.01	8.74	5.27
	500	3.32	6.19	1.4	2.67	17.73	13.02
	600	5.07	8.2	2.31	3.59	35.32	26.79
D3	300	3.29	7.39	0.67	1.56	4.12	3.59
	400	5	10.14	1.08	2.16	8.72	8
	500	6.77	13.27	1.64	2.92	16.42	15.48
	600	8.96	16.77	2.58	3.94	33.07	29.22

Table S 2: Regression parameters obtained from the logarithmic fit.

#### **Required Linear Resolution of the MPI Scanner**

a. Linear regression:

Parameters obtained for the linear regression are enlisted in Table S 3 and shown in

Figure S 3.



*Figure S 3: Required linear voxel resolution from linear interpolation.* 

Table S 3: Linear regression p	parameters and SLP	prediction for	current SLP.
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		Maximum ∆T [°C]	Average $\Delta T$ [°C]	Thermal dose [%]	
D1	SLP [W/g]	384.3	370.53	343.21	
	a [(voxel ×g <sup>2</sup> ) /(mm×W <sup>2</sup> )]	0.02	0.03	0.04	
	b[(voxel ×g) /(mm×W)]	-2.78	-5.63	-10.77	
	$\mathbb{R}^2$	0.99	0.97	0.99	
	SLP [W/g]	378.7	379.21	-	
D2	a [(voxel ×g <sup>2</sup> ) /(mm×W <sup>2</sup> )]	0.02	0.02	-	
	b[(voxel ×g) /(mm×W)]	-4.64	-5.42	-	
	$\mathbb{R}^2$	0.97	0.94		
D3	SLP [W/g]	392.74	371.61	350.52	
	a [(voxel ×g <sup>2</sup> ) /(mm×W <sup>2</sup> )]	0.02	0.03	0.06	
	b[(voxel ×g) /(mm×W)]	-2.02	-5.46	-17.71	
	$\mathbb{R}^2$	1	0.97	0.92	

### b. Quadratic regression

Parameters obtained for the linear regression are enlisted in Table S 4.

Table S 4: Quadratic regression parameters and SLP prediction for current SLP.

		Maximum ∆T [°C]	Average ∆T [°C]	Thermal dose [%]
D1	SLP [W/g]	391.98	390.03	345.02
	a [(voxel ×g <sup>2</sup> ) /(mm×W <sup>2</sup> )]	0	5.30e-5	5.29e-5
	b[(voxel ×g) /(mm×W)]	0	-0.02	0
	c [voxel /mm]	0.07	4.61	-0.72
	$\mathbb{R}^2$	1	1	1
	SLP [W/g]	399.45	408.69	-
D2	a [(voxel $\times$ g <sup>2</sup> ) /(mm $\times$ W <sup>2</sup> )]	4.79e-5	6.83e-5	-
	b[(voxel ×g) /(mm×W)]	-0.02	-0.04	-
	c [voxel /mm]	4.46	7.55	-
	$\mathbb{R}^2$	1	1	-
D3	SLP [W/g]	399.17	387.33	369.92
	a [(voxel ×g <sup>2</sup> ) /(mm×W <sup>2</sup> )]	1.00e-5	5.13e-5	1.98e-4
	b[(voxel ×g) /(mm×W)]	0.01	-0.02	-0.12
	c [voxel /mm]	-0.11	4.11	19.9
	$R^2$	1	1	1

#### Matlab Code

```
% Last Updated 12/2/2022 at 7:00 p.m.
% Reference Forum
% https://www.mathworks.com/matlabcentral/answers/892652-anybody-help-me-by-
providing-matlab-code-for-the-three-dimensional-histograms#answer 863405
% -----<del>-</del>____
_____
clc; close all; clear all;
% -----
_____
% Progress Bar for Script Completion
w = waitbar(0, 'Please Wait...');
% -----
                       _____
  _____
% Inputs
tic
% Import Data & Determine Voxel Count
data= readmatrix('Scaled_MNP.txt');
                          _____
% -----
_____
% Main Function
% 46 for Finsish to prevent points from being outside voxels
start=5;
finish=46; % 54 gives ~0.253 delta x on mesh
for iii=start:1:finish
   if iii==47 || iii==48
      continue
   end
% Max Number of Voxels along each axis
s=iii;
labelcolors = [0 0 .4; 0 .4 0; .4 0 0; 0 0 .6; 0 .6 0; 6 0 0; 0 0 .8; 0 0 .1; 0 .1
0;.1 0 0;0 0 .3;
          0.30;.300;00.9;0.90;0.9.9;.900;00.5;0.50;.500;0
0.2;0.20;
           .2 0 0;0 0 1;0 1 0;0 1 1;1 0 0]; % must be rgb
x = data(:, 1);
y = data(:, 2);
z = data(:, 3);
label = data(:,4);
[groups, ID] = findgroups(label);
ngroups = length(ID);
if ngroups > size(labelcolors,1)
   error('too many groups, provide more labelcolors');
end
Nx = s; Ny = s; Nz = s;
xvox = (max(x)-min(x))/(Nx-1);
yvox = (max(y)-min(y))/(Ny-1);
zvox = (max(z)-min(z))/(Nz-1);
xidx = floor(x/xvox); xbin = xidx - min(xidx) + 1;
yidx = floor(y/yvox); ybin = yidx - min(yidx) + 1;
zidx = floor(z/zvox); zbin = zidx - min(zidx) + 1;
xq = xidx * xvox; yq = yidx * yvox; zq = zidx * zvox;
counts = accumarray([xbin(:), ybin(:), zbin(:)], 1, [Nx Ny Nz]);
```

```
occupied = counts > 0;
oind = find(occupied);
gcounts = cell(ngroups, 1);
for K = 1 : ngroups
   mask = groups == K;
   gcounts{K} = accumarray([ybin(mask), xbin(mask), zbin(mask)], 1, [Ny Nx Nz]);
end
gcounts4 = cat(4, gcounts{:});
[~, biggestgroupidx] = max(gcounts4, [], 4);
colidx = biggestgroupidx(occupied);
[ox, oy, oz] = ind2sub(size(occupied), oind);
oxq = (ox + min(xidx) - 1) * xvox;
oyq = (oy + min(yidx) - 1) * yvox;
ozq = (oz + min(zidx) - 1) * zvox;
noq = length(oxq);
rF = [1 2 3 4 1; 8 7 6 5 8; 1 4 6 7 1; 2 8 5 3 2; 1 7 8 2 1; 3 5 6 4 3]; %in
closed form
rV = [0 0 0; 1 0 0; 1 0 1; 0 0 1; 1 1 1; 0 1 1; 0 1 0; 1 1 0] .* [xvox, yvox,
zvox];
poxq = oxq(1:noq); poyq = oyq(1:noq); pozq = ozq(1:noq);
allF = repmat(rF(:,1:end-1), noq, 1) + 8*repelem((0:noq-1).', size(rF,1), 1);
allV = repelem([poxq, poyq, pozq], size(rV,1), 1) + repmat(rV, noq, 1);
[mappedV, ~, Vidx] = unique(allV, 'rows');
mappedF = Vidx(allF);
cdata = labelcolors(colidx,:);
% -----
       _____
% Plotting
% p = patch('Faces', mappedF, 'Vertices', mappedV, 'FaceVertexCData', cdata, ...
%
     'LineWidth', 0.1, 'EdgeColor', 'none', 'FaceAlpha', 0.1);
F1=figure(1);
p = patch('Faces', allF, 'Vertices', allV, 'FaceVertexCData', cdata, ...
    'LineWidth', 0.1, 'EdgeColor', 'none', 'FaceAlpha', 0.1);
colormap(labelcolors);
xlabel('x'); ylabel('y'); zlabel('z');
view(3)
hold on
plot3(data(:,1),data(:,2),data(:,3),'.b')
hold off
axis square
movegui(F1, 'west')
% % ------
  _____
% Find when Data is inside a Voxel and assign a Value to Voxel Verticies
vals_in=[];
count_in=1;
ind_in=[];
allV=[allV(:,:) zeros(length(allV(:,1)),1)];
for i=0:8:length(allV(:,1)) % 1 to number of voxels
if i==length(allV(:,1))
   % do nothing
else
xmin=min(min(allV(((i+1):(8+i)),1)));
xmax=max(max(allV(((i+1):(8+i)),1)));
ymin=min(min(allV(((i+1):(8+i)),2)));
ymax=max(max(allV(((i+1):(8+i)),2)));
zmin=min(min(allV(((i+1):(8+i)),3)));
zmax=max(max(allV(((i+1):(8+i)),3)));
```

```
for ii=1:length(data(:,1))
      if (data(ii,1)>xmin & data(ii,1)<xmax) && (data(ii,2)>ymin &
data(ii,2)<ymax) && (data(ii,3)>zmin & data(ii,3)<zmax)</pre>
         vals_in(count_in)=data(ii,4);
         ind_in(count_in)=ii;
         count_in=count_in+1;
      else
      end
   end
% Convert to SLP (W/(m^3)) and divided by 8 for vertices in a voxel.
m_au=(26.124/26)*mean(vals_in)-1028.893231;
m au = m au - 2;
m_slp=111349*m_au; % grey value to SLP
if m_slp < 0</pre>
   m_slp=0;
end
allV((((i+1):(8+i)),4)=m_slp/(1); % was divided by 8
% Prevent NaN values for voxel average
if isnan(mean(vals in)) == 1
   error('NaN Detected!');
end
count_in=1;
vals_in=0;
end
end
          _____
% -----
_____
% Output Text Files
% Update Progress Bar
F2=waitbar(iii/finish);
str1=num2str(iii);
C={'BME_504_TEXT_FILE_',str1,'.txt'};
str2=strjoin(C,'');
fileID = fopen(str2,'w');
writematrix(allV, str2, 'Delimiter', 'space');
fclose(fileID);
end
% ------
_____
% Close Progress Bar
close(w)
toc
```

## References

- 1. Goldenberg, H., & Tranter, C. J. (1952). Heat flow in an infinite medium heated by a sphere. British journal of applied physics, 3(9), 296.
- Andrä, W., d'Ambly, C. G., Hergt, R., Hilger, I., & Kaiser, W. A. (1999). Temperature distribution as function of time around a small spherical heat source of local magnetic hyperthermia. *Journal of Magnetism and Magnetic Materials*, 194(1-3), 197-203.