

1-gVirtualXRay_vs_Gate-detector_realistic_phantom

September 6, 2022

```
[1]: from IPython.display import display
      from IPython.display import Image
      from utils import * # Code shared across more than one notebook
```

```
[2]: output_path = "1-output_data/"

      if not os.path.exists(output_path):
          os.mkdir(output_path)
```

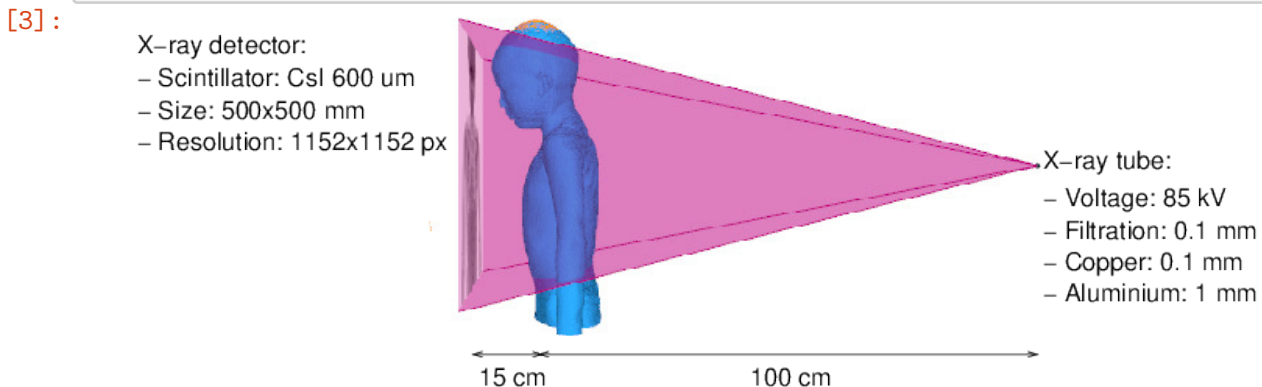
Main contributors: F. P. Vidal and J. M. Létang

Purpose: In this notebook, we aim to demonstrate that gVirtualXRay is able to generate analytic simulations on GPU comparable to images generated with the state-of-the-art Monte Carlo simulation packages. An anthropomorphic phantom is used. It corresponds to a 5-year old boy. We take into account i) a realistic beam spectrum (tube voltage and filtration) and ii) the energy response of the detector.

Material and Methods: We simulate an image with gVirtualXRay and compare it with a ground truth image. For this purpose, we use [Gate](#), a wrapper for CERN's state-of-the-art Monte Carlo simulation tool: [Geant4](#). The number of tracked particles is $1e9$.

In our simulation the source-to-object distance (SOD) is 1000mm, and the source-to-detector distance (SDD) is 1125mm. The beam spectrum is polychromatic. The voltage is 85 kV. The filtration is 0.1 mm of copper and 1 mm of aluminium. The energy response of the detector is considered. It mimics a 600-micron thick CsI scintillator.

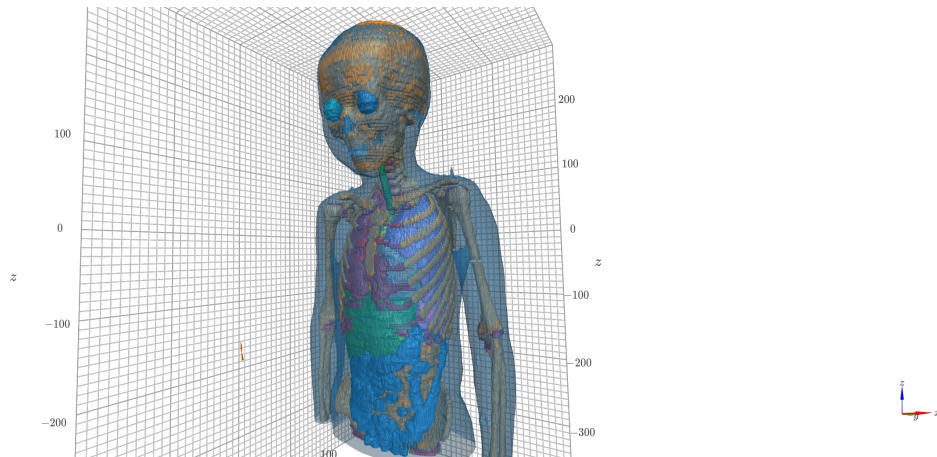
```
[3]: Image(filename="pediatric_phantom_data/pediatric-setup.png")
```



The sample is made of a 70x70x15mm box of water, in which 5 columns of 3 spheres of different radii (2, 3.5, and 5mm) have been inserted. A given material is associated to the spheres of each column (bone (cortical), blood (whole), brain (grey/white matter), breast tissue, and adipose tissue). The columns are ordered in decreasing density. We use the definitions of tissue substitutes provided in the [ICRU Report 44](#) by the [International Commission on Radiation Units and Measurements](#). The material composition is available at <https://physics.nist.gov/PhysRefData/XrayMassCoef/tab2.html>.

```
[4]: Image(filename=output_path+"/pediatric_model.png", width=800)
```

```
[4]:
```



Results: The calculations were performed on the following platform:

```
[5]: printSystemInfo()
```

OS:

```
Linux 5.14.21-150400.24.11-default
x86_64
```

CPU:

```
Intel(R) Core(TM) i9-9900K CPU @ 3.60GHz
```

RAM:

```
31 GB
```

GPU:

```
Name: NVIDIA GeForce RTX 2080 Ti
Drivers: 515.48.07
Video memory: 11 GB
```

The Monte Carlo simulation needed 5.36e6 HS06 seconds to complete.

It is equivalent to **8.68E+08** ms (i.e. ~10 days) on the system used. Only 51 ± 3 ms was needed with the GPU used.

The [mean absolute percentage error \(MAPE\)](#), also known as mean absolute percentage deviation (MAPD), between the two simulated images is **MAPE 2.70%**. The [zero-mean normalised cross-correlation](#) is **99.96%**. The [Structural Similarity Index \(SSIM\)](#) is **0.99**.

As MAPE is relatively low (less than 2%), SSIM is high (close to 1), and ZNCC is high (close to 100%), we can conclude that this X-ray image simulated with gVirtualXRay on GPU in milliseconds is comparable to the same Monte Carlo simulation that ran for days.

1 Import packages

```
[6]: %matplotlib inline

import os # Locate files

import math
import numpy as np # Who does not use Numpy?
import pandas as pd # Load/Write CSV files

import urllib, zipfile

import matplotlib

from matplotlib.cm import get_cmap
import matplotlib.pyplot as plt # Plotting
from matplotlib.colors import LogNorm # Look up table
from matplotlib.colors import PowerNorm # Look up table
import matplotlib.colors as mcolors

font = {'family' : 'serif',
        #'weight' : 'bold',
        'size'   : 22
        }
matplotlib.rc('font', **font)
# matplotlib.rc('text', usetex=True)

from scipy.stats import pearsonr # Compute the correlatio coefficient
from scipy.spatial import distance # Euclidean distance

from skimage.util import compare_images # Checkboard comparison between two_
↪ images
from skimage.metrics import structural_similarity as ssim
from sklearn.metrics import mean_absolute_percentage_error as mape
from skimage.metrics import structural_similarity as ssim
from skimage.transform import resize # Resample the images

from tifffile import imread, imwrite # Load/Write TIFF files
```

```

import datetime # For the runtime

import k3d, base64
import SimpleITK as sitk
from stl import mesh
import random
from sitk2vtk import sitk2vtk

import gvxrPython3 as gvxr # Simulate X-ray images

import json2gvxr # Set gVirtualXRay and the simulation up
from utils import * # Code shared across more than one notebook

```

SimpleGVXR 2.0.2 (2022-08-26T12:06:36) [Compiler: GNU g++] on Linux
gVirtualXRay core library (gvxr) 2.0.2 (2022-08-26T12:06:35) [Compiler: GNU g++]
on Linux

2 Reference image

We first load the reference image that has been simulated using [Gate](#) wrapper for CERN's [Geant4](#). Here we ignore scattering.

```

[7]: raw_reference = imread("pediatric_phantom_data/direct.tif")
Full_field = np.ones(raw_reference.shape) # Perfect full field image
Dark_field = np.zeros(Full_field.shape) # Perfect dark field image

```

Projections are then corrected to account for variations in beam homogeneity and in the pixel-to-pixel sensitivity of the detector. This is the projection with flat-field correction (**Proj**):

$$\mathbf{Proj} = \frac{I - D}{F - D} \quad (1)$$

where F (full fields) and D (dark fields) are projection images without sample and acquired with and without the X-ray beam turned on respectively.

We now apply the flat-field correction to `Image`.

```

[8]: gate_image = (raw_reference - Dark_field) / (Full_field - Dark_field)
# gate_image = raw_reference / np.mean(Full_field)

```

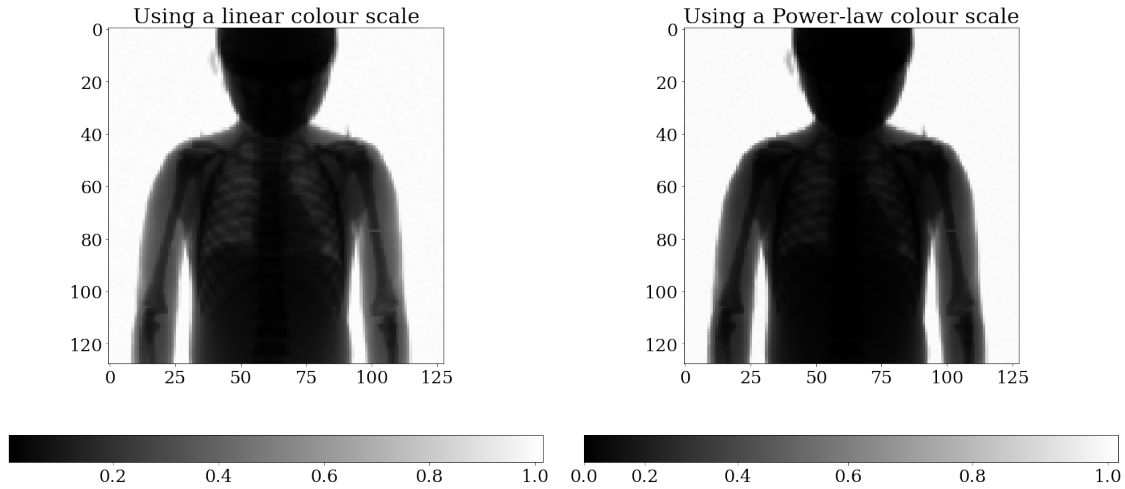
We plot the image using a linear look-up table and a power-law normalisation.

```

[9]: displayLinearPowerScales(gate_image,
                               "Image simulated using Gate wrapper for CERN's Geant4",
                               output_path + "/reference_from_Gate-paediatrics")

```

Image simulated using Gate wrapper for CERN's Geant4



3 Setting up gVirtualXRay

Before simulating an X-ray image using gVirtualXRay, we must create an OpenGL context.

```
[10]: json2gvxr.initGVXR("notebook-1.json", "OPENGL")
```

Create an OpenGL context: 800x450

```
Tue Sep 6 16:09:36 2022 ---- Create window (ID: -1)
Tue Sep 6 16:09:36 2022 ---- Initialise GLFW
Tue Sep 6 16:09:36 2022 ---- Create an OpenGL window with a 3.2 context.
Tue Sep 6 16:09:36 2022 ---- Make the window's context current
Tue Sep 6 16:09:36 2022 ---- Initialise GLEW
Tue Sep 6 16:09:36 2022 ---- OpenGL vendor: NVIDIA Corporation
Tue Sep 6 16:09:36 2022 ---- OpenGL renderer: NVIDIA GeForce RTX 2080
Ti/PCIe/SSE2
Tue Sep 6 16:09:36 2022 ---- OpenGL version: 3.2.0 NVIDIA 515.48.07
Tue Sep 6 16:09:36 2022 ---- Use OpenGL 4.5.
Tue Sep 6 16:09:36 2022 ---- Initialise the X-ray renderer if needed and if
possible
```

3.1 X-ray source

We create an X-ray source. It is a point source.

```
[11]: json2gvxr.initSourceGeometry()
```

Set up the beam

```
Source position: [0.0, 1000.0, 0.0, 'mm']
Source shape: PointSource
```

3.2 Spectrum

The spectrum is polychromatic.

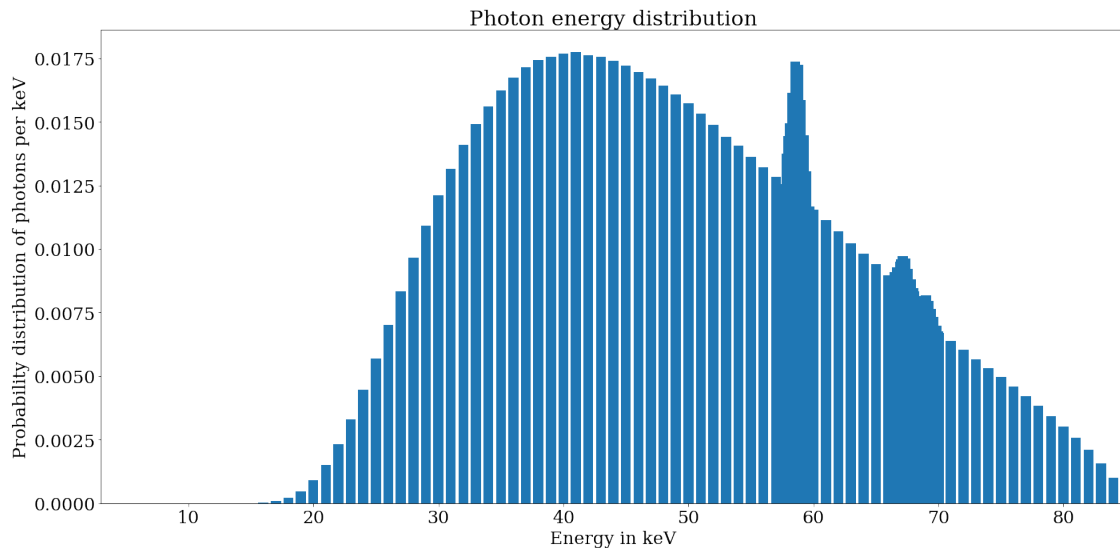
```
[12]: spectrum, unit, k, f = json2gvxr.initSpectrum(verbose=0)
      energy_set = sorted(spectrum.keys())

      count_set = []

      for energy in energy_set:
          count_set.append(spectrum[energy])
```

Plot the spectrum

```
[13]: k *= 1000
      plotSpectrum(k, f, output_path + "/spectrum-paediatrics", xlim=[np.min(k), np.
      ↪max(k)])
```



3.3 Detector

Create a digital detector

```
[14]: json2gvxr.initDetector()
```

Set up the detector

```
Detector position: [0.0, -150.0, 0.0, 'mm']
Detector up vector: [0, 0, -1]
Detector number of pixels: [128, 128]
Energy response: Gate_data/responseDetector.txt in MeV
Pixel spacing: [3.90625, 3.90625, 'mm']
```

Tue Sep 6 16:09:37 2022 ---- Initialise the renderer

3.4 Model the energy response of the detector

Load the energy response

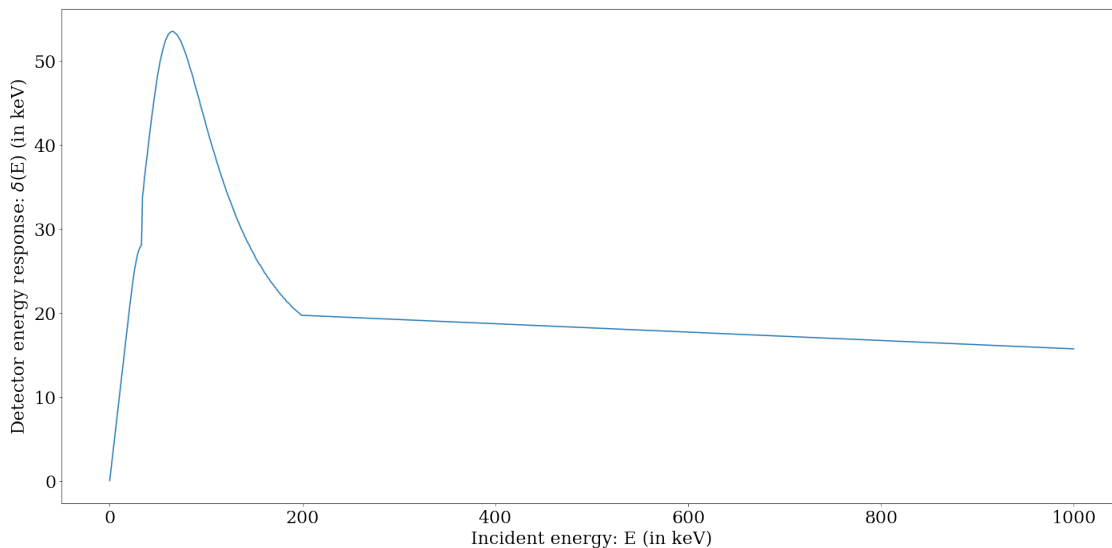
```
[15]: detector_response = np.loadtxt("Gate_data/responseDetector.txt")
```

Display the energy response

```
[16]: plt.figure(figsize= (20,10))
# plt.title("Detector response")
plt.plot(detector_response[:,0] * 1000, detector_response[:,1] * 1000)
plt.xlabel('Incident energy: E (in keV)')
plt.ylabel('Detector energy response:  $\delta(E)$  (in keV)')

plt.tight_layout()

plt.savefig(output_path + '/detector_response.pdf')
plt.savefig(output_path + '/detector_response.png')
```



3.5 Converting the voxelised phantom to surface meshes

Download and unzip the phantom

```
[17]: if not os.path.exists("pediatric_phantom_data/Pediatric phantom.zip"):
    urllib.request.urlretrieve("https://drive.uca.fr/f/384a08b5f73244cf9ead/?
    ↪dl=1", "pediatric_phantom_data/Pediatric phantom.zip")
```

```

with zipfile.ZipFile("pediatric_phantom_data/Pediatric phantom.zip", "r") as zip_ref:
    zip_ref.extractall("pediatric_phantom_data")

```

Load the phantom

```

[18]: phantom = sitk.ReadImage("pediatric_phantom_data/Pediatric phantom/
    ↳ Pediatric_model.mhd")

```

Load the labels

```

[19]: df = pd.read_csv("pediatric_phantom_data/labels.dat")

```

Process every structure of the phantom

```

[20]: if not os.path.exists("pediatric_phantom_data/meshes"):
        os.mkdir("pediatric_phantom_data/meshes")

    if not os.path.exists("pediatric_phantom_data/segmentations"):
        os.mkdir("pediatric_phantom_data/segmentations")

    meshes = []

    for threshold, organ in zip(df["Label"], df["Organs"]):

        # Ignore air
        if organ != "Air":

            print("Process", organ)

            seg_fname = "pediatric_phantom_data/segmentations/" + organ + ".mha"
            mesh_fname = "pediatric_phantom_data/meshes/" + organ + ".stl"
            meshes.append(mesh_fname)

            # Only create the mesh if it does not exist
            if not os.path.exists(mesh_fname):

                # Only segment the image it is not done as yet
                if not os.path.exists(seg_fname):

                    # Threshold the phantom
                    binary_image = (phantom == threshold)

                    # Smooth the binary segmentation
                    smoothed_binary_image = sitk.AntiAliasBinary(binary_image)

                    sitk.WriteImage(smoothed_binary_image, seg_fname)
                else:

```



```

        smoothed_binary_image = sitk.ReadImage(seg_fname)

    # Create a VTK image
    vtkimg = sitk2vtk(smoothed_binary_image, centre=True)

    vtk_mesh = extractSurface(vtkimg, 0)

#         print('Before decimation')
#         print(f'There are {mesh.GetNumberOfPoints()} points.')
#         print(f'There are {mesh.GetNumberOfPolys()} polygons.')

#         decimate = vtk.vtkDecimatePro()
#         decimate.SetInputData(mesh)
#         decimate.SplittingOn()
#         decimate.SetTargetReduction(30)
#         decimate.PreserveTopologyOn()
#         decimate.Update()

#         decimated = vtk.vtkPolyData()
#         decimated.ShallowCopy(decimate.GetOutput())

#         print('After decimation')
#         print(f'There are {decimated.GetNumberOfPoints()} points.')
#         print(f'There are {decimated.GetNumberOfPolys()} polygons.')
#         print(
#             f'Reduction: {(mesh.GetNumberOfPolys() - decimated.
↪GetNumberOfPolys()) / mesh.GetNumberOfPolys()}'
#         )

#         print("\n\n")
#         writeSTL(decimated, mesh_fname)
    writeSTL(vtk_mesh, mesh_fname)

```

Process Muscle
 Process Bone
 Process Stomach-Interior
 Process Cartilage
 Process Brain
 Process Bladder
 Process Gallbladder
 Process Heart
 Process Kidneys-right
 Process Kidneys-left
 Process Small-Intestine
 Process Large-Intestine
 Process Liver
 Process Lung-right
 Process Lung-left
 Process Pancreas

Process Spleen
Process Stomach
Process Thymus
Process Eyes-right
Process Eyes-left
Process Skull
Process Trachea

Load the samples. `verbose=2` is used to print the material database for Gate. To disable it, use `verbose=0` or `verbose=1`.

```
[21]: json2gvxr.initSamples(verbose=0)
```

```
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Muscle.stl      nb_faces:      1756726
nb_vertices:      5270178 bounding_box (in cm):  (-17.9687, -10.8887, -30.9017)
(16.6016, 11.1799, 28.6986)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Bone.stl  nb_faces:      541826  nb_vertices:
1625478 bounding_box (in cm):  (-16.7969, -23.6577, -30.9017) (15.2152,
9.88865, 16.3501)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Stomach-Interior.stl  nb_faces:      9452
nb_vertices:      28356  bounding_box (in cm):  (-1.34334, -2.38867, -17.0041)
(4.16143, 3.05231, -8.50205)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Cartilage.stl  nb_faces:      163322
nb_vertices:      489966 bounding_box (in cm):  (-16.7615, -4.32288, -30.9017)
(15.5041, 8.717, 16.6771)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Brain.stl nb_faces:      124028  nb_vertices:
372084 bounding_box (in cm):  (-7.32082, -9.98695, 16.3501) (7.50031,
5.78681, 28.1222)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Bladder.stl  nb_faces:      3712
nb_vertices:      11136  bounding_box (in cm):  (-3.78536, 2.11808, -30.9017)
(0.175804, 5.49461, -29.7572)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Gallbladder.stl  nb_faces:      4308
nb_vertices:      12924  bounding_box (in cm):  (-5.07422, -1.68659, -17.9851)
(-2.54188, 1.49065, -14.3881)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Heart.stl nb_faces:      48172  nb_vertices:
144516 bounding_box (in cm):  (-3.78536, -3.07617, -9.15606) (6.32529,
5.68903, 1.30801)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Kidneys-right.stl nb_faces:      17512
nb_vertices:      52536  bounding_box (in cm):  (-7.69363, 1.73117, -18.9661)
(-2.47349, 7.23954, -10.4641)
```

```

Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Kidneys-left.stl nb_faces:      16388
nb_vertices: 49164 bounding_box (in cm): (1.37053, 3.46679, -17.9851)
(6.44388, 7.74184, -8.82905)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Small-Intestine.stl nb_faces:      118532
nb_vertices: 355596 bounding_box (in cm): (-7.48809, -2.95731, -30.9017)
(7.59416, 8.32697, -12.0991)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Large-Intestine.stl nb_faces:      94336
nb_vertices: 283008 bounding_box (in cm): (-4.66426, -1.67902, -30.4112)
(7.11153, 6.16473, -13.4071)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Liver.stl nb_faces:      87800 nb_vertices:
263400 bounding_box (in cm): (-9.35286, -3.73856, -19.2931) (5.43096,
7.83896, -6.21304)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Lung-right.stl nb_faces:      80364
nb_vertices: 241092 bounding_box (in cm): (-9.47265, -3.16992, -8.82905)
(0.0788746, 8.15358, 6.54004)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Lung-left.stl nb_faces:      70736
nb_vertices: 212208 bounding_box (in cm): (0.397666, -2.26504, -9.81006)
(8.28139, 8.52371, 6.21304)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Pancreas.stl nb_faces:      14592
nb_vertices: 43776 bounding_box (in cm): (-2.8088, -0.240234, -17.0041)
(5.6632, 4.32215, -10.1371)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Spleen.stl nb_faces:      25468
nb_vertices: 76404 bounding_box (in cm): (1.48829, -0.611202, -14.7151)
(8.10404, 7.94215, -6.86704)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Stomach.stl nb_faces:      28680
nb_vertices: 86040 bounding_box (in cm): (-3.47804, -2.58413, -17.0041)
(5.05955, 4.0295, -7.84805)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Thymus.stl nb_faces:      3136
nb_vertices: 9408 bounding_box (in cm): (-0.846352, -1.87282, -1.30801)
(1.53113, 1.18326, 2.28901)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Eyes-right.stl nb_faces:      3956
nb_vertices: 11868 bounding_box (in cm): (-3.88504, -9.01112, 14.7151)
(-1.28679, -6.41928, 17.6581)
Tue Sep 6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Eyes-left.stl nb_faces:      4116
nb_vertices: 12348 bounding_box (in cm): (1.66718, -8.8147, 14.7151)
(4.47449, -6.12631, 17.6581)

```

```

Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Skull.stl nb_faces:      327028  nb_vertices:
981084  bounding_box (in cm):   (-7.59598, -10.476, 7.84805)   (7.79064,
6.17931, 29.1032)
Tue Sep  6 16:09:39 2022 ---- file_name:
pediatric_phantom_data/meshes/Trachea.stl      nb_faces:      8588
nb_vertices:   25764  bounding_box (in cm):   (-3.48031, -0.996257, -2.61602)
(3.39865, 5.09486, 10.1371)

```

Visualise the phantom

```

[22]: plot = k3d.plot()
      plot.background_color = 0xffffffff

      for sample in json2gvxr.params["Samples"]:

          label = sample["Label"]

          fname = sample["Path"]

          r, g, b, a = gvxr.getAmbientColour(label)
          R = math.floor(255*r)
          G = math.floor(255*g)
          B = math.floor(255*b)
          A = math.floor(255*a)

          k3d_color = 0;
          k3d_color |= (R & 255) << 16;
          k3d_color |= (G & 255) << 8;
          k3d_color |= (B & 255);

          mesh_from_stl_file = mesh.Mesh.from_file(fname)

          if label == "Muscle":
              opacity = 0.4
          else:
              opacity = 1
          geometry = k3d.mesh(mesh_from_stl_file.vectors.flatten(),
                              range(int(mesh_from_stl_file.vectors.flatten()).
↳shape[0] / 3)),

                              color=k3d_color,
                              wireframe=False,
                              flat_shading=False,
                              name=fname,
                              opacity=opacity)

          plot += geometry

```

```

plot.display()
plot.camera = [321.6678075002728, -461.4855245196105, -34.86613985320561,
               0, 0, -1.635009765625,
               0.08017827340927154, -0.083269170696295, 0.9932963755519574]

```

Output()

```

[23]: fname = output_path + '/pediatric_model.png'
      if not os.path.isfile(fname):

          plot.fetch_screenshot() # Not sure why, but we need to do it twice to get
          ↪ the right screenshot
          plot.fetch_screenshot()

          data = base64.b64decode(plot.screenshot)
          with open(fname, 'wb') as fp:
              fp.write(data)

```

4 Run the simulation

Update the 3D visualisation and take a screenshot

```

[24]: gvxr.displayScene()

gvxr.computeXRayImage()
gvxr.useLighing()
gvxr.useWireframe()
gvxr.setZoom(1549.6787109375)

angle = math.pi / 2.0
rotation_matrix_x = np.array([ 1, 0, 0, 0,
                               0, math.cos(angle), -math.sin(angle), 0,
                               0, math.sin(angle),  math.cos(angle), 0,
                               0, 0, 0, 1])

rotation_matrix_z = np.array([ math.cos(angle), -math.sin(angle), 0, 0,
                               math.sin(angle),  math.cos(angle), 0, 0,
                               0, 0, 1, 0,
                               0, 0, 0, 1])

rotation_matrix_x.shape = [4,4]
rotation_matrix_z.shape = [4,4]

transformation_matrix = np.identity(4)

transformation_matrix = np.matmul(rotation_matrix_x, transformation_matrix)
transformation_matrix = np.matmul(rotation_matrix_z, transformation_matrix)

```

```
gvxr.setSceneRotationMatrix(transformation_matrix.flatten())

gvxr.setWindowBackGroundColour(1, 1, 1)

gvxr.displayScene()
```

```
[25]: screenshot = (255 * np.array(gvxr.takeScreenshot())).astype(np.uint8)
```

```
[26]: fname = output_path + 'screenshot.png'
if not os.path.isfile(fname):

    plt.imsave(fname, screenshot)
```

```
[27]: gvxr.setZoom(1549.6787109375)
gvxr.setSceneRotationMatrix([-0.19267332553863525, -0.06089369207620621, 0.
↪ 9793692827224731, 0.0,
                                0.9809651970863342, -0.03645244985818863, 0.
↪ 19072122871875763, 0.0,
                                0.02408679760992527, 0.9974713325500488, 0.
↪ 06675821542739868, 0.0,
                                0.0, 0.0, 0.0,
↪ 1.0])

gvxr.setWindowBackGroundColour(0.5, 0.5, 0.5)

gvxr.useNegative()

gvxr.displayScene()
```

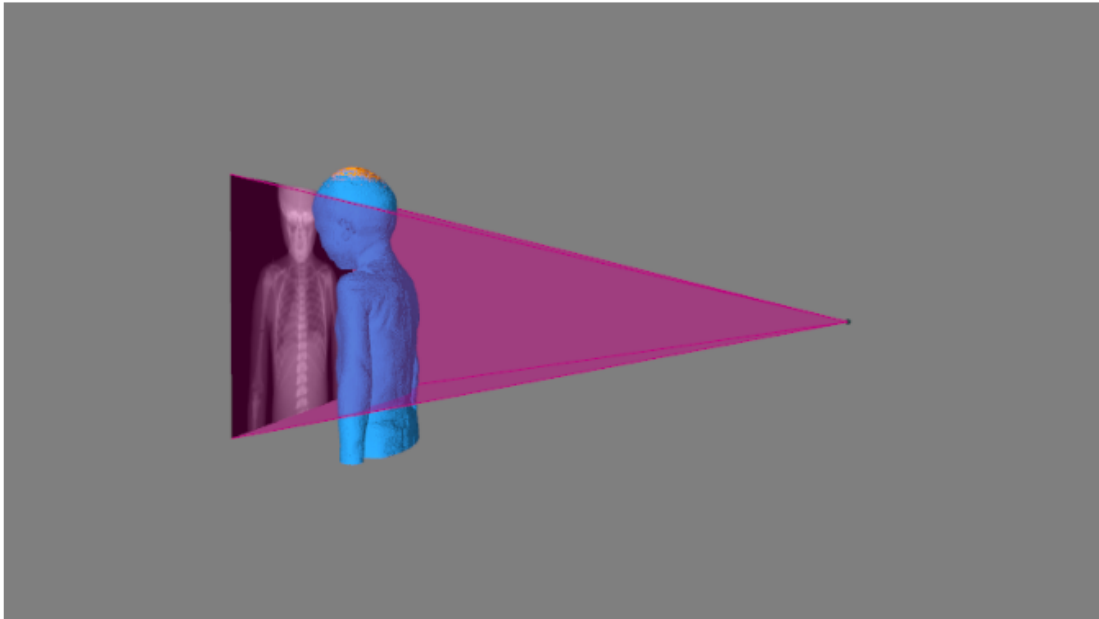
```
[28]: screenshot = (255 * np.array(gvxr.takeScreenshot())).astype(np.uint8)
```

```
[29]: plt.figure(figsize= (10,10))
plt.title("Screenshot")
plt.imshow(screenshot)
plt.axis('off')

plt.tight_layout()

plt.savefig(output_path + '/screenshot-beam-on-paediatrics.pdf')
plt.savefig(output_path + '/screenshot-beam-on-paediatrics.png')
```

Screenshot



Compute an X-ray image 50 times (to gather performance statistics)

```
[30]: # gvxr.enableArtefactFilteringOnCPU()
gvxr.enableArtefactFilteringOnGPU()
# gvxr.disableArtefactFiltering() # Spere inserts are missing with GPU
↳ integration when a outer surface is used for the matrix

runtimes = []

for i in range(50):
    start_time = datetime.datetime.now()
    gvxr.computeXRayImage()
    end_time = datetime.datetime.now()
    delta_time = end_time - start_time
    runtimes.append(delta_time.total_seconds() * 1000)
```

Save an X-ray image

```
[31]: # Compute the L-buffers on the GPU and integrate on the GPU
x_ray_image_integration_GPU = np.array(gvxr.computeXRayImage())
x_ray_image_integration_GPU = resize(x_ray_image_integration_GPU, gate_image.
↳ shape)
imwrite(output_path + '/projection_raw_integration_GPU_paediatrics.tif',
↳ x_ray_image_integration_GPU.astype(np.single))
```

Flat-field correction

```
[32]: total_energy_in_keV = 0.0
      for energy, count in zip(energy_set, count_set):
          total_energy_in_keV += energy * count

      total_energy_in_MeV = gvxr.getTotalEnergyWithDetectorResponse()
```

```
[33]: white = np.ones(x_ray_image_integration_GPU.shape) * total_energy_in_MeV
      dark = np.zeros(x_ray_image_integration_GPU.shape)

      x_ray_image_integration_GPU = (x_ray_image_integration_GPU - dark) / (white -
      ↪dark)
```

Save the corresponding image

```
[34]: imwrite(output_path + '/projection_corrected_integration_GPU_paediatrics.tif',
      ↪x_ray_image_integration_GPU.astype(np.single))
```

```
[35]: plt.figure(figsize= (20,10))

      plt.suptitle("Image simulated using gVirtualXRay,\nintegration on GPU", y=1.02)

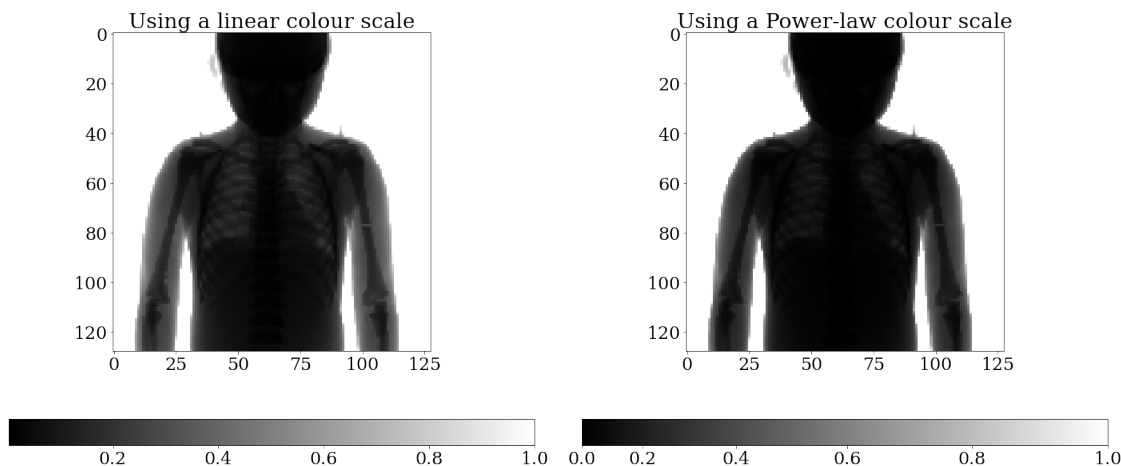
      plt.subplot(121)
      plt.imshow(x_ray_image_integration_GPU, cmap="gray")
      plt.colorbar(orientation='horizontal')
      plt.title("Using a linear colour scale")

      plt.subplot(122)
      plt.imshow(x_ray_image_integration_GPU, norm=PowerNorm(gamma=1./0.75),
      ↪cmap="gray")
      plt.colorbar(orientation='horizontal')
      plt.title("Using a Power-law colour scale")

      plt.tight_layout()

      plt.savefig(output_path + '/x_ray_image_integration_GPU-paediatrics.pdf')
      plt.savefig(output_path + '/x_ray_image_integration_GPU-paediatrics.png')
```


Image simulated using gVirtualXRay,
integration on GPU



5 Comparison the analytic simulation with the Monte Carlo simulation

5.1 Quantitative validation

Compute image metrics between the two simulated images:

1. [mean absolute percentage error \(MAPE\)](#), also known as mean absolute percentage deviation (MAPD),
2. [zero-mean normalised cross-correlation \(ZNCC\)](#), and
3. [Structural Similarity Index \(SSIM\)](#).

We use these three metrics as one is a dissimilarity measurement (MAPE), two are similarity measurement (ZNCC & SSIM). MAPE and ZNCC can be expressed as a percentage, which eases the interpretation of the numerical values. SSIM is a number between 0 and 1. A good value of MAPE is 0%; of ZNCC 100%, and SSIM 1.

```
[36]: # Avoid div by 0
offset1 = min(gate_image.min(), x_ray_image_integration_GPU.min())
offset2 = 0.01 * (gate_image.max() - gate_image.min())
offset = offset2 - offset1

MAPE_integration_GPU = mape(gate_image + offset, x_ray_image_integration_GPU +
    ↪offset)

# MAPE_integration_GPU = mape(gate_image, x_ray_image_integration_GPU)
ZNCC_integration_GPU = np.mean((gate_image - gate_image.mean()) / gate_image.
    ↪std() * (x_ray_image_integration_GPU - x_ray_image_integration_GPU.mean()) /
    ↪x_ray_image_integration_GPU.std())
```

```
SSIM_integration_GPU = ssim(gate_image, x_ray_image_integration_GPU,
    ↪data_range=gate_image.max() - gate_image.min())

print("MAPE_integration_GPU:", "{0:0.2f}".format(100 * MAPE_integration_GPU) +
    ↪"%")
print("ZNCC_integration_GPU:", "{0:0.2f}".format(100 * ZNCC_integration_GPU) +
    ↪"%")
print("SSIM_integration_GPU:", "{0:0.2f}".format(SSIM_integration_GPU))
```

MAPE_integration_GPU: 2.70%

ZNCC_integration_GPU: 99.96%

SSIM_integration_GPU: 0.99

Get the total number of triangles

```
[37]: number_of_triangles = 0

for mesh in json2gvxr.params["Samples"]:
    label = mesh["Label"]
    number_of_triangles += gvxr.getNumberOfPrimitives(label)
```

```
[38]: runtime_avg = round(np.mean(runtimes))
runtime_std = round(np.std(runtimes))
```

Print a row of the table for the paper

```
[39]: print("Paediatric -- polychromatic (85 kV), detector energy response & Gate & "
    ↪+
    "{0:0.2f}".format(100 * MAPE_integration_GPU) + "\\%    &    " +
    "{0:0.2f}".format(100 * ZNCC_integration_GPU) + "\\%    &    " +
    "{0:0.2f}".format(SSIM_integration_GPU) + "    &    $" +
    str(json2gvxr.params["Detector"]["NumberOfPixels"][0]) + " \\pm " +
    ↪str(json2gvxr.params["Detector"]["NumberOfPixels"][1]) + "$    &    " +
    str(number_of_triangles) + "    &    " +
    "8.68E+08    &    " +
    "$" + str(runtime_avg) + " \\pm " + str(runtime_std) + "$ \\\\")
```

```
Paediatric -- polychromatic (85 kV), detector energy response & Gate & 2.70\%
& 99.96\%    & 0.99    & $128 \pm 128$    & 3552778    & 8.68E+08
& $51 \pm 3$ \\\
```

In both cases, MAPE is very small (less than 3%), ZNCC is very high (almost 100%), and SSIM is very high (almost 1). We can conclude that the two images are similar. The main difference lie in the Poisson noise affecting the Monte Carlo simulation.

5.2 Qualitative validation

Checkboard comparison

```
[40]: font = {'size' : 12.5
           }
matplotlib.rc('font', **font)
```

```
[41]: source_position = [json2gvxr.params["Source"]["Position"][0] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Source"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm"),
                        json2gvxr.params["Source"]["Position"][1] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Source"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm"),
                        json2gvxr.params["Source"]["Position"][2] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Source"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm")
    ]

detector_position = [json2gvxr.params["Detector"]["Position"][0] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Detector"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm"),
                    json2gvxr.params["Detector"]["Position"][1] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Detector"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm"),
                    json2gvxr.params["Detector"]["Position"][2] * gvvr.
    ↪getUnitOfLength(json2gvxr.params["Detector"]["Position"][3]) / gvvr.
    ↪getUnitOfLength("mm")
    ]

object_bbox = gvvr.getNodeAndChildrenBoundingBox("root", "mm")
object_position = [(object_bbox[0] + object_bbox[3]) / 2,
                  (object_bbox[1] + object_bbox[4]) / 2,
                  (object_bbox[2] + object_bbox[5]) / 2
                  ]

source_imager_distance = distance.euclidean(source_position, detector_position)
source_object_distance = distance.euclidean(source_position, object_position)

magnification = source_imager_distance / source_object_distance
```

```
[42]: print("SID:", source_imager_distance, "mm")
    print("SOD:", source_object_distance, "mm")
    print("magnification:", magnification)
```

```
SID: 1150.0 mm
SOD: 1062.4489886902375 mm
magnification: 1.082404908133701
```

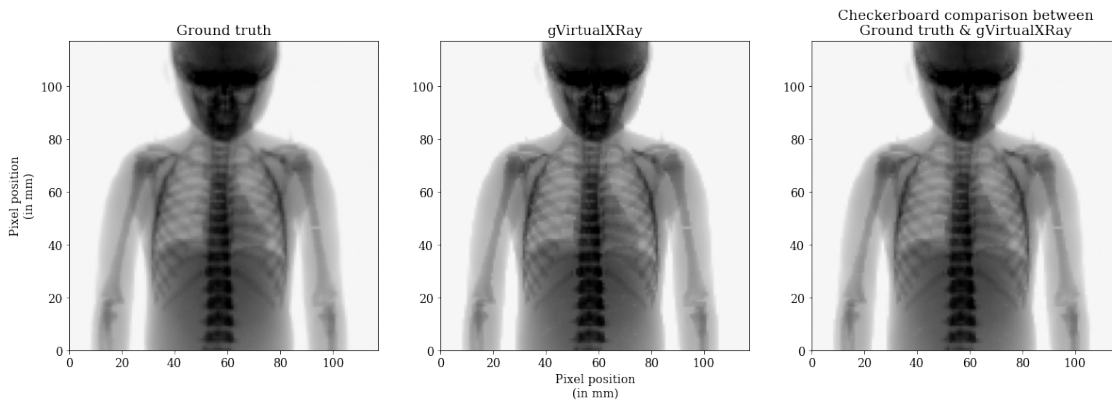
```
[43]: detector_resolution = json2gvxr.params["Detector"]["NumberOfPixels"]
    detector_size = json2gvxr.params["Detector"]["Size"]
```

```

pixel_pitch = np.array([detector_size[0] / detector_size[0] / gvxr.
    ↪getUnitOfLength("mm"),
                        detector_size[1] / detector_size[1] / gvxr.getUnitOfLength("mm"),
])

fullCompareImages(gate_image,
                  x_ray_image_integration_GPU,
                  "gVirtualXRay\n with integration on GPU",
                  output_path + "/full_comparison_integration_GPU-paediatrics",
    ↪pixel_pitch / magnification, log=True)

```



Plot the profiles

```

[44]: font = {'size' : 12.5
            }
matplotlib.rc('font', **font)

```

```

[45]: ground_truth_diag = np.diag(gate_image)
      gvxr_diag = np.diag(x_ray_image_integration_GPU)

      x = np.linspace(0, len(ground_truth_diag), len(ground_truth_diag)) *
    ↪(pixel_pitch[0] / magnification)
      plt.figure(figsize=(15, 5))

      ax = plt.subplot(111)

      ax.set_title("Diagonal profiles")

      ax.plot(x, ground_truth_diag, label="Ground truth (Geant4/GATE)")
      ax.plot(x, gvxr_diag, label="gVirtualXRay")

      ax.legend(loc='best',

```

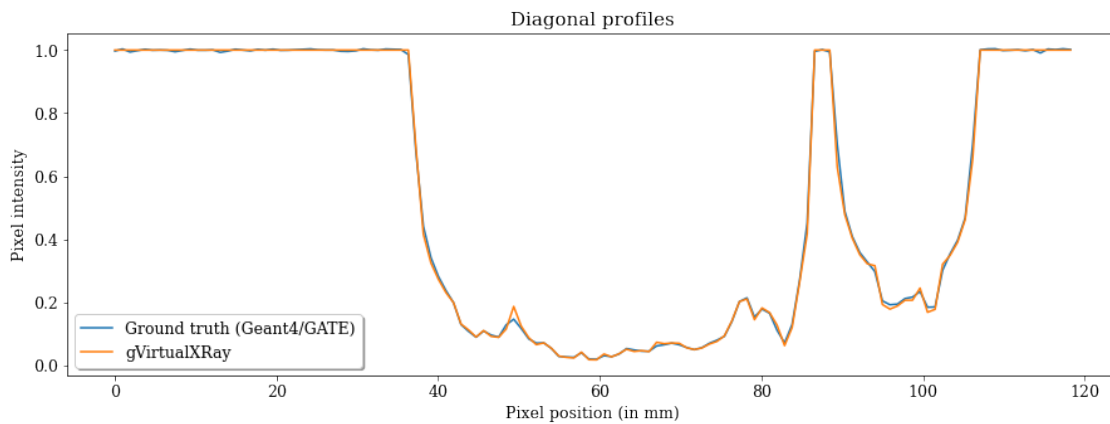
```

ncol=1, fancybox=True, shadow=True)

plt.xlabel("Pixel position (in mm)")
plt.ylabel("Pixel intensity")

plt.savefig(output_path + '/profiles-paediatrics.pdf')
plt.savefig(output_path + '/profiles-paediatrics.png')

```



6 All done

Destroy the window

```
[46]: gvxr.destroyAllWindows()
```

Tue Sep 6 16:09:49 2022 ---- Destroy all the windows

Tue Sep 6 16:09:49 2022 ---- Destroy window 0(0x563d0eda6890)