Iterative reconstruction - a dose saving paradigm in paediatric computed tomography imaging

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Aims and objectives

The Iterative Reconstruction (IR) algorithm alongside filtered back projection (FBP) is now standard on most Computed Tomography (CT) scanners sold today. It allows one to significantly reduce the radiation dose to the patient without reducing diagnostic image quality. This work will demonstrate that Iterative Reconstruction (IR) is an effective dose saving technique in paediatric CT imaging.

With the introduction of "iDose 4" Philips's IR solution at TSCUH patient CT doses have been dramatically reduced without the loss of diagnostic information that is image quality. iDose 4 is a fourth generation IR technique which uses an advanced reconstruction algorithm to produce diagnostic images equivalent or better than those acquired using FBP, the industry standard, however at a fraction of the dose overcoming low dose limitations such as image noise and streak artefacts while optimizing and improving both spatial and contrast resolution. The user is able to alter the level of IR from 1-7 progressively increasing the smoothing effect as more image noise is removed relative to FBP. This enables one to enhance image quality and significantly reduce dose 1.

The principles of justification, optimisation and the idea of ALARA (as low as reasonably achievable) are vital due to the susceptibility and greater lifetime risk of the paediatric population to radiation harm from significant doses of radiation as demonstrated by Pearce et al (2012) 2 and Matthew et al (2013) 3. Following the Pearce study the Alliance for Radiation Safety in Paediatric Imaging remarked that the radiation risk from CT should be discussed and factored into the decision-making process with the immediate benefits outweighing a very small long-term risk. Furthermore non-ionizing imaging alternatives were recommended & "kid-sized" radiation doses 4.

The ALARA principle while at the same time presenting the Radiologist with the required diagnostic information for effective patient management, sufficient diagnostic image quality must be maintained. Too low a dose may be as bad if not worse than too high a dose especially if one has to repeat the scan due to insufficient information the first time around. This was further echoed by Dr Kalendar (ECR 2013) recommending that image quality or diagnostic performance should not be compromised through the Radiation exposure being reduced too much.

It is vital to keep the ALARA principle in mind however the benefit-to-risk ratio has to be as high as reasonably achievable - "AHARA is the goal!" 5. IR is in our opinion is a major step in achieving this goal. Dose reduction is now accepted as required and national standards along with EU directives are imposing same on users. Manufacturers have
responded by selling CT systems on their dose saving capabilities along with diagnostic image quality and workflow abilities rather than just price.

International initiatives such as Image gently (launched January 2008)\textsuperscript{4} and Eurosafe (launched ECR 2014)\textsuperscript{6} are prompting and driving the message of radiation protection, quality and safety within medical imaging not just among the medical community but also for the patient and general public. The key to success lies within DRL’s compliance, clinical audit, "appropriateness" and the use of up-to-date equipment and technology.
Methods and materials

A survey was performed of Temple Street Children’s University Hospital (TSCUH) CT patient data prior to the introduction of IR on the Philips Brilliance CT scanner in 2012. This data was compared to our current CT data for the years following the installation up to 2015. This data is then benchmarked against our pre-IR data, national Irish dose reference levels and international data as presented at the Eurosafe launch at ECR 2014.

In 2010 the office of the Medical Exposures Radiation Unit (MERU) of the Irish Health Service Executive (HSE) with guidance from the National Radiation Safety Committee carried out a baseline national CT Dose Survey under Article 22.6 of SI 478 - in order to "collect and publish statistics on population dose levels from the use of medical ionising radiation". The information requested included exposure parameters such as protocol kVp, mAs in addition to the Dose Reference Levels (DRLs). This in the years following has become an annual requirement.

DRLs were defined by the MERU as "dose levels in medical Radio-diagnostic practices for typical examinations for groups of standard-sized patients for broadly defined types of equipment "and maintained that these levels are not expected to be exceeded "for standard procedures when good and normal practice regarding diagnostic and technical performance is applied.". They also recommended regular review and audit of the doses delivered and guidance on the action to be taken in the event of DRLs being exceeded.

The survey categorised the paediatric population into four age bands (0-1 years, 1-5 years, 5-10 years & >10 years of age).

However it is important to note in TSCUH that while our Head imaging is age-based, all our body imaging is weight-based as per best practice and current literature.

For direct comparison and correlation with national and published data these weight grouping have been converted to approximated age categories.

A local dose audit is performed and reviewed annually in TSCUH resulting in several scan parameters, levels of IR and DRLs being adjusted as necessary yet ensuring a sufficient level of diagnostic image quality is maintained. This information formed the basis of TSCUH annual DRLs as submitted to the MERU.
It must also be noted that following the installation of IR, the additional voltage level of 100kV was obtained offering dose saving opportunities in addition to all the benefits of IR. IR has been the default setting on all TSCUH CT protocols since its’ installation in 2012.

This data from 2012 to 2015 was then compared to the National Irish Dose Reference Levels$^{10,11}$ and international data from the UK$^{12,13,14}$, France$^{15}$ and Switzerland$^{16}$ as presented at the Eurosafe launch at ECR 2014$^6$. Categories chosen to directly compare were CT head, chest and abdomen.
The DRLs have reduced dramatically since the installation in 2012. These dose savings were immediately apparent - for example within the CT Brain 0-2 years age-group protocol, the Dose Length Product (DLP) was reduced from 469mGycm to 197mGycm thus representing a 58% reduction, while the abdominal/pelvis 20-40kg protocol DLP reduced from 273mGycm to 92mGycm resulting in a 66% reduction (Table 1). In over two years TSCUH have achieved substantial dose savings and IR (iDose levels 3-5) is the default setting on all our CT Protocols since its installation in 2012. See Table 2 for current TSCUH 2015 CT protocols and associated parameters.

<table>
<thead>
<tr>
<th>TSCUH CT PROTOCOLS</th>
<th>PRE- IDOSE 2012</th>
<th>POST-IDOSE 2013</th>
<th>2012 vs 2013</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75th Percentile</td>
<td>75th Percentile</td>
<td>Dose Saving</td>
</tr>
<tr>
<td></td>
<td>DLP (mGycm)</td>
<td>DLP (mGycm)</td>
<td>(%)</td>
</tr>
<tr>
<td>Brain Axial 0-2y</td>
<td>469.77</td>
<td>197</td>
<td>58%</td>
</tr>
<tr>
<td>Brain Axial 2-6y</td>
<td>598.35</td>
<td>313</td>
<td>48%</td>
</tr>
<tr>
<td>Brain Axial &gt;6y</td>
<td>728.77</td>
<td>372</td>
<td>49%</td>
</tr>
<tr>
<td>Brain Axial &gt;12y</td>
<td>NEW</td>
<td>586</td>
<td>NEW</td>
</tr>
<tr>
<td>Chest helix &lt;10kg</td>
<td>22</td>
<td>21</td>
<td>4.30%</td>
</tr>
<tr>
<td>Chest helix 10-30kg</td>
<td>38.1</td>
<td>25</td>
<td>34%</td>
</tr>
<tr>
<td>Chest helix 30-40kg</td>
<td>57.52</td>
<td>47</td>
<td>18%</td>
</tr>
<tr>
<td>Chest Helix &gt;40kg</td>
<td>196.8</td>
<td>77</td>
<td>61%</td>
</tr>
<tr>
<td>Abd/pel 0-20kg</td>
<td>64.5</td>
<td>48</td>
<td>25%</td>
</tr>
<tr>
<td>Abd/pel 20-40kg</td>
<td>273</td>
<td>92</td>
<td>66%</td>
</tr>
<tr>
<td>Abd/pel 40-60kg</td>
<td>544.9</td>
<td>131</td>
<td>76%</td>
</tr>
<tr>
<td>Abd/pel &gt; 60kg</td>
<td>724.1</td>
<td>199</td>
<td>72%</td>
</tr>
</tbody>
</table>

*Table 1: TSCUH DRLs represented as the 75th percentile for CT protocols pre and post iDose4 installation for 2012 and 2013 with percentage change.*
<table>
<thead>
<tr>
<th>TSCUH CT Protocols 2015</th>
<th>kV</th>
<th>mAs</th>
<th>Average CTDi</th>
<th>2015 75th DRL DLP (mGycm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain Axial 0-2y</td>
<td>100</td>
<td>140</td>
<td>13</td>
<td>204</td>
</tr>
<tr>
<td>Brain Axial 2-6y</td>
<td>100</td>
<td>200</td>
<td>19.2</td>
<td>291</td>
</tr>
<tr>
<td>Brain Axial &gt;6y</td>
<td>100</td>
<td>250</td>
<td>24</td>
<td>387</td>
</tr>
<tr>
<td>Brain Axial &gt;12y</td>
<td>120</td>
<td>230</td>
<td>36</td>
<td>584</td>
</tr>
<tr>
<td>chest helix &lt;10kg</td>
<td>80</td>
<td>25</td>
<td>0.9</td>
<td>22</td>
</tr>
<tr>
<td>chest helix 10-30kg</td>
<td>100</td>
<td>40</td>
<td>0.9</td>
<td>48</td>
</tr>
<tr>
<td>chest helix 30-40kg</td>
<td>100</td>
<td>55</td>
<td>1.57</td>
<td>82</td>
</tr>
<tr>
<td>chest Helix &gt;40kg</td>
<td>100</td>
<td>60</td>
<td>2.1</td>
<td>102</td>
</tr>
<tr>
<td>chest Helix &gt;60kg</td>
<td>100</td>
<td>100</td>
<td>2.9</td>
<td>115</td>
</tr>
<tr>
<td>Abd/pel 0-20kg</td>
<td>80</td>
<td>50</td>
<td>1.1</td>
<td>41</td>
</tr>
<tr>
<td>Abd/pel 20-40kg</td>
<td>100</td>
<td>60</td>
<td>2.4</td>
<td>123</td>
</tr>
<tr>
<td>Abd/pel 40-60kg</td>
<td>100</td>
<td>100</td>
<td>2.4</td>
<td>205</td>
</tr>
<tr>
<td>Abd/pel &gt; 60kg</td>
<td>120</td>
<td>150</td>
<td>3.4</td>
<td>209</td>
</tr>
<tr>
<td>Abd/pel &gt; 100kg</td>
<td>120</td>
<td>250</td>
<td>4.9</td>
<td>312</td>
</tr>
</tbody>
</table>

*Table 2: TSCUH 2015 CT parameters including kV, mAs, CTDI and 75th percentile.*

Figure 1 shows our CT Brain (sequential acquisition) local DRLs as DLP across the various age categories with Figure 2 displaying the percentage changes from year to year. The pre-iDose\(^4\) data represents the DRL pre-IR installation when filtered back-projection (FBP) was used as the default reconstruction algorithm. The 100kV additional voltage option obtained with IR also contributed to the immediate dose savings for the
0-12yrs age categories. It is clear from these graphs that after our immediate dose reductions following the IR installation, our DRLs have generally plateaued for CT Brain examinations with little variation or change in DRL occurring throughout the years. This audit process clearly demonstrates that optimisation of CT brain protocols has been successful.

Figure 3 and figure 4 represent our CT Chest (helical acquisition) data. Yet again the 100kV option has caused quite an impact on the DRL pre and post iDose\textsuperscript{4} particularly in the >40kg protocols. Of note is the variance with our DLP values creeping up for all ages apart from the <10kg infants. In addition to the 100kV option acquired with IR, Philips DoseRight dose modulation changed its active process which in turn required all the CT body protocols using dose modulation to be modified as the system previously did not take into account the Water Equivalent Diameter (WED)\textsuperscript{17}. In the years following IR installation, the DRLs were increased as higher spatial resolution was deemed necessary for chest examinations however the DRL dose levels are still lower than the pre-IR levels. DoseRight still uses Automatic Current Selection (ACS) and longitudinal dose modulated (Z-DOM), however with IR it also takes into account the WED. The system compares the patient diameter from the surview/topogram to the pre-stored WED phantom diameters based on the body part and infant/child/adult category, and from this it suggests an optimum maximum mA depending on the amount of variation. Z-DOM is also active within the process and the selected kV may also affect the mA value suggested. In addition image filters and iDose\textsuperscript{4} levels of IR were modified for each annual review as the IR worked too efficiently at removing image noise and the resultant images particularly the lung windows were deemed too smooth with an apparent loss of sharp image detail and spatial resolution.

Figure 5 and figure 6 depicts our CT Abdomen (helical acquisition) DLP DRLs since 2012. While again we have significant dose reduction for the larger patient, 84% for the 40-60kg range with 81% seen for the >60kg, but note that dose creep is occurring for the <60kg weights apart from patients <20kg following the initial reduction. Yet again the DoseRight dose modulation process plays a part as it did for the CT Chest protocols however they are still considerably less than the pre-IR data. In the abdominal CT protocols the image filters did not require modification however the mA and iDose\textsuperscript{4} levels were increased as to improve the level of contrast resolution and reduce image noise in the soft tissue image windows.

The box and whisker plots represent our current 2015 DRLs for CT routine brain (Fig. 7), chest (Fig. 8) and abdomen (Fig. 9) protocols. Top of the box represents our 75\textsuperscript{th} percentile while the median value is the straight line through the box. At a glance one can visualise the spread for the population in each category, whether the median or peak of the distribution is leaning towards the upper or lower end of our DRLs indicating that a
change may be required due to inappropriate weight categorisation or that outliers might be affecting our data. However as the national paediatric centre for several specialities such as neurosurgery, craniofacial, metabolic and endocrinology; our patients vary not just due to age and weight but also physical characteristics due to their medical condition. This adds complexity to our patient cohort highlighting the importance of regular review and audit of CT protocols and parameters to ensure they are appropriate and best represents the patient population. For IR to operate efficiently at reducing patient dose while yet maintaining a high level of the required image quality, the box plots may suggest that CT protocols may require further investigation and adjustments.

Figure 10 (CT brain data) and figure 11 (CT chest data) compares our local TSCUH DRLs to published national\textsuperscript{10,11} and international data\textsuperscript{12-16}. In benchmarking data\textsuperscript{9,10} from TSCUH against national and international best practice, there is significant difference between our hospital and the published data apart from Great Ormond Street Children's Hospital (GOSH)\textsuperscript{14}. GOSH uses different weight divisions that are narrower which might explain their slightly lower values. For CT chest examinations in patients <1 years old our DRL DLP is 22mGycm compared to 14mGycm for GOSH. One possibility for this variation is the method of dose modulation if any that is applied.

In TSCUH due to image quality issues related to the CT chest <10kg protocol which used the updated Philips IR DoseRight modulation based on the WED reduced the dose to unacceptable non-diagnostic levels. We therefore switched off dose modulation on the <10kg CT chest protocol only.
Fig. 1: TSCUH DRL DLP for CT brain protocols since 2012

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Fig. 2: TSCUH DRL percentage change for CT brain protocols since 2012

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Fig. 3: TSCUH DRL DLP for CT chest protocols since 2012

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**Fig. 4:** TSCUH DRL percentage change for CT chest protocols since 2012

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**Fig. 5:** TSCUH DRL DLP for CT abdomen protocols since 2012
Fig. 6: TSCUH DRL percentage change for CT abdomen protocols since 2012
Fig. 7: DRLs Box and whisker plots for TSCUH DLP for CT brain 2015 depicting spread (top of the box representing the 75th percentile) and range in each age category

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Fig. 8: DRLs Box and whisker plots for TSCUH DLP for CT chest 2015 depicting spread (top of the box representing the 75th percentile) and range in each age category

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Fig. 9: DRLs Box and whisker plots for TSCUH DLP for CT abdomen 2015 depicting spread (top of the box representing the 75th percentile) and range in each age category

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Fig. 10: TSCUH CT Head DRL DLP age based data compared to published international data

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Fig. 11: TSCUH CT Chest DRL DLP age based data compared to published international data

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Conclusion

Manufacturers have introduced IR as standard on nearly all new scanners, though some are still offering it as an additional option on existing scanners. Through IR significant dose reduction (>50%) are possible without a loss of diagnostic quality and in many cases enhanced spatial and contrast resolution\textsuperscript{6,18}.

Since we are a paediatric centre, radiation dose is of paramount concern to us and we embraced IR and applied it to all protocols with immediate substantial dose savings of up to 68% for brain imaging and 76% for abdominal imaging while yet maintaining a high level of image quality necessary for patient diagnosis and management. It should also be remarked from our data that regular audit and review of image quality and dose is also required.

In the years following the initial dramatic dose reductions in CT examination protocols associated with the installation of IR dose creep may be seen. In several cases the DRL doses are slowly creeping up (CT chest and abdomen) but not to the previous pre-IR levels, in the case of routine CT brain an optimum level was developed quickly and maintained.

Some resistance still exists in the medical community as the resultant images appear smoother due to the difference in the noise texture compared to FBP. This is a similar situation that was encountered during the transition from film (analogue) to digital imaging requiring a change of mind-set and has an inherent learning curve. This may be addressed on a local level during the installation of IR and in the conversion of CT parameters from FBP to IR with some imaging centres initially applying IR settings conservatively with a review date scheduled for further modification.

Too low a dose leading to non-diagnostic images is not in the spirit of the ALARA principle and successful imaging is achieved through constant vigilance from the entire radiology team, radiologists, radiographers, and medical physicists\textsuperscript{6,18,19,20,21}. CT is an important tool in medical imaging however careful and prudent use is advised in paediatric imaging in accordance with the ALARA principle; and in our experience IR is crucial to achieving this\textsuperscript{18}.

In conclusion IR should and must be the default reconstruction algorithm in paediatric CT imaging.
Fig. 2: TSCUH DRL percentage change for CT brain protocols since 2012

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**Fig. 10:** TSCUH CT Head DRL DLP age based data compared to published international data

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