6-gVirtualXRay_vs_Gate-detector_realistic_phantom

March 4, 2022

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

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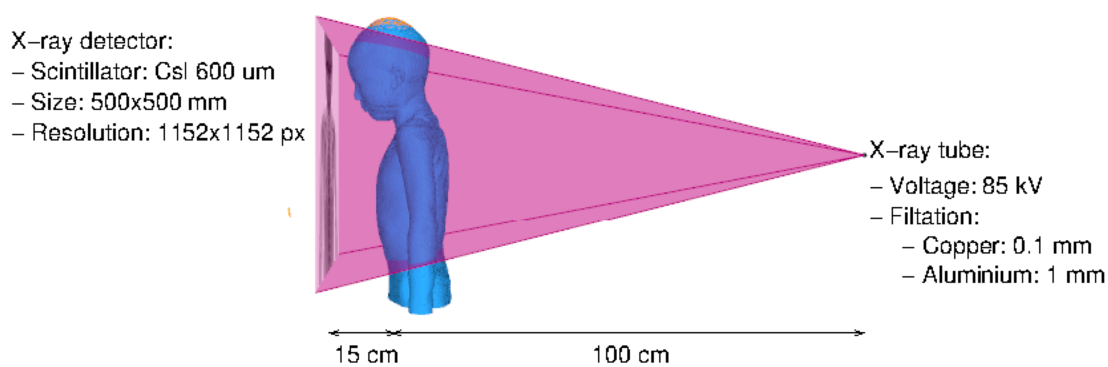
Purpose: In this notebook, we aim to demonstrate that gVirtualXRay is able to generate analytic simulations on GPU comparable to images generated with the state-of-the-art Monte Caro simulation packages. An anthropomorphic phantom is used. It corresponds to a 5-year old boy. We take into account i) a 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 Caro 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.

[2]:
```
Image(filename="pediatric_phantom_data/pediatric-setup.png")
```

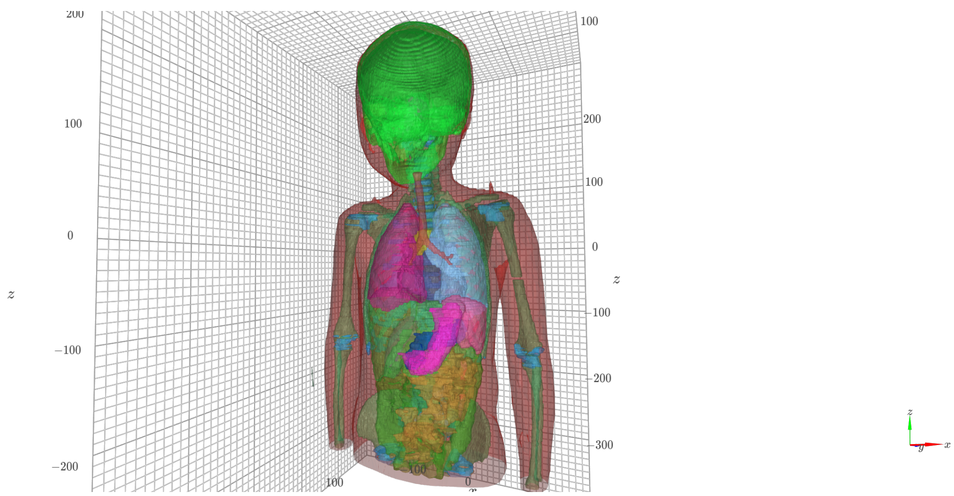
[2]:



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`.

[3]:
```
Image(filename="plots/pediatric_model.png", width=800)
```

[3]:



Results: The calculations were performed on the following platform:

[4]:
```
printSystemInfo()
```

```
OS:
        Linux 5.3.18-150300.59.49-default
        x86_64

CPU:
        AMD Ryzen 7 3800XT 8-Core Processor

RAM:
        63 GB
GPU:
        Name: GeForce RTX 2080 Ti
        Drivers: 455.45.01
        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 218 ± 6 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 2.23%**. The **zero-mean normalised cross-correlation is 99.99%**. The **Structural Similarity Index (SSIM) is 0.99**.

As MAPE is relatively low (less than 5%), 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

[5]:
```
%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 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 1.0.1 (2022-02-22T14:00:25) [Compiler: GNU g++] on Linux
gVirtualXRay core library (gvxr) 1.1.5 (2022-02-22T14:00:25) [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.

[6]:
```
Image = imread("pediatric_phantom_data/direct.tif")
Full_field = np.ones(Image.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**):

$$\mathbf{Proj} = \frac{I - D}{F - D} \tag{1}$$

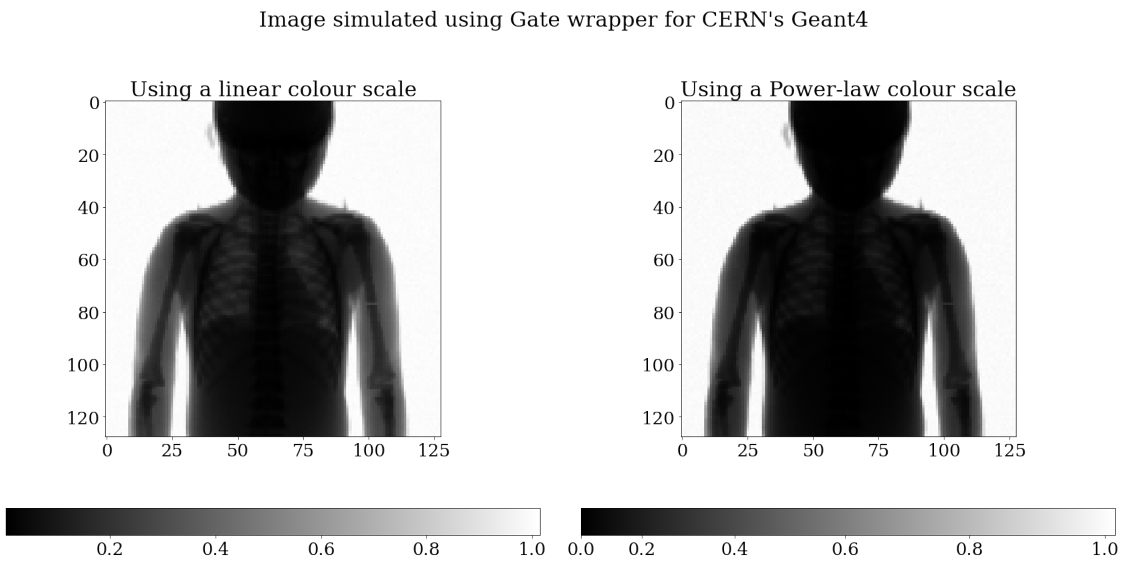
where F (full fields) and D (dark fields) are projection images without sample and acquired with and without the X-ray beam turned on respectively.

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

[7]:
```
gate_image = (Image - Dark_field) / (Full_field - Dark_field)
# gate_image = Image / np.mean(Full_field)
```

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

[8]:
```
displayLinearPowerScales(gate_image,
                         "Image simulated using Gate wrapper for CERN's Geant4",
                         "plots/reference_from_Gate-paediatrics")
```



3 Setting up gVirtualXRay

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

[9]:
```
json2gvxr.initGVXR("notebook-6.json", "OPENGL")
```

```
Create an OpenGL context: 800x450
```

```
0
```

```
Fri Mar  4 11:45:35 2022 ---- Create window gvxrStatus: Create window
0 0 500 500
OpenGL renderer:   GeForce RTX 2080 Ti/PCIe/SSE2
OpenGL version:    3.2.0 NVIDIA 455.45.01
OpenGL vender:     NVIDIA Corporation
Fri Mar  4 11:45:35 2022 ---- Use OpenGL 4.5.0 0 800 450
```

3.1 X-ray source

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

[10]:
```
json2gvxr.initSourceGeometry()
```

```
Set up the beam
        Source position: [0.0, 1000.0, 0.0, 'mm']
        Source shape: PointSource
```

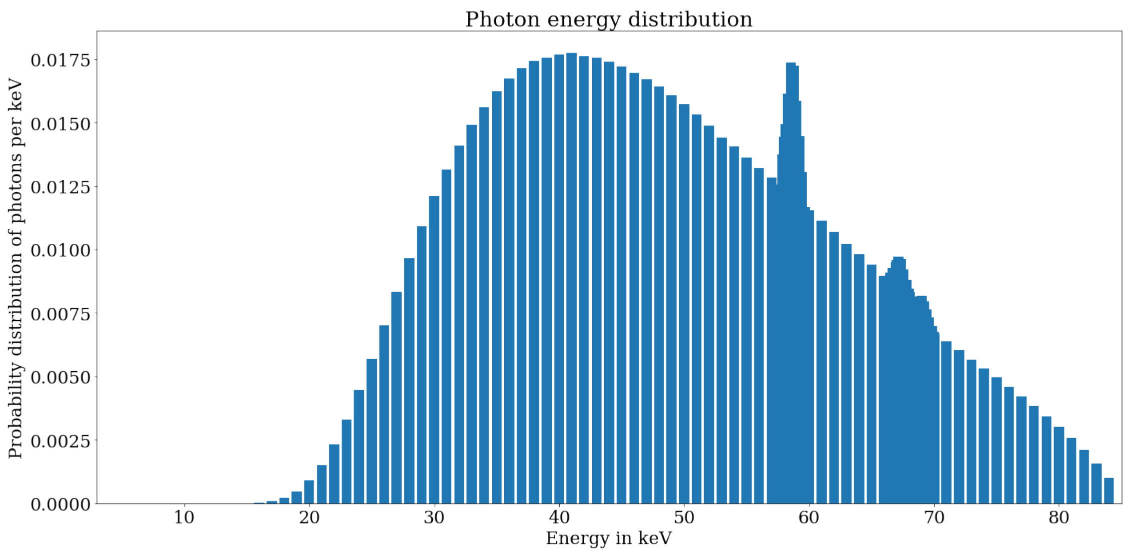
3.2 Spectrum

The spectrum is polychromatic.

[11]:
```
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

[12]:
```
k *= 1000
plotSpectrum(k, f, "plots/spectrum-paediatrics", xlim=[np.min(k), np.max(k)])
```



3.3 Detector

Create a digital detector

[13]:
```
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: [1024, 1024]
        Energy response: Gate_data/responseDetector.txt in MeV
        Pixel spacing: [0.48828125, 0.48828125, 'mm']
```

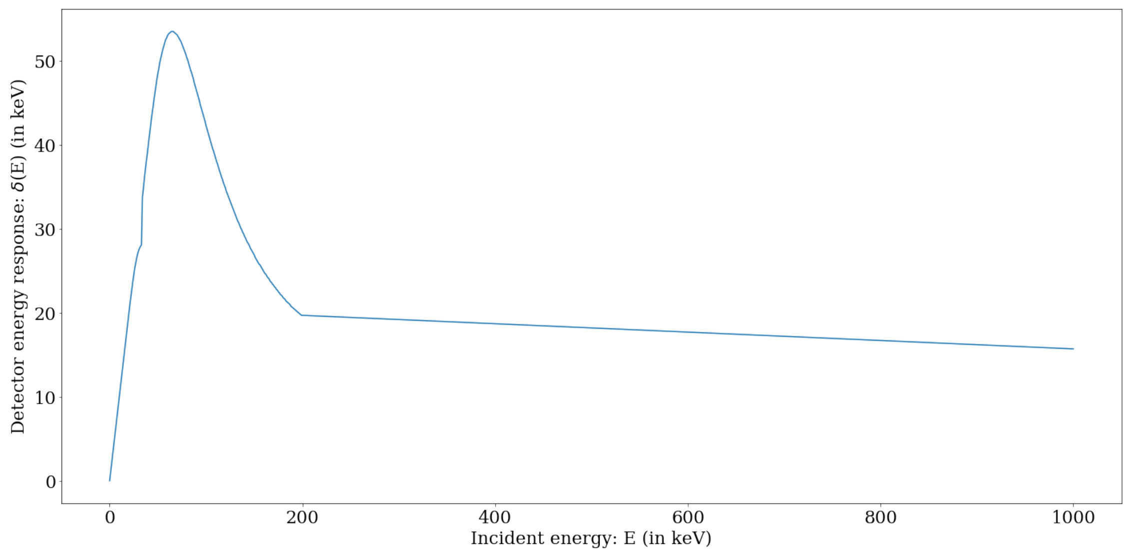
3.4 Model the energy response of the detector

Load the energy response

[14]:
```
detector_response = np.loadtxt("Gate_data/responseDetector.txt")
```

Display the energy response

[15]:
```
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('plots/detector_response.pdf')
plt.savefig('plots/detector_response.png')
```



3.5 Converting the voxelised phantom to surface meshes

Download and unzip the phantom

[16]:
```
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

[17]:
```
phantom = sitk.ReadImage("pediatric_phantom_data/Pediatric phantom/
 ↪Pediatric_model.mhd")
```

```
Fri Mar  4 11:45:36 2022 ---- Initialise the renderer
```

Load the labels

[18]:
```
df = pd.read_csv("pediatric_phantom_data/labels.dat")
```

Process every structure of the phantom

[19]:
```
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)
```

```python
                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`.

[20]:
```
json2gvxr.initSamples(verbose=0)
```

```
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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)
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

[21]:
```python
plot = k3d.plot()
plot.background_color = 0xffffff

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()

[22]:
```
fname = 'plots/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

[23]:
```
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()
```

```
Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ----
file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4
11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:
Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ----
file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4
11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:
Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ----
file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4
11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:
Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ----
file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4
11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:
```

```
Fri Mar  4 11:45:38 2022 ---- file_name:        Fri Mar  4 11:45:38 2022 ----
file_name:        Fri Mar  4 11:45:38 2022 ---- file_name:        0 0 500 500
0 0 800 450
```

[24]:
```python
screenshot = (255 * np.array(gvxr.takeScreenshot())).astype(np.uint8)
```

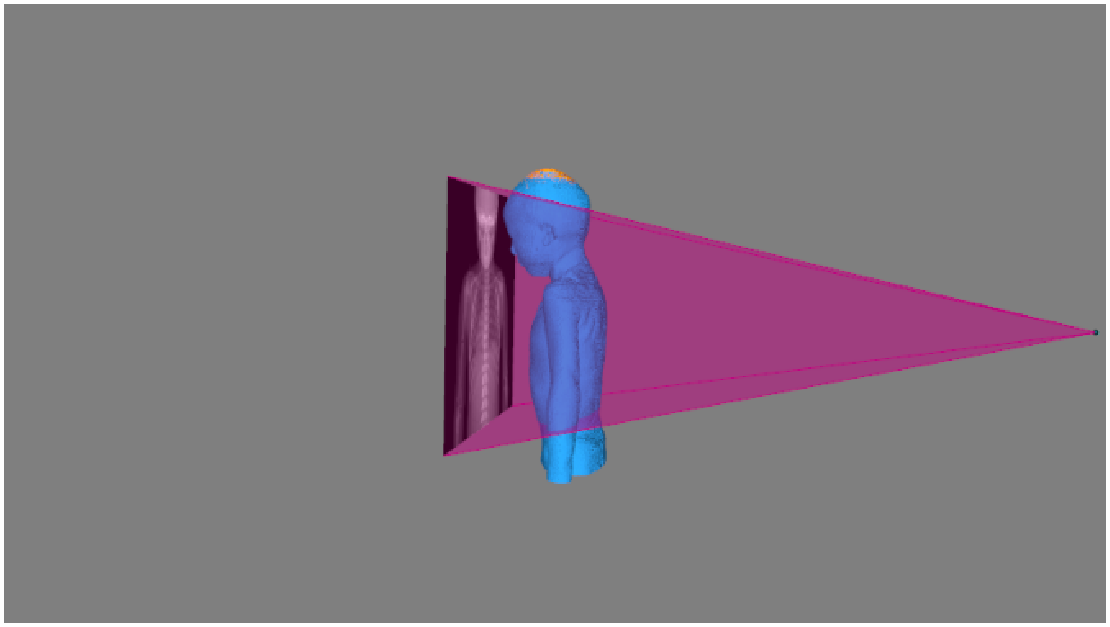
[25]:
```python
fname = 'pediatric_phantom_data/screenshot.png'
if not os.path.isfile(fname):

    plt.imsave(fname, screenshot)
```

[26]:
```python
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()
```

[27]:
```python
screenshot = (255 * np.array(gvxr.takeScreenshot())).astype(np.uint8)
```

[28]:
```python
plt.figure(figsize= (10,10))
plt.title("Screenshot")
plt.imshow(screenshot)
plt.axis('off')

plt.tight_layout()

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

Screenshot



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

[29]:
```
# 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

[30]:
```
# 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('gVirtualXRay_output_data/projection_raw_integration_GPU_paediatrics.
↪tif', x_ray_image_integration_GPU.astype(np.single))
```

Flat-field correction

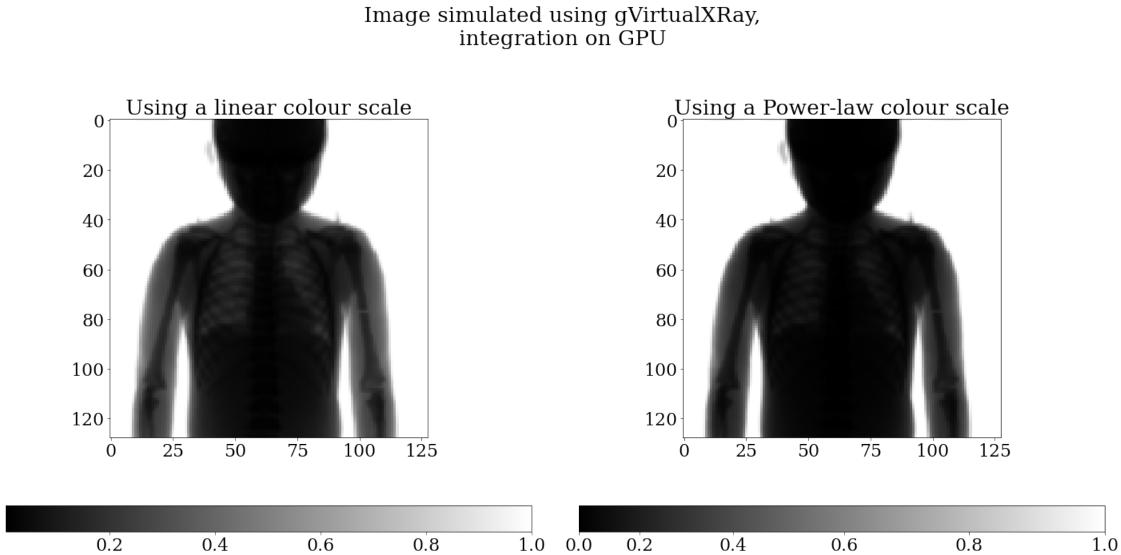
[31]:
```
total_energy_in_keV = 0.0
for energy, count in zip(energy_set, count_set):
    total_energy_in_keV += energy * count

total_energy_in_MeV = gvxr.getTotalEnergyWithDetectorResponse()
```

[32]:
```
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

[33]:
```
imwrite('gVirtualXRay_output_data/
 ↪projection_corrected_integration_GPU_paediatrics.tif',
 ↪x_ray_image_integration_GPU.astype(np.single))
```

[34]:
```
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('plots/x_ray_image_integration_GPU-paediatrics.pdf')
plt.savefig('plots/x_ray_image_integration_GPU-paediatrics.png')
```



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 disimilarity 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 s 0%; of ZNCC 100%, and SSIM 1.

[35]:
```
# 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: 2.23%
ZNCC_integration_GPU: 99.99%
SSIM_integration_GPU: 0.99
```

Get the total number of triangles

[36]:
```
number_of_triangles = 0

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

[37]:
```
runtime_avg = round(np.mean(runtimes))
runtime_std = round(np.std(runtimes))
```

Print a row of the table for the paper

[38]:
```
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 & 2.23\%
&    99.99\%    &    0.99    &    $1024 \pm 1024$    &    3552778    &
8.68E+08    &    $157 \pm 5$ \\
```

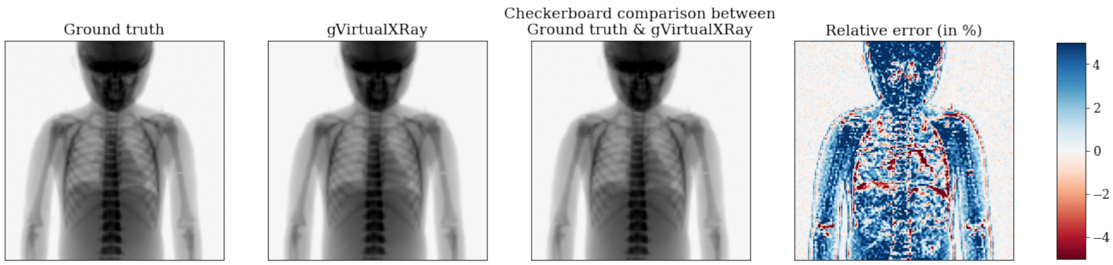
In both cases, MAPE is very small (less than 5%), ZNCC is very high (more than 99%), and SSIM is very high (almost 1). We can conclude that the two images are similar. The main difference lie in the Poisson noise affecting the Monte Carlo simulation.

5.2 Qualitative validation

Checkboard comparison

[39]:
```
font = {'size'   : 12.5
       }
matplotlib.rc('font', **font)
```

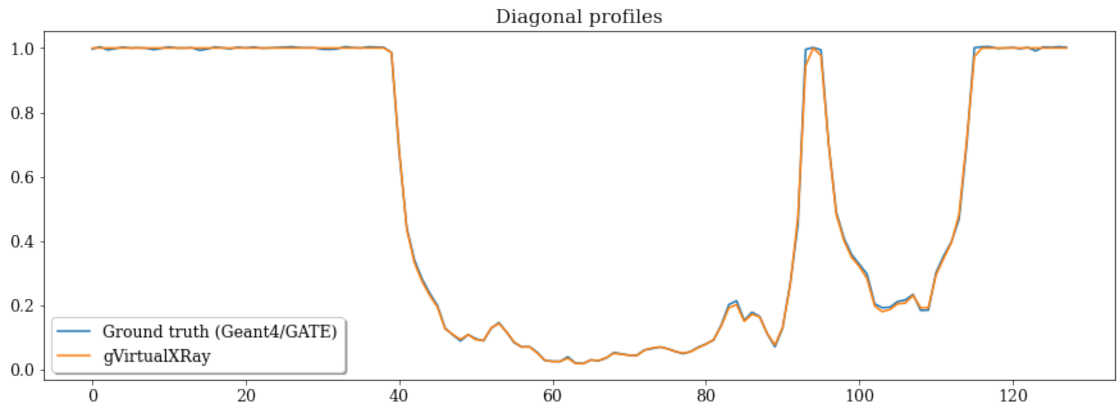
[40]:
```
fullCompareImages(gate_image,
                  x_ray_image_integration_GPU,
                  "gVirtualXRay\n with integration on GPU",
                  "plots/full_comparison_integration_GPU-paediatrics", log=True,
                 avoid_div_0=True)
```



Plot the profiles

[41]:
```
font = {'size'   : 12.5
       }
matplotlib.rc('font', **font)
```

[42]:
```
ground_truth_diag = np.diag(gate_image)
gvxr_diag = np.diag(x_ray_image_integration_GPU)

plt.figure(figsize=(15, 5))

ax = plt.subplot(111)

ax.set_title("Diagonal profiles")

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

ax.legend(loc='best',
          ncol=1, fancybox=True, shadow=True)

plt.savefig('plots/profiles-paediatrics.pdf')
plt.savefig('plots/profiles-paediatrics.png')
```



6 All done

Destroy the window

[43]:
```
gvxr.destroyAllWindows()
```

0(0x5603fb9848e0)