Faculty of Science and Technology of the University of Coimbra

Master´s in Biomedical Engineering

M. Sc. Thesis

Study of Pediatric Exposure in CT: Assessment of Radiosensitivity Issues

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DISCLAMER

In the framework of the studies undertaken reported in this work, two representative pediatric hospitals in Portugal were visited and access to the existing pediatric data was kindly provided by the managers and responsibles of the services in those hospitals.

For the sake of maintaining the anonymous aspects concerning the data kindly provided and of the professionals and patients of the Services visited, these Hospitals will not be explicitly identified or named but instead they will be referred to in the study as “Hospital A” and “Hospital B”.

List of Acronyms

AAPM – American Association of Physicists in Medicine
ACR – American College of Radiation
ASRT – American Society of Radiologic Technologists
BEIR – Biological Effects of Ionizing Radiation
CDRH – Center for Devices and Radiological Health (US)
CT – Computed Tomography
CTDI – Computed Tomography Dose Index
DFOV – Display Field of View
DLP – Dose Length Product
DRL – Dose Reference Levels
FWHM – Full Width at Half Maximum
HU – Hounsfield Units
IAEA – International Atomic Energy Agency
ICRP – International Commission on Radiological Protection
KERMA – Kinetic Energy Released per Unit Mass
LET – Linear energy Transfer
LNT – Linear Non-Threshold
MRI – Magnetic Resonance Imaging
NCRP – National Commission on Radiological Protection (US)
OER – Oxygen Enhancement Ratio
PACS – Picture Archiving and Communication system
PDU – Power Distribution Unit
PMMA – Polymethyl-methacrylate
RBE – Relative Biological Effectiveness
SFOV – Scan Field of View
SPR – Society for Pediatric Radiology
UNSCEAR – United Nations Scientific Committee on the Effects of Atomic Radiation

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ABSTRACT

Since its first clinical implementation in the early 1970s, Computed Tomography (CT) became a powerful and accurate imaging tool for medical diagnostic. The technological developments in CT during the last decades triggered the worldwide dissemination of this technique, with a dramatic increase in the frequency of medical examinations using CT. However, despite of its many advantages, especially for non-invasive diagnostic in traumatic cases, CT scans are characterized by a significantly higher patient exposure to ionizing radiation, in some cases by a factor of 100 higher doses, compared to those in Conventional Radiology examinations. This impressive surge in the patient doses and the associated potential detrimental consequences for the health of individuals became lately in recent years a matter of concern in different communities of experts worldwide.

This concern is amplified by the uncertainties currently affecting the scientific state-of-the-art about the biological effects of low dose radiation and radiological risk versus dose relationship in the dose range covered by typical CT examinations. Moreover, accumulated evidence for a strong radiosensivity dependence with the age of the exposed individuals associated to the longer lifetime of individuals, made of pediatric exposures in the framework of CT examinations a burning subject.

Many campaigns aiming at increasing the awareness about these topics and calling for the reduction of dose exposure while keeping the necessary image quality have been initiated in the last decade, especially concerning children, due to their high radiosensitivity and potentially harmful effects caused by exposures to ionizing radiation of newborns, babies, children and adolescents.

Recently, the Image Gently campaign, the American College of Radiology, the International Commission on Radiological Protection (ICRP) and several other international institutions, have alerted the scientific and non-scientific communities for the potential harmful effects resulting from excessive exposure at young ages; these entities and organizations are trying to promote the awareness of medical doctors, radiographers, radiation protection experts, regulators, the general public as well as other stakeholders, about the need to correctly justify and optimize the medical practices involving the utilization of ionizing radiation. The ultimate goal being to lower radiation doses in medical imaging examinations while keeping image quality necessary for an accurate and correct diagnostic.

In the present study, data corresponding to pediatric CT examinations performed for a certain period of time in two Portuguese hospitals were collected, compiled and analyzed; the technical parameters (kV, mAs, pitch, etc.) of the performed scans are compared to those recommended in international pediatric

protocols in other countries. Evidence was gathered that, for certain types of exams, and for certain age groups, the Computed Tomography Dose Index ($CTDI_{vol}$) or the Dose Length Product (DLP) values were higher than those used in in pediatric protocols in other countries, leading to higher (and in some cases excessive) exposures to ionizing radiation doses.

This study also reports on the measurements performed using four CT equipments in two Portuguese hospitals together with appropriate equipment (namely a PMMA phantom and an ionization chamber), of dosimetric CT parameters namely the $CTDI_{vol}$. For some of the measurements performed, using the same parameters (kV and mA) as in some pediatric protocols, the $CTDI_{vol}$ exceeds the recommended values; therefore, there is a need for protocol review and optimization.

RESUMO

A Tomografia Computorizada (CT) é actualmente uma ferramenta de diagnóstico amplamente utilizada em todo o mundo. Desde a sua primeira utilização no início dos anos 70 que a CT tem vindo a evoluir consideravelmente, registando-se actualmente cerca de 62 milhões de exames anuais apenas nos EUA. Apesar das suas múltiplas vantagens, especialmente em diagnóstico não-invasivo em casos de traumatismo, os exames de Tomografia Computorizada expõem os paciente a uma maior dose de radiação ionizante, quando comparados com Radiologia Convencional. Este facto, e os problemas de saúde que advêm de uma exposição excessiva, têm vindo a ser discutidos por várias comunidades de profissionais de radiologia mundialmente.

As incertezas quanto aos efeitos biológicos de radiação de baixa dose, a relação risco radiológico-dose e as recentes descobertas sobre a dependência da radiosensibilidade com a idade, especialmente em crianças, tornam os exames de CT, especialmente pediátricos, alvo de preocupação e discussão.

Na última década, várias campanhas de sensibilização sobre o assunto foram publicadas, prevenindo os profissionais de saúde sobre os riscos inerentes a uma exposição excessiva em crianças, particularmente radiosensíveis; estas campanhas promovem a redução de dose em exames de CT, advertindo que, ainda assim, é possível manter uma boa qualidade de imagem para diagnóstico.

Actualmente, associações de profissionais de radiologia como o "American College of Radiology", a "International Comission on Radiological Protection (ICRP)", a campanha "Image Gently" e várias outras instituições tentam através de publicações aumentar a sensibilização da comunidade científica e não-científica para os efeitos prejudiciais da exposição excessiva em crianças de tenra idade. O principal objectivo é sensibilizar a comunidade médica para a redução de doses em exames de imagiologia médica, mantendo a qualidade de imagem necessária.

Neste estudo, dados de exames pediátricos de CT de dois hospitais Portugueses foram recolhidos e analisados. Parâmetros como kV, mA, pitch, etc. foram comparados com os valores recomendados em estudos europeus semelhantes. Foi provado que, para algumas idades, e para certos tipos de exames, o CTDI (CT Dose Index) e o DLP (Dose Length Product) são mais elevados do que o recomnedado, levando a um aumento da exposição.

Neste estudo procedeu-se também a medições em quatro equipamentos dos dois hospitais visitados; com um fantoma de PMMA e uma Câmara de Ionização, efectuou-se a medição de parâmetros dosimétricos de CT, como o $CTDI_{vol}$. Conclui-se

que em alguns protocolos pediátricos definidos nos hospitais se utilizam parâmetros que tornam excessivos os valores de exposição, devendo se revistos e optimizados.

ACKNOWLEDGMENTS

I would like to express my gratitude and appreciation to my supervisor, Dr. Pedro Vaz, from ITN, *Instituto Tecnológico e Nuclear* in Sacavém, for the advice, guidance, collaboration and availability that made this project attainable.

For the same reasons I want to phrase my gratefulness to my supervisor, Master Paula Madeira, senior radiographer at the Hospital S. José in Lisbon, who was always available to provide new suggestions, criticism and ideas to the work in progress.

I would like also to thank both for the contacts established with the Hospitals in which I was able to do research and improve my work.

In these contacts I include the five hospital's service directors, medical doctors and radiographers that authorized, supervised and monitored the data gathering process and the measurements performed using the equipments available; also to the engineers of the equipments (namely tomographs) manufacturers, for their explanations and skillful technical advice about the equipment's performance, components and the procedural aspects during calibration, maintenance and assemblage of CT or PET/CT scanners.

Last but not least, I would like to thank my parents, my close family and friends, and to Ignacio Lázaro, for the furtherance and strength provided along this year.

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1. INTRODUCTION

Evidence for the existence of a new form of radiation was gathered since around 1875 by scientists performing experiments using Crookes tubes, although Wilhelm Roentgen, a German physics professor, was the first to systematically study them and formally named them "X-rays", in 1895. Wilhelm Roentgen discovered accidentally in November of 1895 a new type of radiation, while experimenting on Crookes tubes; he realized that some invisible rays had a glowing effect on the black casing of the tube; he also noticed that these rays could also be transmitted through papers and even books. As they were an unknown type of rays, he referred to it as radiation X. Two months after his discovery, he published his paper, "*On a new kind of ray: A preliminary communication",* receiving the Nobel Prize in Physics for his studies. Several other studies over the origin and production of X-rays were developed by Nikola Tesla, Thomas Edison, Johann Hittorf, among others. This important discovery paved the way for the development of medical imaging techniques, materialized several decades later by the revolutionary discovery of Computed Tomography, in the late 1960s and its implementation and utilization in clinical environment since the 1970s.

It was during World War II that Godfrey Newbold Hounsfield, working at Central Research Laboratories of EMI Ltd. and studying radar air defense, started to develop work that would lead to the creation of the first CT scanner. The CT scanner was finally patented by Hounsfield in 1968. In September 1971, with the collaboration of several neurologists, the first CT scanner, named EMI Mark I, was installed at the Atkinson Morley's Hospital in Wimbledon, although it only allowed head examinations, due to its small opening (1).

During the period from the early seventies and the mid-nineties of the last century (say between 1971 and 1995), the outstanding achievements made possible by CT scanners and associated technology (succinctly described in the next Chapter) in terms of the image quality and unprecedently high accurate diagnostic possibilities overcame the assessment of the dosimetric assessment and characterization of this formidable tool. However, since the nineties, the communities of specialists started to become gradually aware and concerned about the higher ionizing radiation doses delivered to the patients and their potential detrimental aspects to the human health.

This was a consequence of the more accurate perception, supported by scientific studies during the last decades, about the risk associated to the exposure to ionizing radiation and of the establishment of a robust system of Radiological Protection, based on a continuously evolving scientific knowledge about the biological effects of ionizing

radiation, the different radiosensitivity of organs and tissues, and the age- and sex-dependent radiosensitivity of individuals.

International organizations and institutions (such as the UNSCEAR and the ICRP) and several communities of scientist and experts conducted studies, compiled scientific data, performed their analysis and published several studies and reports drawing the attention to the potential detrimental aspects resulting from an increasing exposure to ionizing radiations from medical imaging and diagnostic purposes.

The need to perform a more accurate assessment of the radiological risk versus dose and of the time-dependence of the radiological risk resulting from exposures to ionizing radiation in the framework of CT examinations became of paramount importance. As an example, the next Figure, extracted from reference (2) displays the estimated radiation-induced risk of cancer as a function of the age at exposure for two of the most common radiogenic cancers, using data from the BEIR-VII report (3) published by the United States National Academy of Sciences.

As a result of the aforementioned studies and growing awareness, pediatric exposures became during the last years a major cause of concern for the involved stakeholders, worldwide.

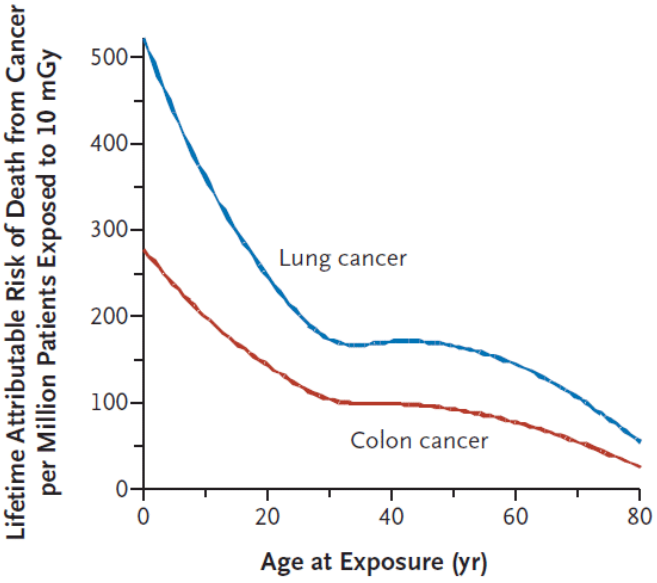


Figure 1. 1 - Lifetime radiation-induced risk of cancer as a function of the age at exposure for two of the most common radiogenic cancers. Reproduced from (2).

The scientific state-of-the-art on the biological effects of low dose radiation does not permit to unravel the shape of the radiological risk versus dose curve for representative doses of CT examinations (typically in the few mSv range). Next figure

(extracted from reference (3)) exhibits the almost complete lack of predictive power for the risk for low dose radiation.

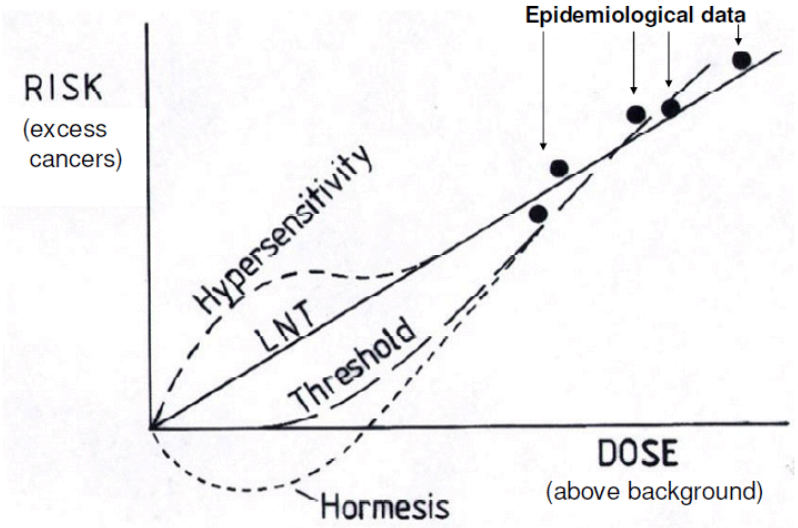


Figure 1. 2 – Cancer risk versus dose: uncertainty in the relationship for the low dose region (in the dose range of CT examinations) renders the extrapolation from the "high-dose" linear relationship to the low dose. Reproduced from **(3)**.

In recent years, the need to access with a better than existing accuracy, the risk versus dose relationship, was pinpointed by several communities of experts and the robustness of the international system of Radiation Protection was questioned. It is nowadays commonly accepted that during the coming years more emphasis must be placed – through scientific studies (experimental, epidemiological and computational) to produce major findings – on the following topics:

- Shape of dose-response for cancer
- Tissue sensitivities for cancer
- Individual variability in cancer risk
- Effects of radiation quality
- Risks from internal exposure
- Non-cancer diseases (risks and shape of dose response relationships)

Another source of concern is related to the dissemination, over the last two decades, of the utilization of CT scans for medical imaging purposes, in Diagnostic Radiology. The frequency of CT examinations has grown at a very strong page and the consequences, in terms of patient doses and exposures are still to be determined. As an example, the time-variation of the frequency of CT and MRI exams as well as the collective dose for the German population (extracted from (4)) are displayed in the next Figures. The overwhelmingly domination of the CT contribution to the total

effective dose per caput and per year is clearly depicted, with a duplication of its value during the period 1996-2008.

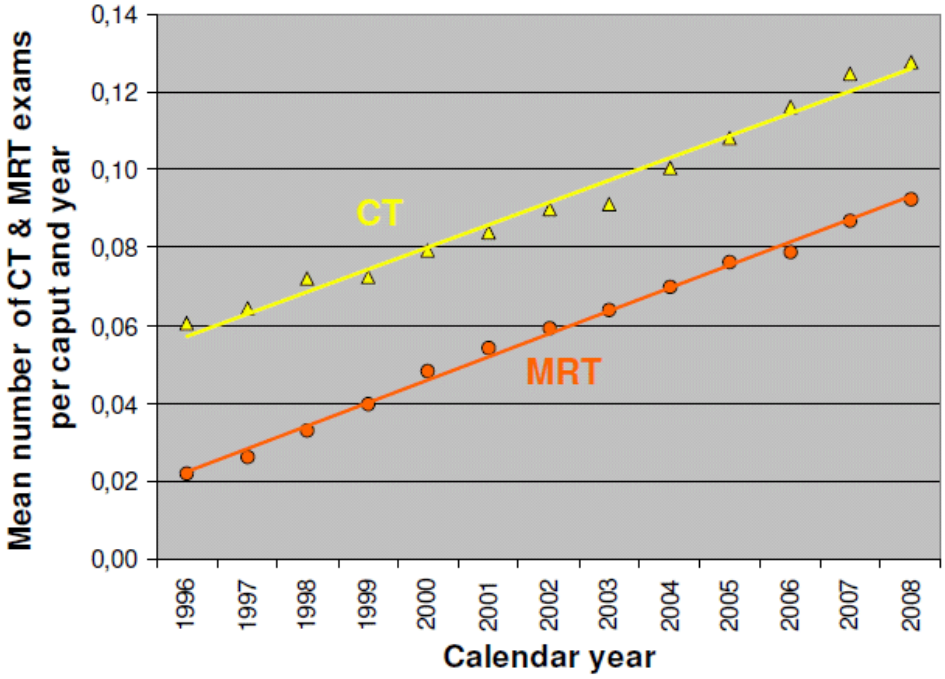


Figure 1. 3 – Mean number of CT exams per caput and per year, as a function of time in Germany, for the period 1996-2008. Reproduced from (4).

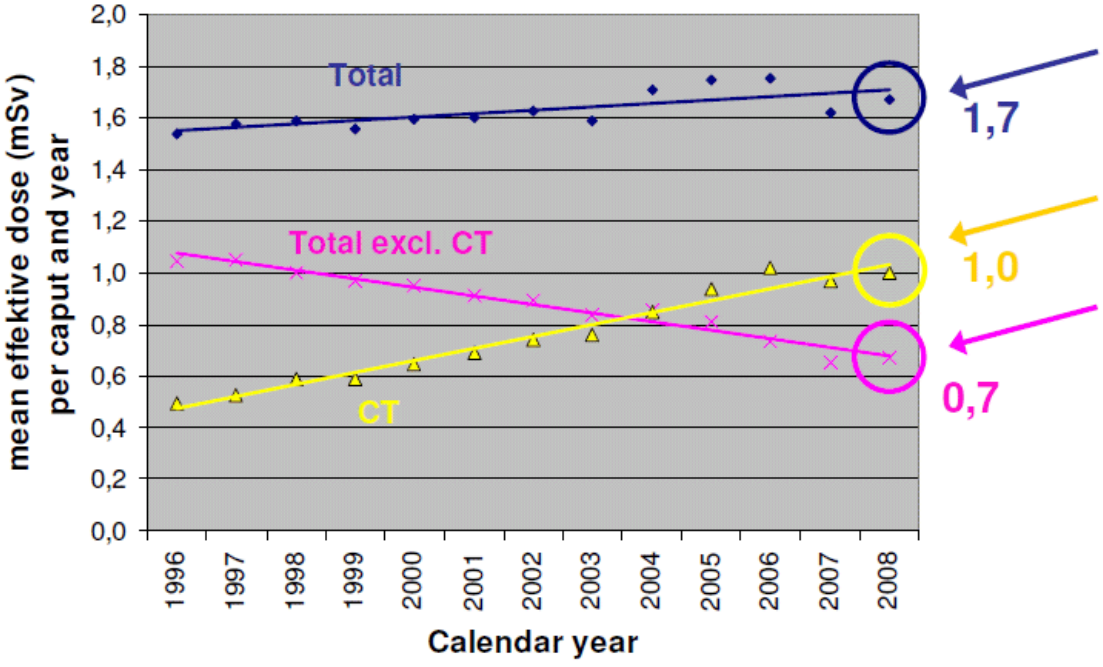


Figure 1. 4 - Mean effective dose per caput and per year, as a function of time in Germany, for the period 1996-2008. Reproduced from **(4)**.

In this study:

- The assessment of radiosensitivity issues associated to the pediatric CT examinations is performed. The compilation of available scientific information (reports of major international organizations such as UNSCEAR, BEIR, ICRP, refereed papers, etc.) and data on cancer risk data.
- The compilation and analysis of data, retrieved in two pediatric hospitals in Portugal is presented, namely concerning the technical parameters (Kv, mAs, others) used to undertake these examinations and the resulting dosimetric implications.
- Comparison of data with international protocols and recommendations or with protocols used in other countries is also performed.
- Measurements of CT dosimetric quantities to assess pediatric exposures are described, using CT equipments available in different hospitals and phantoms and appropriate radiation detection equipment (ionization chambers and electrometers).

The document is structured as follows:

- This Chapter sets the scene and puts in perspective the relevance of conduction the study with the aforementioned components
- Chapter 2 provides a technical analysis and description of the CT technology and associated dosimetric aspects which are of concern for the Radiation Protection of the patients undergoing CT scans and of workers.
- Chapter 3 describes dosimetric quantities in CT and also the structure and robustness of the International System of Radiological Protection is analyzed, in view of the currently observed uncertainties in the low dose region and associated scientific (open) topics.
- Chapter 4 is devoted to the issue of “Radiosensitivity”. The biological effects of ionizing radiation are described and the effects of radiation on the cellular mechanisms and on the DNA level are discussed.
- In Chapter 5, the pediatric data retrieved from the 2 pediatric hospitals is analyzed from a radiological protection and dosimetry point of view; the results are compared with protocols used in other countries and international recommendations about pediatric exposures
- In Chapter 6, the measurements performed in the two hospitals are presented, analyzed and compared with the European recommendations, followed by the final conclusions.

2. Technical Foundations of CT

2.1 Time Evolution of the Computer Tomography Technology

Since the beginning in 1971, CT scanners have been subjected to several modifications due to the further research performed and major technological developments aiming at improving image quality in diagnostic as well as the time required to perform each examination. The first CT scanners were named First-Generation scanners and used a parallel X-ray beam and two types of movement for the tube-detector array, a lateral movement to make a projection and a circular movement to assemble all the projections (Figure 2.1, top, left)). These features made the scanning time very long (around 5 minutes, and the same time to process the image data).

Around 1972, the Second-Generation scanners appeared, having 3 to 52 detectors in the array and a triangular beam shape, which allowed, in each single projection, to cover a larger area of the patient, and therefore, to reduce the number of projections (Figure 2.1, top, right)). However, the lateral and rotational motions were still used for the tube and detector matrix.

Only 4 years after the creation of the Second-Generation scanners, new progress was made when the lateral movement of the tube-detector system was eliminated, due to the wider triangular shaped beam (40º to 55º), which now covered the whole patient body (Figure 2.1, bottom)). Therefore, the movement was now exclusively rotational, and the Continuous Rotation Scanner or Third-Generation Scanners appeared.

To keep up with the new shape of the beam, these new scanners needed up to 1000 detector elements, and accordingly, the acquisition time was quite reduced. In this type of scanners, several projections are made for the first image, then the patient's table moves and the process is repeated for the next sections (1).

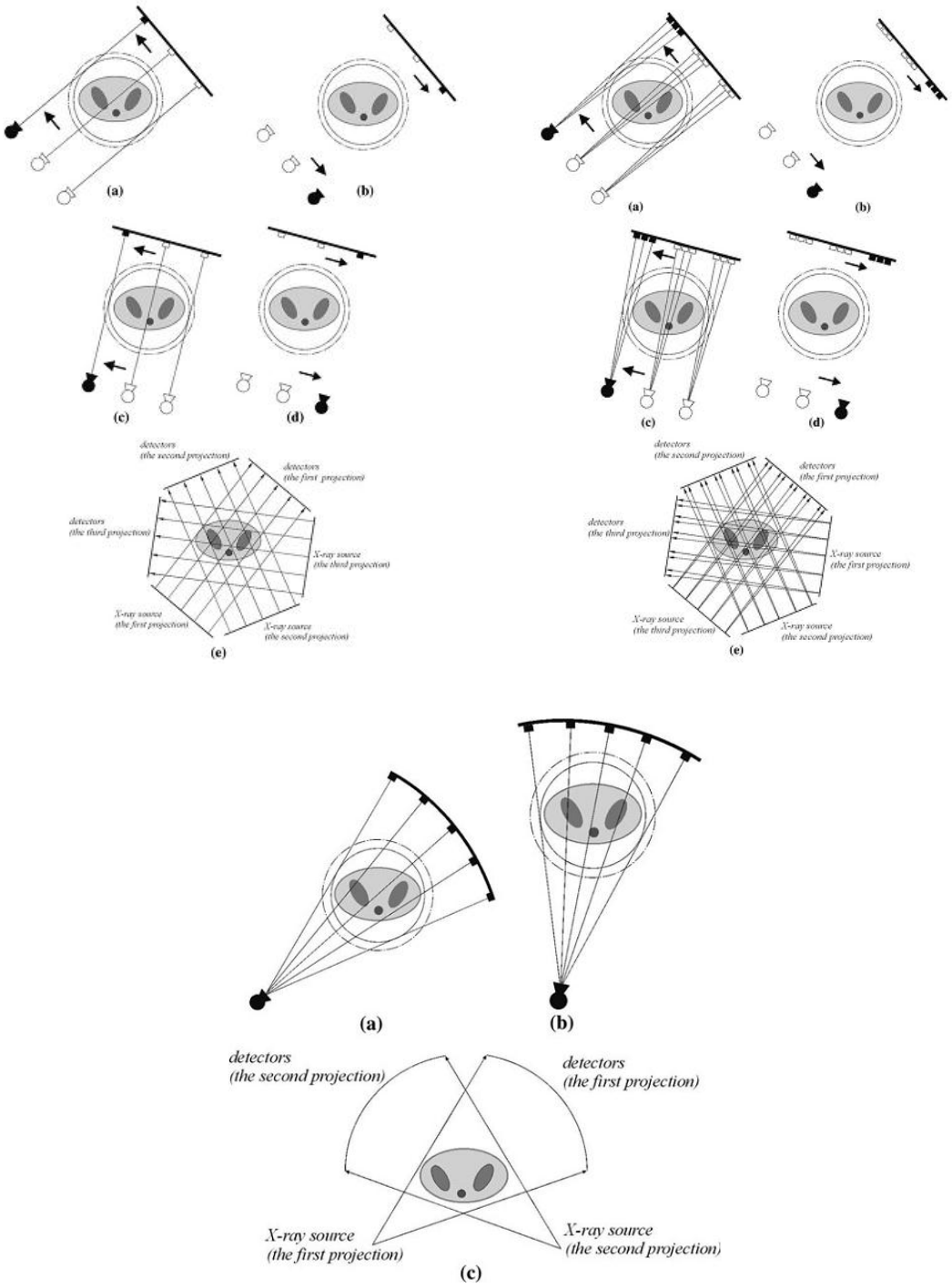


Figure 2. 1 – Top, left: Operating mode of a First-Generation CT scanner. The four upper images represent the acquisition-return pass process; the lower one is the series of the three acquisitions; Top, right: Operating mode of a Second-Generation CT scanner. The four upper images represent the acquisition-return pass process; the lower one is the series of the three acquisitions; Bottom, center: Third-Generation CT scanners. a) First acquisition, b) Second acquisition, c) set of two continuous acquisitions. Images reproduced from (1)**.**

The following generation of CT scanners, the Fourth-Generation, was introduced in 1978, also known as Rotate-Fixed Scanner. The main difference of the Third-Generation scanners was that the detector array was now immobilized in a ring bigger than the circle mapped by the X-ray tube (Figure 2.2, left)). The number of

detectors also increased, from 600 to 5000 elements, but the one image was still only completed after 5 seconds.

In 1989 the first CT scanner that joined both movement of the patient's table and the circular movement of the gantry was developed and named Single-Slice Spiral CT; however, only 9 years later, in 1998, the system was able to obtain four adjacent slices at the same time, due to a design of 8 to 34 rows of detectors in the matrix: Multislice Spiral CT.

Another improvement made from the previous CT scanners, was the cone-shaped X-ray beam, which permitted the acquisition of three dimensional projections (Figure 2.2, right)).

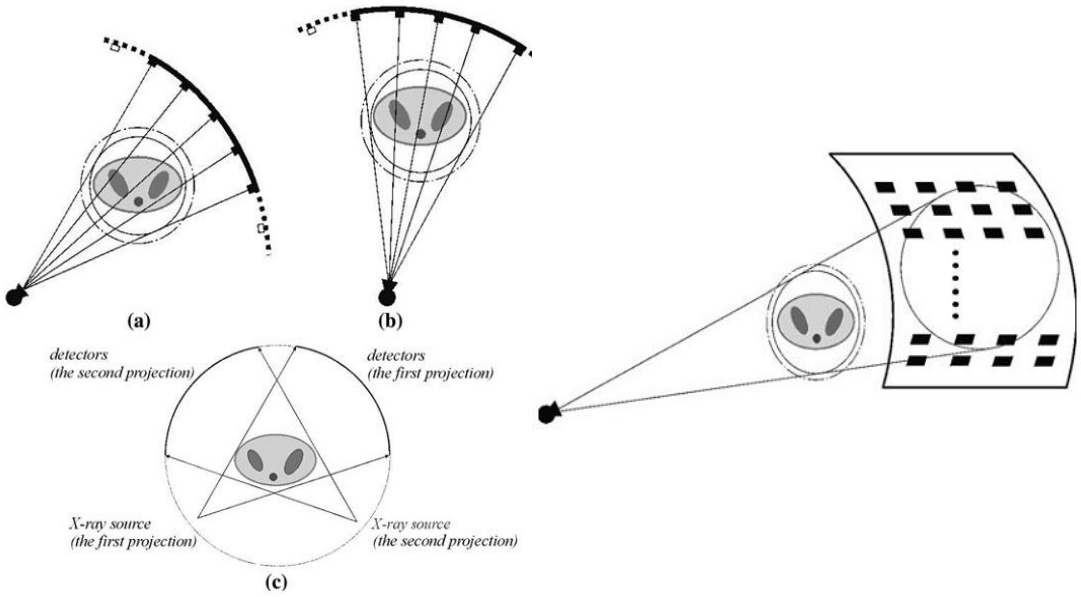


Figure 2. 2 – Left: Operating mode of a Fourth- Generation CT Scanner. a) First acquisition, b) Second acquisition, c) set of two continuous acquisitions. Right: The new cone-shaped beam, introduced in the beginning of the 21th century. Both images reproduced from (1)**.**

The new shape of the X-ray beam allowed to increase the size of the detector matrix, from 16 to 320 elements, and so, enabling the possibility of acquiring 256 adjacent images in a short time. This fact led to a reduction of the collimation artifacts, and therefore to a decrease of the X-ray power. With this new technology, the spatial resolution obtained was around 0,23 mm in each slice. The CT scanners used nowadays are still Multislice Helicoidal CT, and due to the low scan time, it's possible the observation of organs with permanent motion, such as the heart and lungs, and also of patients which for certain reasons cannot hold still, such as children (1).

Since the first tomographic examination in October 1971, CT scanners initiated a new era in medical imaging, allowing the obtainment of clear anatomical imaging non-invasively. It permitted the simultaneous acquisition of several slices, and along with its development, it was possible to achieve better temporal and spatial resolution, as well as the signal-noise relation. Its multiple advantages have avoided several surgeries in traumatic cases; this equipment can only be compared, on terms of versatility, precision and ease of image acquisition to a few devices in the medical field;

2.2 THE EQUIPMENT

A CT scan has the main objective to acquire data when X-rays go through the patient's body part, and then hit the detectors, subsequently generating an image (2). The equipment has two mains parts, the gantry and the patient table, as seen in figure 2.3:

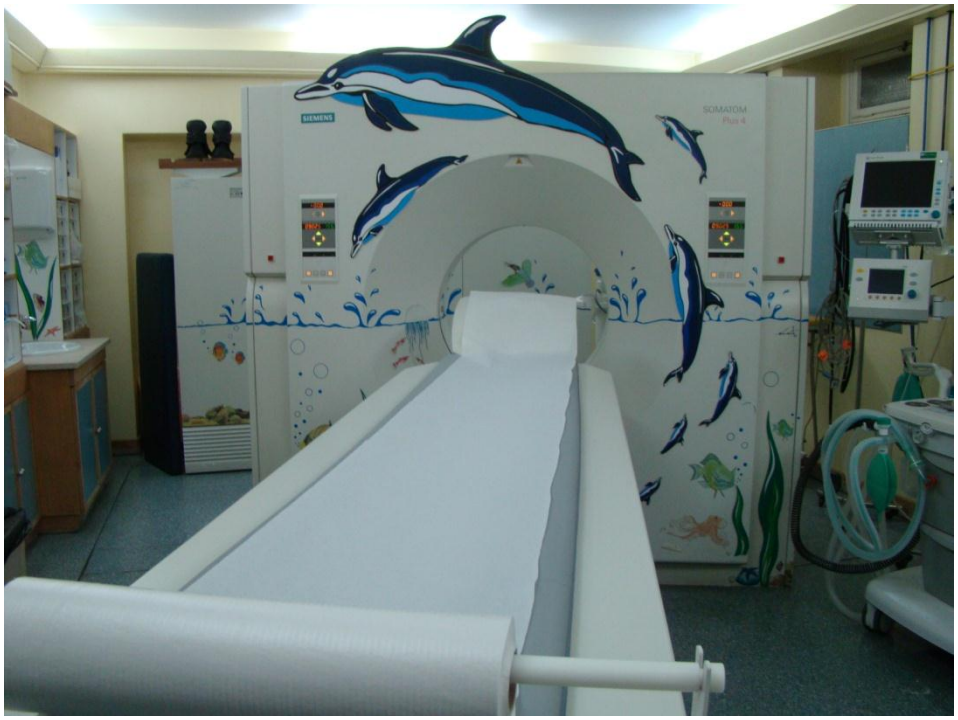


Figure 2. 3– CT scan of a Pediatric Hospital.

2.2.1 THE GANTRY

The gantry is the main component of the CT scan (Figure 2.4); the diameter of the aperture ranges from 70 cm to 90 cm, and all the components are placed around it. Components such as the power supply are made currently very light and with small dimensions, so they can be positioned in the mobile part, to achieve very high rotation speed. The first CTs used cables to rotate the frame, so a sequential rotation wasn't permitted: the gantry had to stop and change direction (2). Nowadays, the gantry has a system called *slipring*, which contains rings and brushes in contact, allowing a connection between the mobile and the fixed part of the gantry, and so, enabling the helical rotation, which turns much more efficient (3).

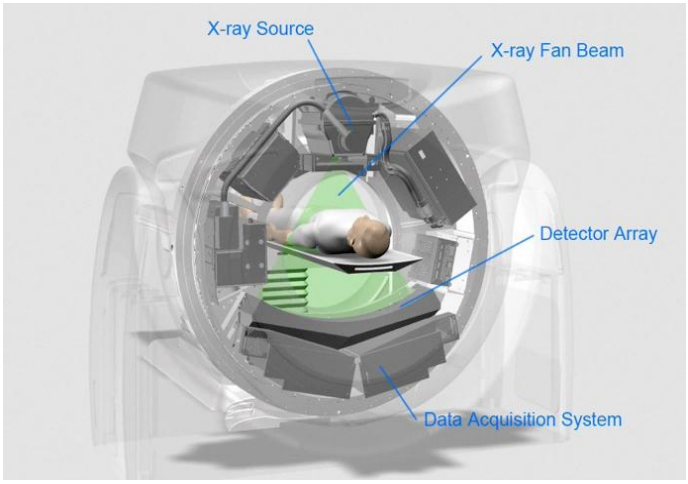


Figure 2. 4– Components of the gantry. Reproduced from (4)**.**

X-RAY SOURCE

The X-ray source is composed by an anode tube (Figure 2.5), slightly adapted to a CT scan, usually containing more than on focal spot, which is the region of the tube from which the X-rays emanate. The smaller the focal spots (one scan often contains more than one), the bigger is the spatial resolution, since there is less diffraction of the rays (2).

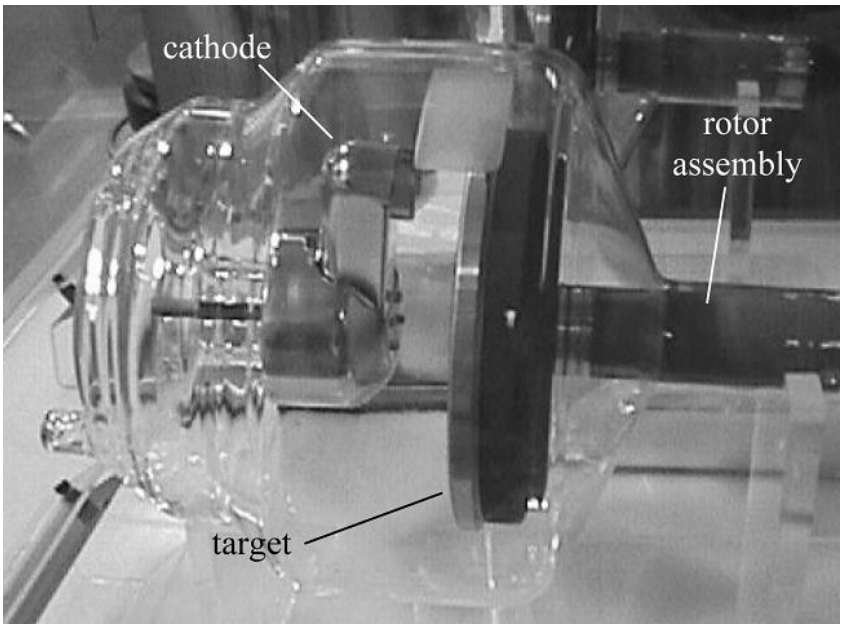


Figure 2. 5 – Components of an X-ray tube. Reproduced from (5).

The X-ray tube contains two sets of voltage sources, one, of low voltage, to heat the cathode, and other, of high voltage (between 80kV and 140 kV in CT) to produce the cathode rays. Therefore, a beam of high energy electrons is created, then collides with the anticathode and produces a beam of X-rays.

Other component of the X-ray tube is the Beryllium window, through which the final radiation crosses the glass of the tube.

At the atomic level, there are two physical processes that generate X-rays: the characteristic X-ray radiation and Bremsstrahlung radiation. The first process consists in an electron transition between the inner shells of the atom, caused by the interaction of a charged particle (such as electrons, protons or α-particles) with high kinetic energy, with that electron. This transition from a shell to another, with lower energy, generates the emission of radiation with energy equivalent to the energy difference between the two shells involved in the transition, usually between 0,052 and 129,544 keV (Figure 2.6.a)).

The other process occurs when charged particles are decelerated when going through a electromagnetic field, where they lose energy, released as X-rays or Bremsstrahlung radiation of up to 20 MeV (Figure 2.6.b)) (1).

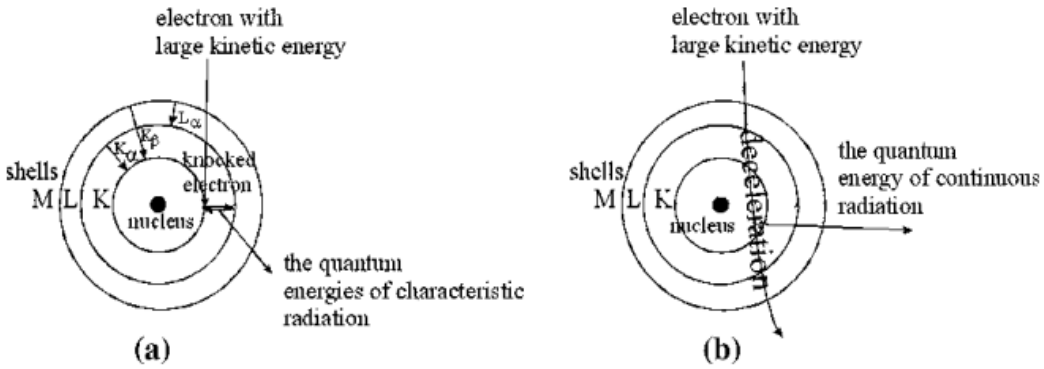


Figure 2. 6 - The two possible processes for generating X-rays. a) Emission of characteristic radiation, b) Bremsstrahlung (continuous X-ray). Reproduced from (1).

Almost all the energy produced in an X-ray tube is converted into heat, being only 1% efficient. Thus, it's necessary a cooling system, using water or oil. In the 64 slice CT, it is used a dual focus technology, which means that two beams are produced, due to a powerful electromagnetic deflection system, allowing few artifacts and a reconstructed slice thickness of 0,4 mm (1).

GENERATOR

The generator produces the high voltage (kV) needed to increase the X-ray beam, which increases the penetrating efficiency of the beam and reduces the radiation dose to which the patient is subjected. A high kV also enables the use of less mA, which reduces the temperature rise on the X-ray source (2).

COOLING SYSTEM

The cooling system is set to maintain the equipment temperature constant, so the scan performance is not affected (2).

FILTRATION SYSTEM

The filtration system is used to define the shape of the beam, according to each medical case. This also helps to reduce the patient's dose and scatter radiation, as it removes the low energy X-rays that are emitted by the beam but never reach the detectors (3). Source collimators can narrow or wide the X-ray beam according to the slice thickness necessary for the exam (2).

DETECTORS

The detectors are placed in the same direction as the X-ray beam and patient, and collect the information regarding to each anatomic structure (Figure 2.7.a)). The

detectors can be made of xenon-gas filled chambers, not as efficient as the other type of detectors, most common nowadays, made from a solid-state crystal. This last type can also be called scintillation detectors, because of the fluorescent behavior of the crystal, when hit by an X-ray beam.

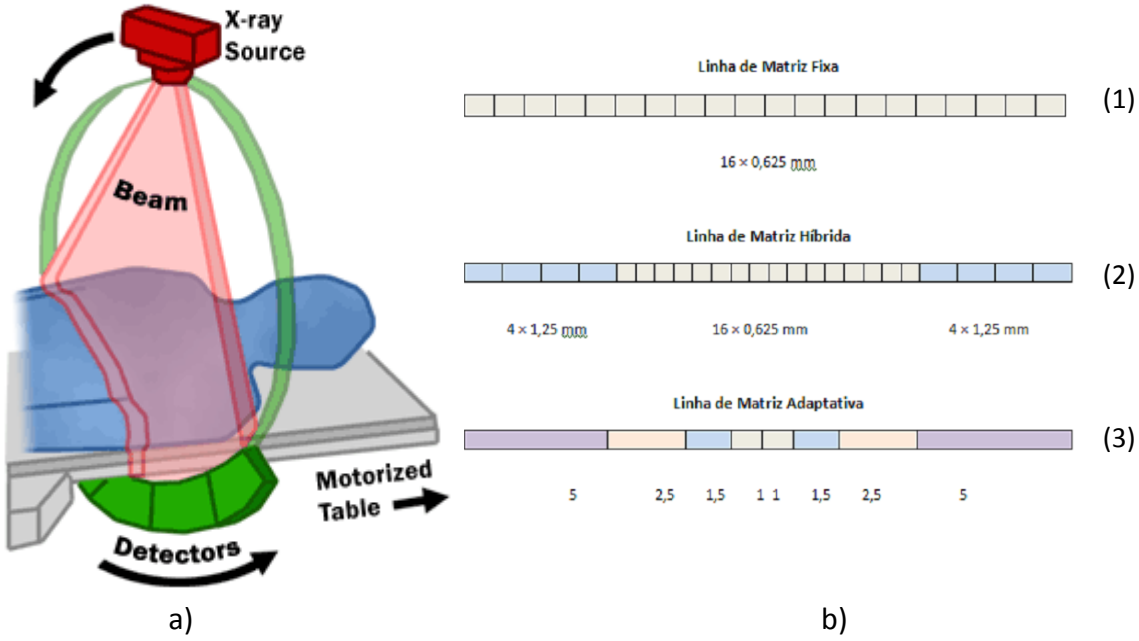


Figure 2. 7 - a) Scheme of the X-Rays beam passing through the patient and hitting the detectors. Reproduced from (6) ;b) the three different types of detector matrix: (1) Fixed Matrix Line; (2) Hybrid Matrix Line; (3) Adaptive Matrix Line. Reproduced from (7)**.**

Scintillation detectors are very efficient, absorbing almost 100% of the photons that hit them, although they are harder to calibrate, more expensive than the xenon-gas detectors and more sensitive to temperature fluctuations (2).

The detectors can be divided into three types, according to their shape (Figure 2.7.b)). In the fixed matrix type, all the elements have detectors with the same shape. This type of detector allows the acquisition of a higher number of slices per rotation. In the hybrid matrix, some elements in the center are smaller than the ones more distant from the center. Finally, in the case of the adaptive matrix, the elements start being bigger with the distance from the center. This type has the best performance, since it has the fewer elements, allowing less dead spaces between the detectors (8).

2.2.2 Other CT Elements

The DAS, Data Acquisition System, positioned next to the detectors, turns the information captured by the detectors into a digital signal and then sends it to the

computer. More specifically, it's the ADC, analog-to-digital converter, which performs this task. The output can now be processed and filed in the PACS System - Picture Archiving and Communication System (2).

Patient Table

The patient's table, as seen in figure 2.3, is responsible for the movement of the patient across the gantry, movement called increment or step. In helical CT, since the movement is continuous, the increment is measured in mm/s.

Power Distribution Unit (PDU)

The PDU is an electrical device used to control the distribution of power to the scan.

Operator Console

The Operator Console consists of several computers, where the operator can choose the adequate parameters for the exam, and can process and store the information given by the Data Acquisition System.

2.3 CT's Technical Factors

The main factors on which the image quality depends can be controlled by the operator. They include miliampere level (mA), the scan time in seconds, the kilovolt peak (kV), the pitch for the helical scan methods, slice thickness, field of view and image reconstruction algorithms, among others.

Current Intensity and Rotation Time (mAs)

Current intensity (mA) measures the current of electrons from the cathode to the anode in the X-rays tube; therefore, the flow is controlled by the mA that the operator sets: increasing the mA, it increases the flow. A higher flow is necessary to reduce scan time, and by doing so, a poor image quality (due to patient movement, like cardiac motion and peristalsis) might be improved. A structure more dense like the abdomen will require more mA than, for example, the thorax, which is mostly composed by the lungs, filled with air.

Usually, the equipment has two different filaments, one, smaller, for lower mA values, and other, for higher mA values. This happens because a small filament can't tolerate high current, but it has a big advantage: it concentrates the focal spot (reducing penumbra), which improves image quality (2).

Tube Voltage (kV)

The tube voltage, typically around 120 kV for adults, is the potential difference applied to the X-ray tube and is what defines the quality, or average energy, of the X-Ray beam. As with mA, higher kV increases the intensity of the beam and its ease to penetrate into thicker body structures. If the mA is constant, decreasing the tube voltage helps to reduce the radiation dose to patient; however, if the intensity is too weak, all the X-rays will be attenuated by the patients' body. It's the mA value which is most commonly changed in the equipment settings by the operator because it's less limited and its influence on image quality is more foreseeable than with tube voltage (2). In a standard CT exam, the total amount of X-ray energy is defined by mA and the scanning time. Along with the kV value, the beam is fully defined.

Pitch

It's used to describe the CT table movement during a helical scan, defined as the travel distance per 360º of the gantry, divided by the X-ray beam collimation width. Information is collected for each table position, however, with the increase of this parameter for a value bigger than 1, fewer data is acquired for each table position, and it will result in a scan covering more body parts lengthways for the total exam time; also, a lower dose is given to the patient. There might occur a case of overlapping slices, when the pitch is set for values smaller than 1. Thus, decreasing the pitch will decrease the amount of anatomy covered by the scan, and raise the radiation dose to the patient.

Pitch can also be described as a ratio of table speed and slice thickness; for example, a pitch of 2:1 means that the table will move twice the distance of the slice thickness for every 360º of the gantry. The operator may select the pitch on the most modern CT scans, taking into account the type of exam to be performed, and the ideal pitch range, from 1 – 2, along with other parameters like the mA (2).

Slice Thickness

Slice thickness is the thickness of the image cross-section, it is a parameter directly connected with image quality. The slice thickness is based on the FWHM of the CT, measured in the sensitivity function, a characteristic of the scanner. This parameter has values of 0,4 to 10 mm (1).

Collimation

To limit the size of the X-ray beam to the desired area of the patient, some beam restriction devices are attached to the tube, where the primary radiation exits it.

The most common is the collimator, a single device, attached to the X-ray tube housing, which is able to model itself to a wide range of square and rectangular shapes, corresponding to all the sizes necessary for the exam. Additionally, the collimator includes one system, composed by lasers, to determine the exact patient position. A collimator is composed by two sets of shutters, each one with four leaded-leaves, that move longitudinally and transversely (9).

Field of View

The Scan Field of View (SFOV) determines the area in the gantry for which the primary information is acquired; still, the Display Field of View (DFOV) determines the quantity of this primary data is used to create the image (2). These parameters are selected by the operator, along with pitch, for example, and in CT it can vary between 12 and 50 cm.

Image Processing and Reconstruction

The Reconstruction Algorithms determine how the raw data is going to be filtered and post-processed. There is a large variety of filters and algorithms available for the operator. The Smoothing Filters can, for example, reduce the appearance of artifacts by reducing the difference between two adjacent pixels, but they compromise spatial resolution. This type is used to visualize soft tissues. Another kind is the Detail Filters, that emphasize the difference between adjacent pixels to improve spatial resolution, used for bone exams (2).

Uncoupling Effect

This effect establishes the difference between conventional radiography and CT scanners. When an operator increases the radiation dose, in film-screen radiography, the film is overexposed and the image appears too dark – the image quality is highly related with the dose. On the other hand, if the same happens in a CT scanner the image quality is not severely affected, so when high mA and kV are used, good results are obtained. In this technology, the quality is uncoupled with the dose, which makes it difficult to analyze when doses are excessive.

2.4 The Hounsfield Units

Since CT image acquisition is based on the attenuation produced by body tissues to X-rays, for convenience during diagnosis, it was introduced a scale named

after Godfrey Hounsfield, Hounsfield units. It relates the degree of attenuation for a certain tissue (μ_{tissue}) and the attenuation of water (μ_{H_2O}):

$$HU = 1000\ \frac{\mu_{tissue} - \mu_{H_2O}}{\mu_{H_2O}} \qquad (2.1)$$

The Hounsfield units have a range of -1000 for gases to 3000 for bone; body tissues with a high amount of water have HU = 0, as shown in table 1.

Table 2. 1 – HU for different body tissues, with and without the application of contrast. Reproduced from (1).

Tissue	Before the application of contrast	After the application of contrast
Brain	35	45
Fresh blood in the brain	65	–
Liver	50	80–90
Kidneys	27–30	100
Spleen	50	70–80
Pancreas	20–30	50
Muscles	40	–
Fat	−70 to −110	–
Bone	300–1,300	–

2.5 Image Quality in CT

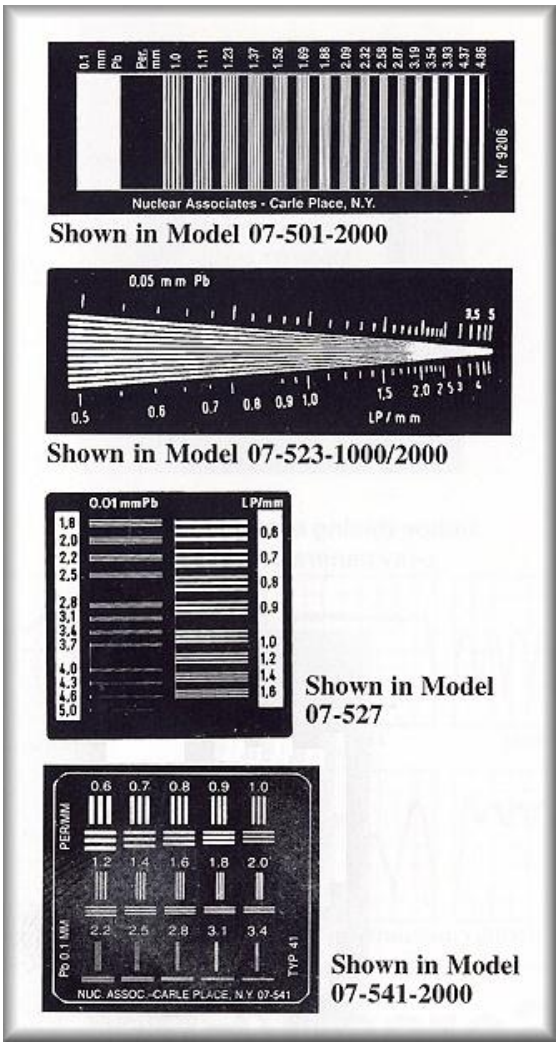
The assessment of image quality in a CT can be very subjective, but usually, an image has good quality if it has a good resemblance with the original object, and if it fulfills the purpose for which it was acquired - in CT, if it provides an exact diagnosis.

Image quality depends on certain factors that can be controlled by the system operator such as Current Intensity and Rotation Time, Tube voltage, Slice thickness, Field of View, Uncoupling effect, Pitch and Reconstruction Algorithm, described in chapter 2.3.

Some other parameters represent a more specific evaluation of the image quality in a CT scanner, allowing comparisons between different systems - Spatial Resolution, Low Contrast Resolution, Contrast Resolution, Temporal Resolution, Noise, Pitch and also the dosimetric factor CTDI (CT Dose Index), which will be further detailed in this chapter.

SPATIAL RESOLUTION

Spatial resolution is defined as the system's ability to distinguish too objects very close together, or, in other words, the minimum area in which the system can detect changes (1).



As an example, a system with good spatial resolution has very good imaging definition in a case of small bone fragments in a crushed ankle. There are two possible ways to measure the spatial resolution, using a line pairs phantom or by analyzing the Modulation Transfer Function, MTF, which gives information about the spread of information within the system (2).

The first process consists in the analysis of an acrylic phantom that contains metal strips with varying distances between each other (Figure 2.8). A line pair is the set of a line and the adjacent space; therefore, if 20 lines are clearly visible in a 1 cm section of the phantom, the spatial resolution of the equipment is 20 line pairs per centimeter, or 20 lp/cm.

Figure 2. 8 – Different models of line pair phantoms. Reproduced from (10)**.**

The second process, based in the MTF, is the most used to determine spatial resolution, also for conventional radiography. This function represents the relationship, in the frequency domain between the scanned object and the image acquired through the scanner, and so, it determines the sensitivity of the scanner to quick changes in the attenuation coefficient.

The MTF graph represents the spatial frequency on the x axis and the MTF on the y axis; this way, if the curve is more to the right, it indicates a higher spatial resolution, meaning that the system has a good ability to distinguish small objects.

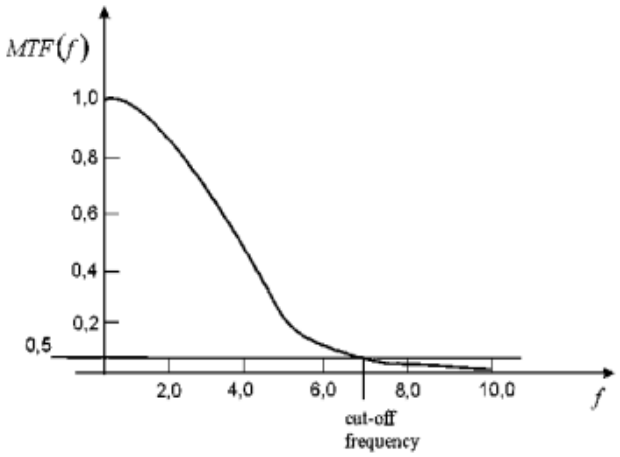


Figure 2. 9– **Example of a MTF. Reproduced from (1).**

In this process, resolution it is mostly defined as the cut-off frequency of the MTF (Figure 2.9), or the value at which the function reached the level of 50%, 10% and 2% (1). With these two methods, it's possible to make a comparison between different CT scans or to examine the time changes in one CT equipment. Spatial resolution can be affected by equipment parameters such as the matrix size and the DFOV (which determines the pixel size), slice thickness used, pitch and focal spot size (2).

CONTRAST RESOLUTION (OR LOW CONTRAST RESOLUTION)

Contrast resolution is the ability of the system to distinguish small differences in density, i.e., in the attenuation coefficient in tissues, for example, to differentiate between grey and white matter in a brain scan (2). It can be explained as the relationship between the smallest attenuation coefficient that the system can differentiate (in HU), and the average value for an object of a certain size, for a specific dose. Thus, it's perceivable how low contrast resolution is directly proportional to the radiation dose, and, by increasing it (or the scanning time of the exam), it is possible to achieve higher resolution, which normally has a value of 0,3% to 0,4% (which means a difference of 3 to 4 HU) (1).

Due to these small values, background noise and artifacts are extremely important in determining image quality. Other parameters that affect contrast resolution are the slice thickness, the mAs selected and the reconstruction algorithm used (for example, algorithms for soft tissues improve contrast resolution) (2).

Temporal Resolution

This factor expresses the time needed for the acquisition of data, and for CT, it is in the order of ms. It is controlled by the gantry rotation, the number of detector elements and the amount of time the system required to record different signals. It is an important factor specially when scanning moving body structures.

Uniformity

Uniformity is the level of heterogeneity of the image acquired. It is calculated through the following formula:

$$Heterogeneity = \frac{\mu^{max}(x,y) - \mu^{min}(x,y)}{\mu^{max}(x,y) + \mu^{min}(x,y)} \qquad (2.2)$$

Where $\mu^{max}(x,y)$ is the highest average attenuation coefficient possible from a measurement obtained in all the area of a water phantom, and being $\mu^{min}(x,y)$ its smallest value.

Linearity

Linearity is a parameter which represents the relation between several values of the attenuation coefficient (obtained at the average scanner energy) and its respective amount of the Hounsfield scale (for all types of tissues). The following formula translates this factor:

$$\sqrt{\frac{1}{I}\sum_{i=1} I(\mu_i - \mu_i^{average})^2} \qquad (2.3)$$

Being μ_i the attenuation coefficient for a specific tissue on the Hounsfield scale, $\mu_i^{average}$ the attenuation coefficient measured the average radiation energy, and *I* the specific number of the tissue that's being analyzed. Figure 2.10 represents a study of the linearity of certain equipment, using different types of phantoms, each one with its own value of *I*.

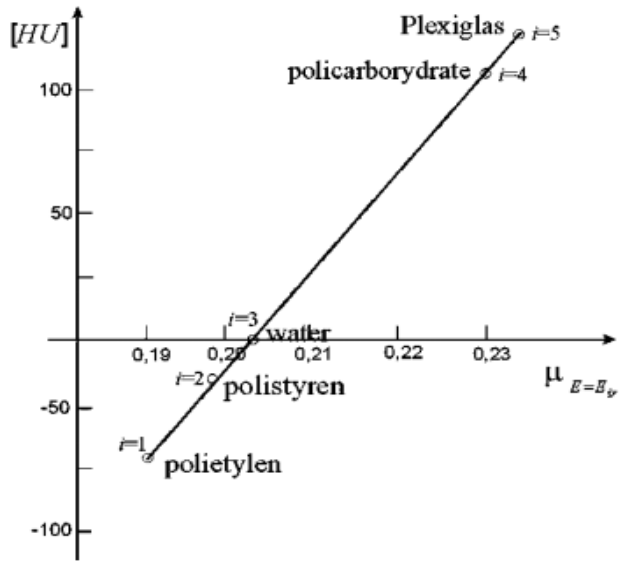


Figure 2. 10 - Assessment of the linearity of a CT scanner. Reproduced from **(1)**.

NOISE

When the number of photons measured by the detectors is insufficient, quantum mottle occurs, being this event the principal cause of noise. At the image level, fluctuations in the pixel values occur, thus having the grainy or 'salt-and-pepper' appearance. Noise obviously degrades the quality of image acquired, specially its contrast resolution.

Signal-to-noise ratio (SNR) is often used to express the meaningful information of a signal and the background noise, as follows:

$$SNR = \frac{P_{signal}}{P_{noise}} \qquad (2.4)$$

It is usually defined in decibels (dB), since it has a wide dynamic range.

3. Radiological Protection and Dosimetry in CT

3.1 Radiation Dosimetry

There is no universal definition of Dosimetry. Dosimetry aims at measuring, computing or assessing radiation doses using a well-defined set of units and quantities as well as radiation detection equipment and techniques. In Radiation Protection, the doses are used to assess the interaction of ionizing radiation with the biological media (cells, tissues and organs) and the associated potential detrimental effects.

3.1.1 Dosimetric Quantities

Exposure (X)

This quantity is based on the ability of X- and γ- rays to produce ionization in air; in the S.I., it's expressed in Coulomb/kg (C/kg) although in the literature the (non S.I.) unit Röntgen (R) is widely used, being 1 R= 0,000285 C/kg (11).

Absorbed Dose (D) and Kerma (K)

D, expressed in Gray (Gy) or Joule per kg (J/kg), it represents the average energy imparted to matter per unit of mass by ionizing radiation. In radiology it's numerically identical to another radiation quantity designated Kerma (K) - Kinetic Energy Released per Unit Mass - , which is defined as the sum of the energy of all the ionizing particles that are released when uncharged ionizing particles go through matter (per unit of mass) (11).

Equivalent Dose (H)

Different types of radiation produce different effects in the biological media. The equivalent dose (H) takes into account the estimated radiobiological effectiveness of the different types of radiation, and is obtained multiplying the Absorbed Dose (D) by a radiation-specific weighting factor, ω_R, that depends on the type of radiation considered:

$$H_{T,R} = \omega_R \; D_{T,R} \qquad (3.1)$$

Where $D_{T,R}$ is the Absorbed Dose in a certain tissue or organ T, due to the radiation of type R (R=photons, electrons, positrons, protons, neutrons, alpha particles, muons, pions, etc). Table 2 displays some values of the radiation weighting factors.

Table 3. 1 – Weighting factors for different types of radiation. Adapted from (12).

Radiation type	Radiation weighting factor, w_R
Photons	1
Electrons and muons	1
Protons and charged pions	2
Alpha particle, fission fragments, heavy ions	20
Neutrons:	
< 10 keV	5
10 keV to 100 keV	10
> 100 keV to 2 MeV	20
> 2 MeV to 20 MeV	10
> 20 MeV	5

This quantity allows the comparison, in terms of biological effects, between different radiation and is expressed in Sievert (Sv) (11).

Effective Dose (E)

The Effective Dose (E) takes into account the different radiosensitivity of organs and tissues. To each organ or tissue (T) is assigned a tissue weighting factor, ω_T. Effective dose is then calculated as:

$$E = \sum_T \omega_T \, x \, H_T \qquad (3.2)$$

Which is the sum of the Equivalent Dose in each tissue (H_T), multiplied by the corresponding tissue's weighting factor. Equivalent Dose it is also expressed in Sievert (Sv) (13).

The tissue weighting factors are recommended by the International Commission on Radiological Protection (ICRP) and for the same organs and tissues have evolved throughout the years, as a result of the evolution of the scientific state-of-the-art about the biological effects of ionizing radiation and of new data released by scientific studies, epidemiological studies, etc.. The tissue weighting factors (ω_T) have been primarily obtained from studies of the Hiroshima and Nagasaki atomic bombs survivors of but more recently also from other populations exposed to ionizing radiations and by Monte Carlo simulation studies (11). Table 3 shows the latest weighting factors published by the ICRP in 2007, and a comparison with the ones published 17 years before.

Table 3. 2 – ICRP values of ω_T for different organs in 1990 and 2007. Reproduced from (14).

w_T values for the different organs

	1990	*2007*		*1990*	*2007*
Gonads	0.20	*0.08*	bone marrow (red)	0.12	*0 .1*
Colon	0.12	*0.12*	lung	0.12	*0.12*
Stomach	0.12	*0.12*	bladder	0.05	*0.04*
Breast	0.05	*0.12*	liver	0.05	*0.04*
Oesophagus	0.05	*0.04*	thyroid	0.05	*0.04*
Skin	0.01	*0.01*	bone surface	0.01	*0.01*
Kidney	-	*0.01*	salivary glands	-	*0.01*
Remainder	0.05	*0.12*			

Effective dose is often used for regulatory compliance (to assess the exposure of workers and members of the public and its compliance to the legally established dose limits) and does not apply to any specific individual but instead for an average representative individual.

3.1.2 Dosimetric Quantities in CT

Computed Tomography Dose Index (CTDI)

CTDI, or Computed Tomography Dose Index was proposed to better characterize the dose of clinical environment, consisting of multiple scans. Several derivations of CTDI, with different formulations are used nowadays; for example

$CTDI_{100}$, which consists of the dose index measured on a standard PMMA (polymethyl-methacrylate) phantom, although it refers to the dose absorbed in air (Figure 3.1): The ‘’100” index refers to the length of 100 mm, on which the dose is integrated when CTDI measurements are performed using a pencil ionization chamber:

$$\mathrm{CTDI}_{100} = \frac{1}{\mathrm{nT}} \int_{-50\ \mathrm{mm}}^{50\ \mathrm{mm}} \mathrm{D_a(z)dz} \qquad (3.3)$$

In this formula, $D_a(z)$ represents the distribution of the absorbed dose in the z axis for a single scan, the number of detector rows is represented by *n* and T is the thickness of each row (5).

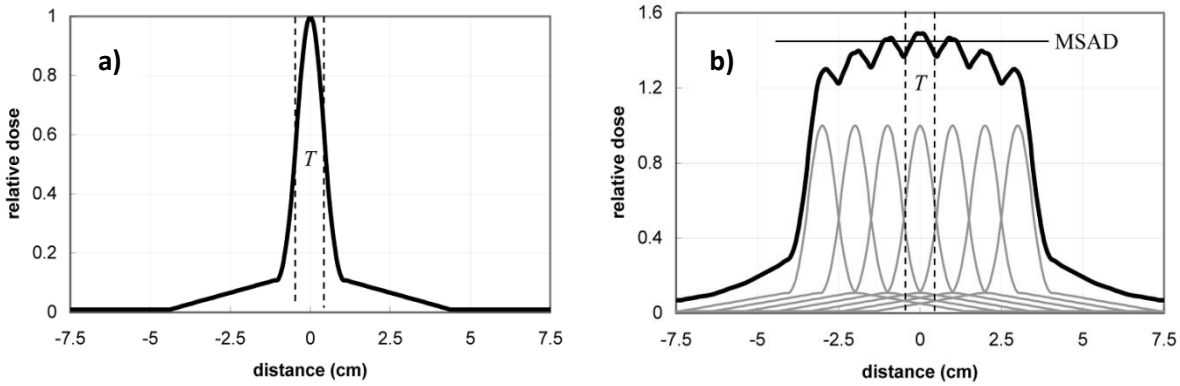


Figure 3. 1 - a) A single-scan dose profile for 100 mm slice thickness. b) Multi scan (7 scans) with 100 mm slice thickness at 10 mm increments. MSDA is the multiple scan average dose obtained by summing all the dose contributions. Reproduced from (5).

Through figure 3.2 it is clearly visible the difference in dose distribution between conventional X-ray, where the dose at the angle of X-ray entrance is maximum and slowly decreases with depth, and CT, being the dose equally distributed along the 360 degrees covered by the gantry rotation.

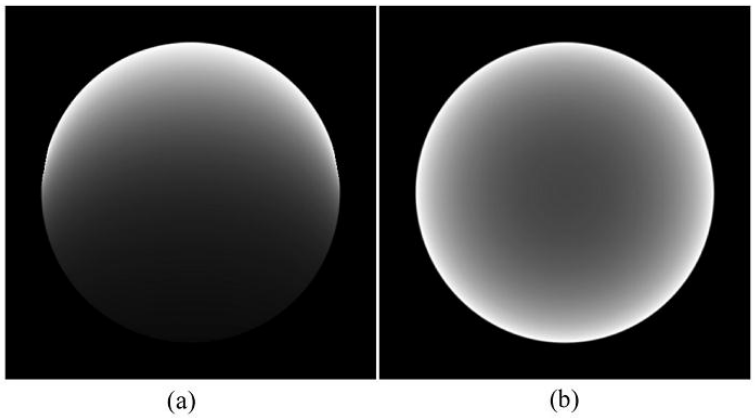
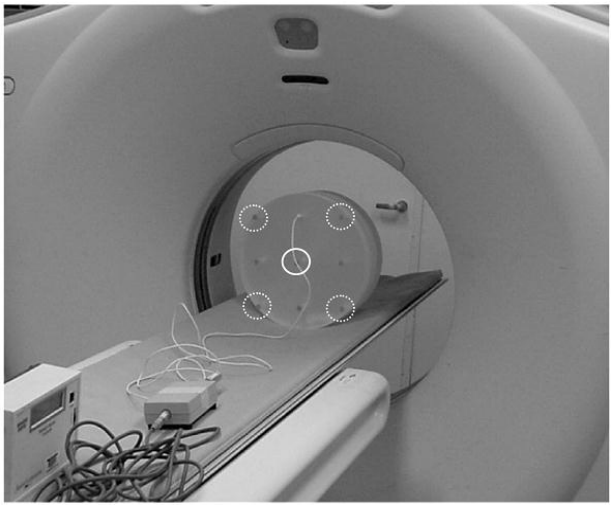


Figure 3. 2 – Comparison between dose distribution in a) conventional X-ray and b) CT scann for a water phantom. Reproduced from (5).



Usually a PMMA phantom is used to measure $CTDI_w$, with four openings in the peripheral part, and one in the center, where a pencil-like ionization chamber can be inserted (figure 3.3) (5). The measurements are performed with the X-ray beam irradiating the phantom and the ionization chamber, placed in the center of the gantry, for the nominal technical parameters (kV, mAs, pitch, etc.) of the CT examination.

Figure 3. 3 – Experimental setup for $CTDI_w$ measurements with a 32 cm of diameter body phantom and a ionization chamber of 100 mm length. Reproduced from (5).

Although with a CT scanner the dose is more evenly distributed, it's still visible the attenuation that the X-rays suffer from the periphery to the center of the phantom, and it depends highly on the size, shape and composition of the scanned object. For instance, in a body of 35 cm of diameter there is a difference of 1/5 to 1/3 between the dose at the center and the dose at the periphery. Therefore, another quantity was introduced, the $CTDI_w$, to take into account the depth differences, and can be computed using the formula:

$$CTDI_w = \frac{1}{3}\, CTDI_{100}(central) + \frac{2}{3}\, CTDI_{100}(peripheral) \qquad (3.4)$$

Since $CTDI_w$ is only considered for step-and-shoot scans, a new index was introduced, to compensate the patient's table travel and constant data acquisition, characteristic of helical scanners. Thereby, $CTDI_{vol}$ describes the dose distribution taking in account the helical pitch – as seen before, the distance travelled by the table over the nominal beam width – which means: higher pitch, higher value of z, higher the dose distribution over the length:

$$CTDI_{vol} = \frac{CTDI_w}{pitch} \qquad (3.5)$$

All the CTDI values are expressed in mGy, as dose, and usually they are displayed in the operator´s console during the exam. It is a valuable parameter, as it allows the comparison between protocols and equipments.

Even though $CTDI_{100}$ is nowadays the most accepted and used quantity, originally the CTDI was described as the 14-slice average dose by the U.S. Center for Devices and Radiological Health (CDRH),

$$CTDI = \frac{1}{nT}\int_{-7T}^{7T} D(z)dz \qquad (3.6)$$

It was only valid for the width of 14 scans (14T), as it considered that all the regions not covered by this limit were not meaningful for the study.

Another CTDI quantity also originally accepted was $CTDI_{\infty}$, defined over an infinite range:

$$CTDI_{\infty} = \frac{1}{T}\int_{-\infty}^{\infty} D(z)dz \qquad (3.7)$$

Dose-Length Product (DLP)

Since different exams have different scan lengths, it is important to assess the total dose for the entire exam, which can be represented by the Dose-Length Product, or simply DLP, expressed in mGy.cm:

$$DLP = CTDI_{vol} \times L \qquad (3.8)$$

L is the scan length in *z*. Through DLP, it is also possible to calculate an estimation of the Effective Dose value, E (5) using the following relation:

$$E = K \times DLP \qquad (3.9)$$

Where *K* is the conversion factor, expressed in $mSv.mGy^{-1}cm^{-1}$, which converts the DLP to the effective dose (E). The values of K for different regions are displayed n table 4 (5):

Table 3. 3 - Conversion factor *K* for several body regions. Reproduced from (5)

Region of Body	K ($mSv\ mGy^{-1}\ cm^{-1}$)
Head	0.0021
Neck	0.0059
Chest	0.014
Abdomen	0.015
Pelvis	0.015

3.1.3 DIAGNOSTIC REFERENCE LEVELS (DRL)

In 1996, ICRP introduced, in its Publication 73, the term *Diagnostic Reference Levels,* explaining its meaning and utilization. This new concept was defined with an advisory purpose, representing a method to detect high radiation dose levels in medical practice, which, if confirmed, would lead to a local investigation. The same has been suggested for low dose levels, which would cause insufficient image quality for a correct diagnostic. These levels "*are not for commercial purposes, not a dose constraint, and not linked to limits or constraints*", states ICRP Publication 73 (16).

According to *Council Directive 97/43/EURATOM* (20), article 2, from June 30th 1997, Diagnostic Reference Levels are defined as the maximum dose levels adaptable to radiodiagnostic or radiopharmaceutical practices for standard-sized patients or phantoms, for several types of medical equipment. When good diagnostic and technical practice is performed, these levels must not be exceeded in standard procedures (15).

The main goals of establishing DRLs are a) to identify and reduce the number of unjustified dose levels, both high and low, in a regional or national distribution for a specific imaging procedure, b) to improve specific medical imaging practices, and finally, c) to implement an adequate range of dose levels for a specific medical imaging procedure.

DRLs must be implemented by regional, national or local authorized bodies, since these values are purely advisory and allow flexibility in their implementation.

DRLs are established for the medical practices using ionizing radiation, such as in diagnostic radiology and nuclear medicine, including all types of equipment. Table 5 displays a few DRLs for CT scans, for several types of exams:

Table 3. 4 - DRL ($CTDI_{vol}$ and DLP) for cranial CT. Reproduced from (22).

Examen / problématique				NRD (75^{e} percentile)			
				$CTDI_{Vol}$ [mGy]		PDL [mGy·cm]	
				H	B	H	B
1	**Crâne / cerveau**	Age (ans)	nouveau-né	**27**	-	**290**	-
			0-1	**33**	-	**390**	-
			1-5	**40**	-	**520**	-
			6-10	**50**	-	**710**	-
			11-15	**50**	-	**920**	-

3.2 THE INTERNATIONAL SYSTEM OF RADIATION PROTECTION

According to the Publication 60 (1990) of the International Commission on Radiological Protection, *"The basic role of radiation protection consists in avoiding undue exposure of man and the environment to ionizing radiation*" (23). In spite of the benefits arising from the utilization of ionizing radiation in practically all sectors of activity, namely in Medicine, the radiological risks associated with such radiation exposures must be correctly assessed.

Radiation Protection standards have evolved over time, incorporating at each phase the state-of-the-art of scientific knowledge about the biological effects of ionizing radiation. International bodies such as UNSCEAR (United Nations Scientific Committee for the Effects of Atomic Radiation), the ICRP (International Commission for Radiological Protection), the IAEA (International Atomic Energy Agency) and others (such as the NCRP - National Commission on Radiation Protection of the USA), conduct or sponsor scientific studies and publish regularly reports containing scientific data (UNSCEAR, ICRP), recommendations (ICRP) and safety standards and guides for the safe utilization of ionizing radiation (IAEA).

X-rays have many benefits in industry, research, power-generation and medicine. However, these activities have a risk of exposure of workers, as well as the risk of an eventual accident. The main objective of radiation protection is to balance the benefits and risks of occupations involving the use of ionizing radiation.

Several associations and committees have established the recommended dose limits for the different types of occupations. Nonetheless, the acceptance of these recommendations depends on the particular individuals or group to which they are directly assigned to. Also, while dealing with radiation sources, whether in medical procedures, research or other type of occupation, work members must take in account three main aspects that will help reduce the dose received: distance to the source, the duration of the task (time) and the use of shielding (which proves to be more reliable in decreasing the dose rate) (17).

In 1991, ICRP issued its Publication 60, which defines the three fundamental principles of radiological protection later revisited in ICRP Publication 103 (2007):

The Principle of Justification (of practices) – It assumes that any practice which involves exposure to ionizing radiation carries a certain risk to the workers, and it must be justified. The outcome benefit (for example, a correct diagnostic in a medical imaging procedure) must outweigh the risk of harmful health effect on the exposed individuals. (18).

The Principle of Optimization (of protection) – any exposure must be kept as low as possible according to the **ALARA (**As Low As Reasonably Achievable) **Principle.** In the context of the medical exposures this can be achieved, for instance, by avoiding the unnecessary repetition of exams and by performing imaging exams using technical parameters to which result the lowest dose (to the patient), without compromising the image quality for the intended diagnostic. The establishment of DRLs previously described is an example of the application of the Optimization principle. (17).

The Principle of Dose Limitation – Involves the implementation of dose limits, mainly for regulatory purposes.. Different sets of effective dose limits apply for workers and members of the public. It is essential to distinguish the type of exposure, namely whether it's an occupational exposure, a public exposure or a medical exposure of patients (and comforters and volunteers in research) (18). Table 3.5 shows the dose limitation purposed by ICRP and NCRP for occupational and public exposure.

Table 3. 5 - Exposure limits for NCRP report 116 and ICRP Publication 60. Reproduced from (17).

	NCRP-116	ICRP-60
Occupational Exposure		
Effective Dose		
Annual	50 mSv	50 mSv
Cumulative	10 mSv × age (y)	100 mSv in 5 y
Equivalent Dose		
Annual	150 mSv lens of eye; 500 mSv skin, hands, feet	150 mSv lens of eye; 500 mSv skin, hands, feet
Exposure of Public		
Effective Dose		
Annual	1 mSv if continuous 5 mSv if infrequent	1 mSv; higher if needed, provided 5-y annual average ⩽1 mSv
Equivalent Dose		
Annual	15 mSv lens of eye; 50 mSv skin, hands, feet	15 mSv lens of eye; 50 mSv skin, hands, feet

3.3 Justification, Optimization and Dose Limitation Applied to Pediatric CT Exposures

As mentioned in the Introduction, a continuous and vigorous growth of CT examinations is observed since the 1980s in several countries. It is estimated that since the 80's, the number of CT examinations increased 800% (19), being annually

performed 62 million CT scans in the USA (figure 3.4), out of which 4 million in children (20). 33% of all the pediatric examinations are performed in the first 10 years, and 17% in the first 5 years of life (21). For specific body examinations, it's reported an increase of 366% for spine CT, 435% for chest and 49% for abdominal examinations (19).

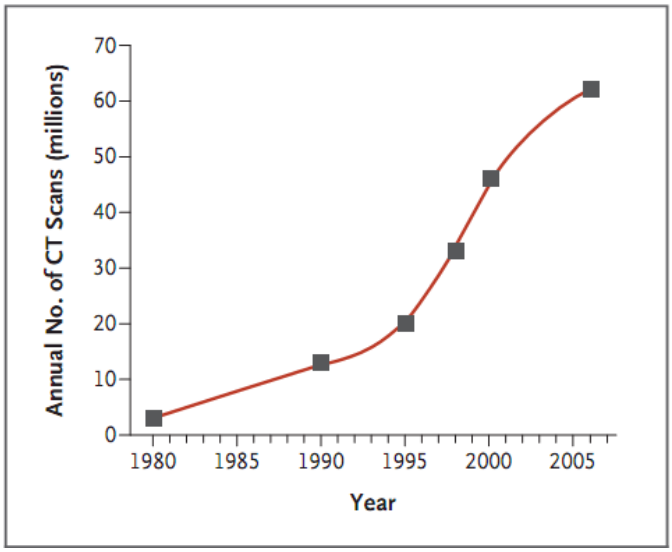


Figure 3. 4 - Estimated number of CT examinations performed annually in the U.S. Reproduced from (20).

CT is a common diagnostic equipment for surveillance and to detect disorders in children: cancer detection, trauma cases and inflammation evaluation; also, for the assessment of cardiac and vascular diseases the most recent helical technology has demonstrated a high potential - CT's 3D abilities avoid the use of the more evasive and expensive cardiac angiography (21).

The large increase of CT exams can be explained by the fact that the most recent CT scanners, with 256 or 320 row detectors, allow the capture of a heart image in less than a second; the precision and accuracy of CT diagnosis has avoided the use of surgery in trauma patients. For example, in children with appendicitis, CT exams reduced the use of laparotomy from 18% in 1997 to less than 5% in 2002. However, in spite of the clear benefits of this type of equipment and associated technology, the inherent radiological risk might become a potential public health issue; it requires special approach to ensure that CT scans are performed with the lowest dose possible for an accurate diagnostic (19).

As stated by Brenner and Hall in "The New England Journal of Medicine" (2), the vulnerability of children to CT scanning is underestimated, due to the higher radiosensitivity of their organs (characteristic of the young age) and to the long lifetime expectancy (figure 3.5 and 3.6), that increases their lifetime cancer risk (2). The thyroid, breast and gonads´ tissues are of special importance, due to their high sensitivity to radiation (21). Brenner et al. published in 2001 a controversial report,

stating that 1 in each 1000 children less than 15 years-old that perform a CT scan will die from carcinogenesis caused by the X-ray exposure (22).

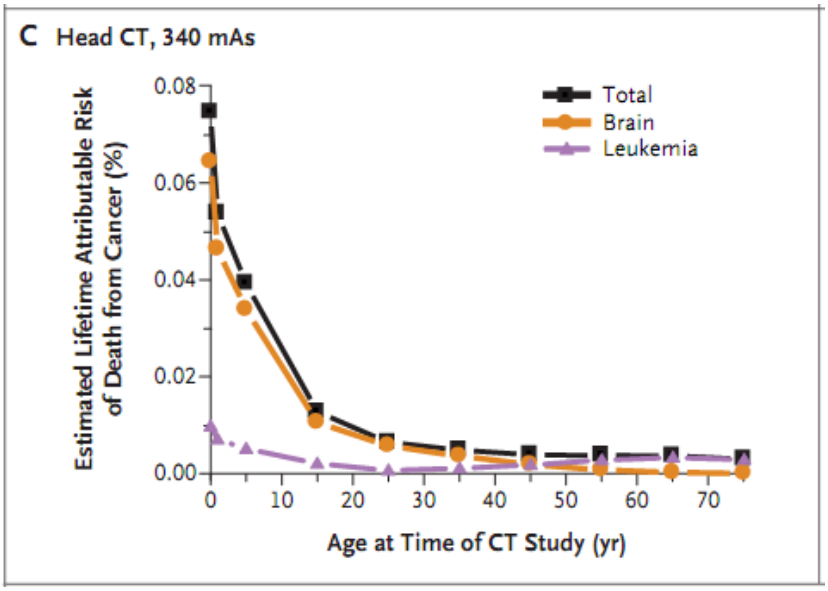


Figure 3. 5 – Estimated lifetime attributed risk of death from carcinogenesis for head CT. Reproduced from (20).

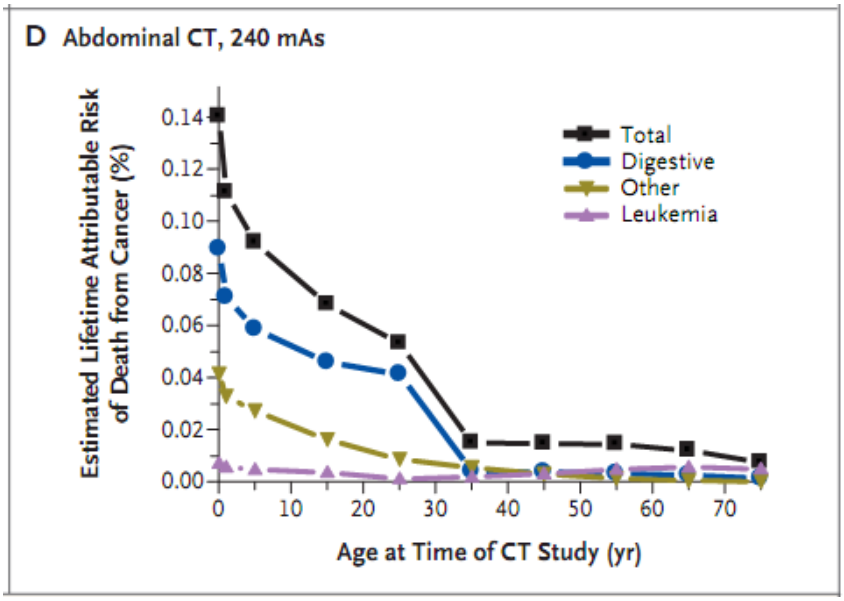


Figure 3. 6 – Estimated lifetime attributed risk of death from carcinogenesis for abdominal CT. Reproduced from (20).

3.3.1 IMAGE WISELY, IMAGE GENTLY

In recent years, the growing awareness, at the international level, about the pediatric exposures in the framework of CT examinations resulted in a new impulse to correctly implement and make operational the Radiation Protection principles, in clinical environment, especially when it becomes to pediatric exposures.

One of the first Associations to demonstrate concern for this issue was the Society for Pediatric Radiology (SPR), founded in 1958 in the USA in order to raise awareness for the risks of pediatric radiology. Along with the American Society of Radiologic Technologists (ASRT), the American College of Radiology (ACR), the American Association of Physicists in Medicine (AAPM) and nine other medical organizations and agencies, the Alliance for Radiation Safety in Pediatric Imaging was created, having as affiliated members about 400.000 health care professionals (19).

Image Gently™, a campaign launched by the Alliance in January 2008, had as one of the main objectives to train and educate radiologists and radiological technologists about the need to perform imaging exams in children with the appropriate technical parameters to ensure that the resulting dose would comply to the internationally accepted radiological protection and safety principles.

As stated by Donald Frush, M.D., chair of the American College of Radiology Pediatric Imaging Commission "*This agreement is a fundamental change in responsibility and accountability for the dose estimates that our children – and actually adults, too – receive during CT examinations*".

Quoting Keith Strauss, M.Sc., of the American Association of Physicists in Medicine and director of Radiology Physics and Engineering at Children's Hospital Boston, "*Models need to be developed specifically for estimating dose to children undergoing CT exams utilizing phantoms that more appropriately take into consideration the size, shape and composition of children's anatomies*." (29)

The Alliance has several ways to advertise its purposes and to make the information available to all the concerned, such as periodic editorials in "American Journal of Roentgenology" and the journal "Pediatric Radiology", e-mails to the organizations' members, posters in the journal "Pediatric Radiology" and internal publications of the ACR, AAPM and ASRT, and finally, articles and public service announcements; the campaign has also its own website, which provides radiographic protocols for children depending on their size or age (figure 3.7) (19).

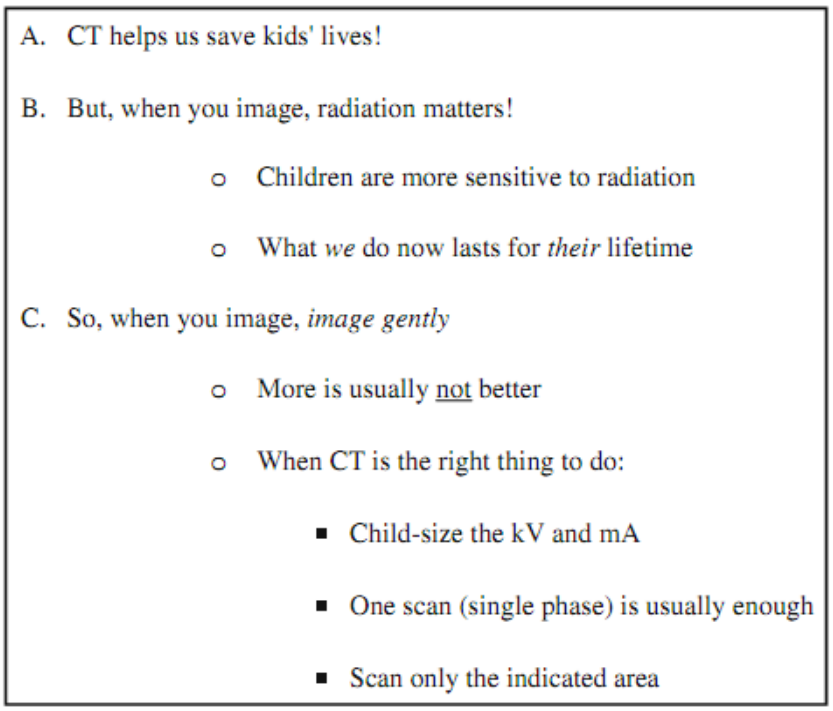


Figure 3. 7 – One of the first messages of the Image Gently™ Campaign. Reproduced from (19).

All the affiliate members of the alliance compromised in raising awareness in the medical community for the need to reduce children's exposure to radiation, with the goal to engender changes in practice, to communicate the Alliance messages, to provide access to the information through meetings and conferences and to contribute to the knowledge within the Alliance. Yet, the campaign also has advertisements to improve health literacy for parents about CT scans for their children.

In 2009, the campaign launched its 10 steps to lower CT dose for pediatric patients (30):

1. Raise awareness and understanding of radiologists for CT exposure. It was only after 2007 that education about the physics of a CT scanner was mandatory; thus, many technologists now benefit from the additional information. All radiological technologists should participate in professional development programs and profit the free educational modules available online, for example, in the Image Gently™ website.
2. Access the services of a qualified medical physicist. To achieve good image quality at lower doses, most of the times a medial physicist can certify that technical aspects of the scanner are correctly applied to the specific equipment and the different types of examinations.
3. Every radiologist should have accreditation from the American College of Radiation (required in the USA).

4. Use other types of imaging, not involving ionizing radiation, whenever possible. In cases of trauma by accident, it is highly recommended the use of a CT scanner. For other situations, such as ventriculo-peritoneal shunt malfunction, the use of ultrasound or MRI is more appropriate.
5. Justification of the CT examination. It can help to decrease the number of CTs prescribed inappropriately.
6. Set a dose baseline for adult-sized patients. The CT technical factors for adults must be verified, to ensure that a higher dose than the recommended is not being received by the patient.
7. "Child-size" the CT dose parameters. For example, the FOV and collimation must be adjusted to the children's size, to ensure the dose doesn't exceed the recommended limits. Child-size protocols and the specific CT equipment parameters must be analyzed carefully, always taking in account changes in image quality.
8. Optimize the CT equipment's parameters. a) Ensure the patient is centered in the gantry, since the dose to the skin is directly related with the distance of the skin from the focal spot – it might help reduce the exposure; b) Decrease dose during the scout, i.e., instead of an anteroposterior image, a posteroanterior scout image may be obtained, reducing the dose in more radiosensitive organs, such as gonads and thyroid.; c) Helical and axial mode must be considered in each different pediatric exam – usually head studies are more appropriate in helical mode and body studies in axial mode; d) Decrease the size of detectors in the *zz* direction – allows an image reconstruction without loss of contrast resolution; e) Adjust exposure time and mA; f) Adjust kilovoltage – 120 kV is reasonable for most of the pediatric soft-tissue imaging; g) Increase pitch;
9. Only one scan, only in the area of interest. Exceeding the indicated area unnecessarily increases radiation dose.
10. The CT room must be "Child-Friendly". The equipment room must be prepared to allow a fast and proper scanning of the child. The medical professionals responsible for the exam must have a certain care to keep the infant as comfortable and quiet as possible, to avoid the need for anesthesia or for a second examination.

4. RADIOSENSITIVITY, RADIOBIOLOGY AND RADIATION PROTECTION

4.1 THE SYSTEM OF RADIATION PROTECTION – ROBUSTNESS AND UNCERTAINTIES

The following figure (3) displays in a pictorial way, the structure, the underlying principles, the issues and the assumptions of the international system of Radiation Protection. It is based on a fundamental hypothesis, the LNT (Linear Non-Threshold) that assumes a linear relationship between the (radiological) risk and the dose. Such hypothesis is today very disputed by some specialists and is at the center of controversial views, studies and discussions about its adequacy, as well as the limitations it introduces in the robustness of the system of Radiation Protection to address low dose exposures (typically below 100 mSv), such as the ones that characterize the medical imaging exposures for diagnostic purposes.

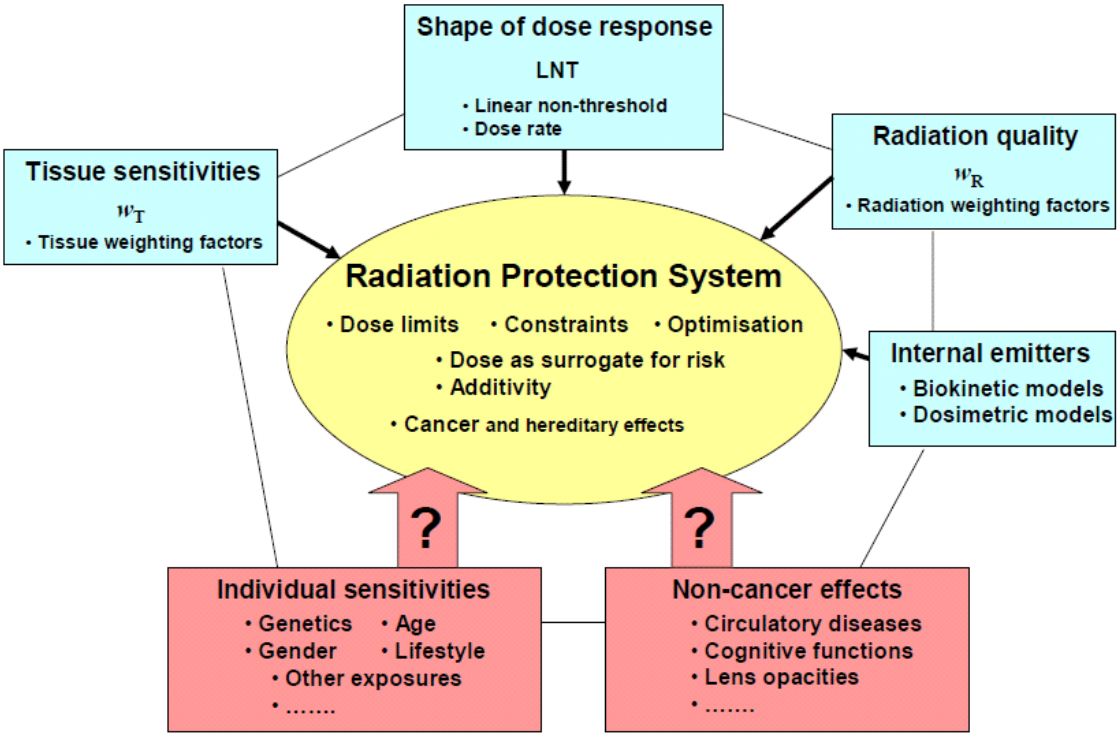


Figure 4. 1 - The structure, underlying principles, issues and assumptions of the International System of Radiation Protection. Reproduced from (3).

Also shown in the figure (lower boxes with interrogation arrows superimposed) are some the main issues that remain to be satisfactorily addressed and incorporated in the system. Together with the shape of dose response (currently assumed to the LNT hypothesis), individual sensitivities to ionizing radiation and the importance of

factors such as genetics, gender, age, lifestyle, etc. constitute very hot topics that are currently being addressed by several communities of experts (radiation biologists, radiation physicists, chemists, geneticists, epidemiologists, amongst several others). However, the state-of-the-art on these topics still presents large uncertainties and unraveled variables.

In this context, radiosensitivity issues are of paramount importance in order to correctly assess the age-, sex- and other types of dependences of the risk associated to the exposure to ionizing radiations. Radiosensitivity issues can only be understood performing studies in the area of Radiobiology, understood at large.

4.2 RADIOBIOLOGY

Radiobiology was firstly introduced after several scientists started reporting the detrimental health consequences of unshielded radiation sources. Since the discovery of X-rays in 1985 by Wilhem Conrad Roentgen, the subsequent observation of radiation emitted by an uranium source by Antoine Henri Becquerel in 1896 and the discovery of Radium by Pierre and Marie Currie in 1898, radioactivity has been linked to health issues, such as erythema, epilation, anemia, and, in worst scenarios, finger amputations and higher incidence of leukemia in radiologists (25).

In 1906 a study was performed by Jean Bergonie and Louis Tribondeaus, to evaluate cell changes in rodent's testis submitted to X-rays. It was observed that mature cells wouldn't divide and immature cells, such as spermatocytes, are more affected by lower doses than mature cells. With these and other studies' conclusions, a few theories were developed to explain radiation effects on eukaryotic cells (12).

LAW OF BERGONIE AND TRIBONDEAU

Based on their studies, Bergonie and Tribondeau concluded that a fetus is much more radiosensitive than a child or adult. They stated four important aspects (25):

1. The most radiosensitive cells are stem or immature cells (the embryo in the blastocyst phase of embryological development) in comparison with mature cells (specialized cells in any organ or tissue).
2. Older tissues and organs are less radiosensitive then younger tissues and organs.
3. Cells with more metabolic activity (such as heart muscle cells) are also more radiosensitive.
4. If a tissue has a very high growth rate (such as the embryo), it becomes more radiosensitive.

Law of Ancel and Vitemberger

In 1925, Ancel and Vitemberger reformulated the Law of Bergonie and Tribondeau, suggesting that cell damage by radiation is very similar, although the timing of damage manifestation depends on the cell type – the *latency time* concept was then introduced (12). Therefore, there are two factors that affect cell injury:

1. It depends on the amount of stress received by the cell.
2. Cell conditions before and after exposure.

In their theory, the cell is most susceptible when it needs to reproduce, but only in this stage the radiation damage will be demonstrated. Then, two mechanisms of tissue ionization were recognized, the direct effect, where the target molecule is directly ionized, and the indirect effect, a process where a water molecule is ionized, producing free radicals, responsible for possible subsequent cell damage (25).

Fractionation Theory

From the 20s to the 30s, radiologist Claude Regaud, studied the effects on sheep testicles when exposed to a large dose. With this experiment, it was found that a fractioned dose spread over a period of time would cause less damage to the skin than with one only large exposure, although the animals would still become sterile – thus, Fractionation Theory was introduced (25).

Mutagenesis

Mutagenesis is a concept developed by Herman Muller in 1927, while he was a researcher at the University of Texas, especially interested in physical and chemical operation of genes and chromosomes. In 1927, he subjected male fruit flies to high doses of radiation, mated them to female fruit flies; Muller observed, in a few weeks, more than 100 mutations in the progeny.

Some of these mutations were lethal, but others were merely noticeable in the offspring – but not deadly. Whit this study, Muller concluded that radiation particles affected the molecular structure of the chromosomes, leading to changes in their functions or just simply disabling them (25).

Effects of Oxygen and Water Hydrolysis

In the 1940s three main experiments lead to the classification of oxygen as a radiosensitizer. Firstly, geneticist Charles Rick discovered that oxygen is responsible for the increase in cell death when exposed to a certain dose. In 1946, D. Lea, a physicist, confirmed the indirect mechanism of cell damage by the free radicals (Figure 4.1)

resulting in water hydrolysis. And finally, John Read and John Thoday, in 1947, confirmed that the number of mutations is directly proportional to the amount of oxygen present in the surrounding environment.

All these experiments confirmed the existence of indirect effects of radiation, opposing to direct ones. A direct effect is usually caused by charged particles and with high energy transfer to mater, such as α particles, neutrons or protons. The target molecules are ionized by radiation, causing biological damage, and might have a genetic effect on future generations. On the other hand, indirect effects involve other types of molecules that absorb radiation energy and produce free radicals of high chemical reactivity with cells and tissues. As an example, water radiolysis is a process that generates the hydroxyl radical, with a high tendency to damage DNA chains, proteins and lipids. The formation of free water radicals is represented in the following equations (12):

$$H_2O \rightarrow H_2O^+ + e^- \qquad (4.1)$$

$$H_2O^+ \rightarrow H^+ + OH^* \qquad (4.2)$$

$$e^- + H_2O \rightarrow H_2O^- \rightarrow H^* + OH^- \qquad (4.3)$$

$$H^* + H^* \rightarrow H_2 \qquad (4.4)$$

$$OH^* + OH^* \rightarrow H_2O_2 \qquad (4.5)$$

$$OH^* + H^* \rightarrow H_2O \qquad (4.6)$$

Also the interaction with oxygen may lead to the deactivation of cellular processes and harm of genetic material:

$$H_2O \rightarrow H_2O^+ + e^- \qquad (4.7)$$

$$e^- + O_2 \rightarrow O^* \qquad (4.8)$$

$$O^* + H_2O \rightarrow OH^- + HO \qquad (4.9)$$

$$H^* + O_2 \rightarrow HO \qquad (4.10)$$

$$HO + H^* \rightarrow H_2O_2 \qquad (4.11)$$

$$HO + HO \rightarrow H_2O_2 + O_2 \qquad (4.12)$$

H∗ and O∗ are uncharged particles but, due to their unpaired electron, are extremely reactive, being able to propagate through the cell and interact afterwards. Therefore, they are capable of breaking molecular bonds even far away from the original place submitted to radiation. Along with the formation of these two free radicals, also H^+ and OH^- are formed; they can simply recombine and produce a new water molecule, or be more harmful for cellular macromolecules through several chemical reactions (12).

4.3 Cellular and Molecular Effects of Radiation

The cells more susceptible to radiation are undifferentiated, have a low life expectancy and frequent divisions. For example, pluripotential hematopoietic cells – lymphocytes and erythroblasts – spermatogonial and intestinal crypt cells are very radiosensitive.

On the other hand, cells such as osteoblasts, fibroblasts and endothelial cells, which have an irregular frequency of reproduction and a variable life expectancy, show a medium radiosensitivity; also some types of cells have low radiosensitivity, due to their long life expectancy and few mitosis, like liver, kidney and salivary gland cells. Some cells are practically not affected by radiation, like neurons and erythrocytes, which are much differentiated and never reproduce (12).

Radiosensitivity depends highly on the stage of the cellular cycle the cell is in when it is exposed to ionizing radiation; mitosis and late G_1 are the most affected, and mid to late S-phase is the least affected stage (25). The cell damage results mostly from detriment of the DNA chain. It can occur by direct or indirect mechanisms, as shown in figure 4.2, where an electron, that received part of the absorbed photon energy may interact directly with the chain, causing a break, or interact with a water molecule, producing the hydroxyl radical, as seen before. If the damage occurs on only one DNA strand, it might be easily repaired using the opposite strand pattern, otherwise both strands are affected, and the chromatin breaks – this process is called DSB, Double Strand Break. If the broken chromosomes rejoin in an unnatural way, probably cell death will occur; if the chromosomes rejoin and the result it's still viable, the cell might

continue to reproduce – although this type of translocation is associated with some types of leukemia (26) and development of other solid tumors.

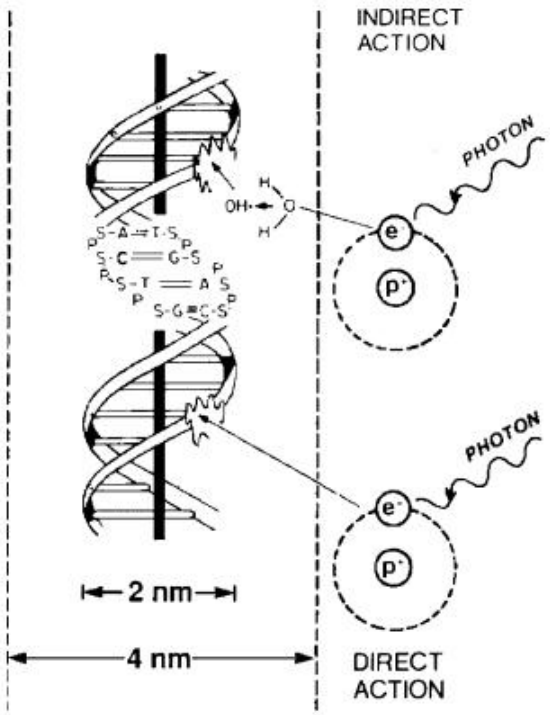


Figure 4. 2 – Schematic representation of direct and indirect radiation action in a DNA chain. Reproduced from (26).

Molecular damage by radiation is of great complexity; it can be separated in four main stages (12):

1. Initial physical state – in this state energy is transferred to the tissue or matter by radiation, and ionization occurs. It lasts about 10^{-16} seconds.
2. Physico-chemical stage – In 10^{-6} seconds, free radical are created by interaction of water with ions.
3. Chemical stage – Lasts a few seconds, and in this stage the free radicals and oxidant agents interact with the organic molecules of the cell: DNA and other types of bonding.
4. Biological stage – the longest stage, may last minutes or several years, several changes occuring in the cell, which leads to several consequences, as will be explained ahead.

The cell response to irradiation depends on three main factors, Linear Energy Transfer, Relative Biology Effectiveness and Oxygen Enhancement Ratio. The first factor, Linear Energy Transfer, or LET, represents the rate at which energy is transferred to matter as a charged particles goes through it. As the ionization intensity increases, also the probability of energy deposition directly in the molecule gets higher, i.e, the probability of occurring cellular damage also increases (12). LET is

expressed in keV/μm; for example, X-rays have around 3 keV/ μm, being considered low LET radiation, as compared for example with alpha or neutron particles, of high LET radiation (table 4.1) – particles have much higher probability of interacting with tissues than electromagnetic radiation (25).

Table 4. 1- Example of several types of radiation and their correspondent LET. Reproduced from (27).

Radiation	Energy	Relative LET value (keV/μm)
250 kV X-ray	250 kV	3
3 MV X-ray	3 MV	0.3
Cobalt 60	1.17–133 MV	0.3
Beta 10 kV	10 kV	2.3
Beta 1 MV	1 MV	0.25
Neutron 2.5 MV	2.5 MV	20
Neutron 19 MV	19 MV	7
Proton 2 MV	2 MV	16
Alpha 5 MV	5 MV	100

Increase of biological interaction

Relative Biological Effectiveness (RBE) is a parameter that describes quantitatively the relative effect of LET. It is based on a comparison between the biological effects of the radiation under study and a dose of 250 keV X-rays that produces the same biological effects. RBE depends on the type of radiation, the type of tissue considered and the radiation dose ratio, among others. As shown in figure 4.3, RBE for diagnostic X-rays is around 1 (12), whereas the RBE of fast neutrons or alpha particles is much higher.

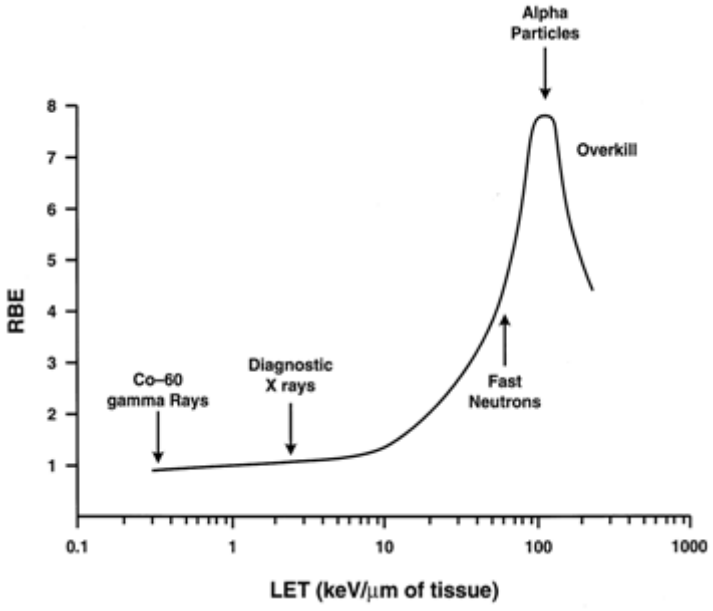


Figure 4. 3 - RBE and LET plotted for different types of radiation. Reproduced from (34).

RBE is expressed through the following equation (25):

$$\boldsymbol{RBE = \frac{dose from\ 250\ keV\ X-ray\ necessary\ to\ cause\ a\ certain\ effect}{dose\ of\ the\ radiation\ in\ study\ to\ cause\ the\ same\ effect}} \quad (4.13)$$

For oxygen related effects, Oxygen Enhancement Ratio or OER was introduced, describing numerically the oxygen effect. It depends on LET, being bigger for low LET radiation and vice versa (25), and can be described as:

$$\boldsymbol{OER = \frac{in\ anoxic\ conditions, dose\ that\ produces\ a\ certain\ biological\ response}{in\ aerobic\ conditions, dose\ that\ produces\ the\ same\ biological\ response}} \quad (4.14)$$

Oxygen is essential for the generation of a free radical by water; therefore, without O_2 the damage is small. For mammalian cells, OER is around 2 to 3.

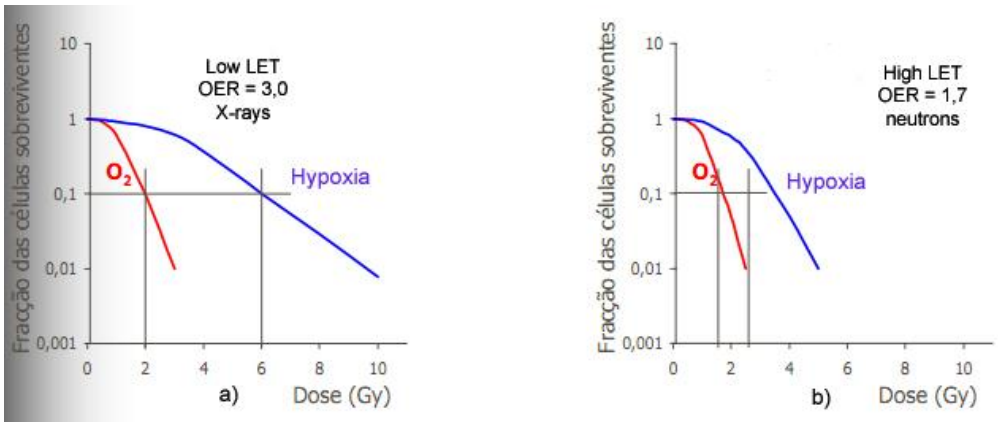


Figure 4. 4 – Relation of cellular survival and OER, for a) low LET radiation and b) high LET radiation. Reproduced from (12).

As can be seen in figure 4.4.b), for high LET radiation, dose has a bigger effect on cell population, both in the presence of O_2 and in hypoxia situation, than with Low LET radiation (figure 4.4.a): for example, the fraction of surviving cells of 0,1, in the presence of O_2 is reached with a dose of approximately 1,5 Gy for high LET and 2 Gy for Low LET. Therefore, high LET radiation has a more damaging effect on cells (12).

4.4 ACUTE EFFECTS OF RADIATION

When an organism is exposed to a high (to be quantified in the sequence) amount of radiation within a time interval of seconds or some minutes, symptoms and specific lesions appear, depending on the amount of radiation it was exposed to. The full body syndrome arises when an organ or the whole body is submitted to very high doses (several Gy) of radiation. This might be caused both by external contamination to very intense radiation fields and by internal contamination, by inhalation of contaminated air, ingestion of contaminated food or water and also even by absorption through an open sore.

Depending on the dose received, usually a shortening of life expectancy occurs, in some cases it's instantly fatal. Studies performed in animals suggest the existence of some differences in the whole population, in life expectancy, for the same whole body exposure. Table 8 represents some dose quantities and the direct effects caused.

Table 4. 2 - Relation dose – caused effects for full body irradiation. Adapted from **(35)**.

< 0,05 Gy	• No immediate observable effects
~ 0,05 Gy to 0,5 Gy	• Slight blood changes may be detected by medical evaluations
~ 0,5 Gy to 1,50 Gy	• Slight blood changes will be noted and likely symptoms of nausea, fatigue, vomiting, etc.
~ 1,5 Gy to 11 Gy	• Severe blood changes will be noted and symptoms appear immediately. • Approximately 2 weeks later, some of those exposed may die. • At about 3 - 5 Gy, up to one half of the people exposed will die within 60 days without intensive medical attention. • Death is due to the destruction of the blood forming organs. • Without white blood cells, infection is likely. • At the lower end of the dose range, isolation, antibiotics, and transfusions may provide the bone marrow time to generate new blood cells and full recovery is possible. • At the upper end of the dose range, a bone marrow transplant may be required to produce new blood cells.

~ 11 Gy to 20 Gy	• The probability of death increases to 100% within one to two weeks. • The initial symptoms appear immediately. • Once the Gastrointestinal system ceases to function, nothing can be done, and medical care is for comfort only
>20 Gy	• Death is a certainty. • At doses above 5,000 rad, the central nervous system (brain and muscles) can no longer control the body functions, including breathing and blood circulation. • Nothing can be done, and medical care is for comfort only.

When full body irradiation occurs, several organs and systems can be damaged, but death only results from a specific organ's failure. As a response to radiation's actions, the body can enter in one of four different stages, dose dependent – the lower the dose received, the longer is the stage's duration.

- Firstly, the *Prodromal Stage;* it can occur with just 0,5 Gy, causing nausea, vomit and diarrhea, lasting minutes to a few days.
- In the second stage, *Latent Stage*, the organism seems free of symptoms, although internal lesions occur, leading to recovery or, in the worst scenarios, to death.
- In the third stage, the organism clearly presents sickness signals and symptoms – *Manifest Illness Stage*. Both the second and third stage are dose dependent, lasting from several hours to several weeks.
- *Recovery or Death Stage* is the most severe case, and as the name suggests, the animal or recovers or dies. The type of lesions and survival time depends highly on the specie, being humans relatively sensitive.

Three acute irradiation syndromes have been demonstrated, related to the damage of a specific main system, depending on the received dose. These syndromes are not characteristic of human beings, and also, death may result of the overlap of two types of system lesions.

- Bone Marrow Syndrome

Occurs from full body irradiations of approximately 1 Gy, resulting in reduction of platelets, white and red blood cells' counts, leading to the destruction of the bone marrow; usually death is caused by anemia and infection. In some cases, the bone marrow can recover the minimum for the organism to be kept alive (12).

- Gastrointestinal Syndrome

When the received dose is up to 2 Gy, symptoms like nausea and vomit, fever, dehydration and anorexia occur immediately (12). The gastrointestinal mucosa becomes atrophic, and if the patient survives long enough, the hematopoietic system starts to get damaged.

- Central Nervous System Syndrome

This syndrome occurs for exposures to doses of 3-4 Gy or higher. The survival time, typically of few weeks, will depend on the dose, the type of exposure, the organs exposed, etc. The lethal dose lies in the interval 4-6 Gy.

4.5 CHRONIC EFFECTS OF RADIATION

Since the beginning of the 20th century that occupational exposures have been reported, namely in the case of radium watch painters, uranium miners, nuclear arsenal testers, aviation personnel and astronauts, scientific investigators and radiologists, amongst several others. Ionizing radiation can cause damage that does not produce visible effects for years, for example cancer, cardiovascular problems and cataracts.

Since 1946 several studies have been performed to evaluate the effects (namely cancer) of the ionizing radiation on health of the survivors of the atomic bombs of Hiroshima and Nagasaki. Also studies were later undertaken seeking to infer on the hereditary effects manifesting on the children whose parents were exposed to the radiation of the atomic bombs. The purpose of these studies was to determine how ionizing radiation affects germ cells that form offspring, and how it was manifested as long-term health effects and hereditary effects. Immediately after the incidents, this group exposed to high radiation doses was considered a unique source of information, "…*a group without parallel in human history, regardless of individual feelings about the use of the two bombs, and the significance of an intensive follow-up of this group was at that time immediately apparent to laypersons and scientists alike of all nationalities*." (28)

Data provided by some of these studies indicate that the incidence of leukemia was much higher than expected: through 1950 to 1956, 64 new cases of leukemia were detected, adding to the 117 already confirmed. In Hiroshima were observed 61 deaths by leukemia, and only 12 were expected; thus, the relative risk was 5,08. In Nagasaki, 20 deaths against 7 expected: 2,85 of relative risk. The explanation for this difference is quite clear right now: in Hiroshima half of the dose was X-rays and the

other half neutrons; in comparison, in Nagasaki, almost 90% of the dose was X-rays; since neutrons have a higher RBE, they have a more severe biological effects, thus the consequences were more severe in Hiroshima (12).

According to the BEIR VII report, among the research on the effects of ionizing radiation on the atomic bomb survivors carried out in Japan, some revealed “adverse pregnancy outcomes (i.e., stillbirths, early neonatal deaths, and congenital abnormalities); deaths among live-born infants over a follow-up period of about 26 years; growth and development of the children (Figure 4.6 and 4.7); chromosomal abnormalities; and specific types of mutations” (3)

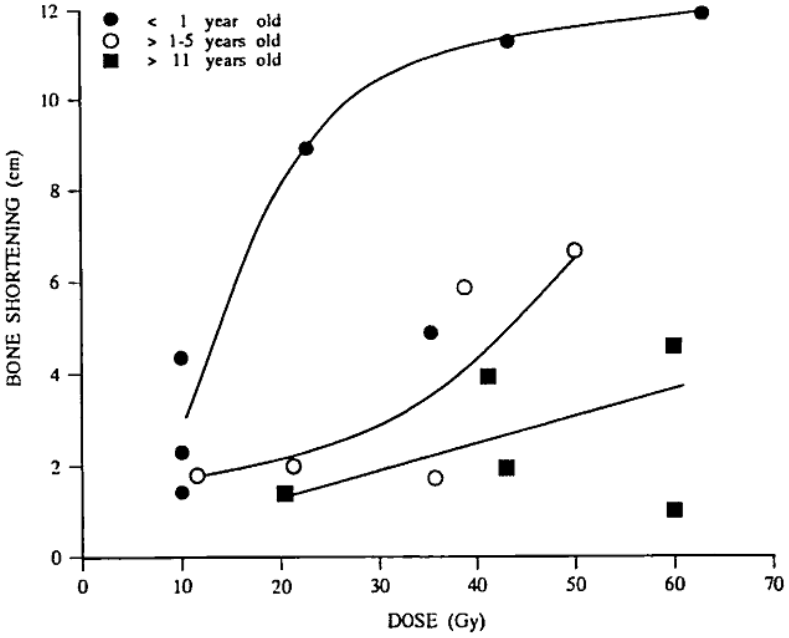


Figure 4. 5 – Bone shortening in children of several ages according to the dose received (UNSCEAR 1993 Report). (37)

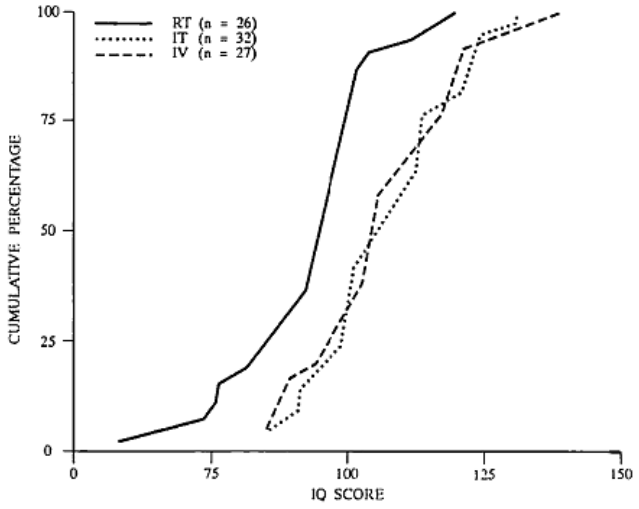


Figure 4. 6 – IQ distribution in children treated with cranial radiotherapy (RT) and two chemotherapy drugs: intrathecal methotrexate (IT) and intravenous methotrexate (IV) (UNSCEAR 1993 Report). **(37)**

In the late 20th century, the final results on these studies were published, and concluded that there was no statistically significant damage detected on the surviving children of the atomic bombs, and, for low doses of about 400 mSv or less, the genetic risks are very small. Many advances have occurred in the last 10 years on radiation-induced mutation, showing that for low or chronic doses of low-LET radiation, the genetic risk is very low compared to natural genetic diseases of the population. These new findings are also consistent with the fact that only the genetic changes compatible with a certain stage of embryonic development are revealed in live births (3).

According to UNSCEAR 2006 Report, all the research made on the estimation of cancer risk has a high uncertainty: few radiation-exposed individuals have been followed up to the end of life; for example, only 45% of the survivors of the Hiroshima and Nagasaki incidents were still alive, 55 years after. To conduct a precise study on the subject, it is important to predict the variation of risk with time after the exposure (Figure 4.5), particularly for the individuals exposed in childhood (38).

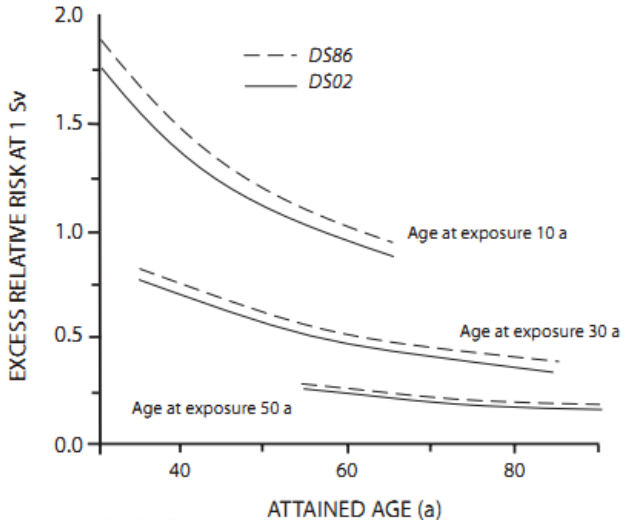


Figure 4. 7 – Descriptions of the ERR of cancer (in the Japanese atomic bomb survivors).

It's clear by Figure 4.5 that ERR, excess relative risk (a risk model that assumes that cancer-rate depends on the baseline cancer-rate), is influence by age and age of exposure. There is a decrease of the ERR with increasing age of exposure. Also, for the population exposed under 20 years, the estimated number of cancer-related deaths has doubles in each of the last three decades (38).

In 1935, a group of 15 000 people suffering from Ankylosing Spondilitis, a chronic autoimmune disease, characterized by inflammatory arthritis, that affects the spine and pelvis, received whole and fractionated doses of 1 to 20Gy as part of the treatment. A follow-up study 2 years later, revealed a high incidence of leukemia; 7 cases were documented, and only 1 was expected, leading to a relative risk of 7.

Also during the 20th century, in the USA, high incidence of leukemia among radiologists was reported (from 1948 to 1961), with a relative risk of 3. A similar study was performed in the UK (in 1921), showing contradictory results: a number of leukemias higher than expected could not be observed. Nowadays, the incidence of leukemia is not related with this medical specialty, being considered a rare disease: only 70 cases in each 10 000 are reported;

The other type of cancer possibly related to radiation is melanoma, which has been reported with a high incidence among radiologists and also in acne treatments, in both cases a few years after the discovery of X-rays; the radiation used was unfiltered and with few kV, leading to the release of high doses in the superficial layers of the skin.

Thyroid cancer has been reported in radiotherapy treated children with hypertrophy of the thymus, in the 1920's, with doses varying from 1,29 to 30 Gy: the cancer incidence increased 100 times. This type of cancer has also been related with the Hiroshima and Nagasaki incidents and with the population of the Marshall Islands due to the tests of atomic bombs.

Table 4. 3 - Incidence and mortality for solid cancers and leukemia for a dose of 1Gy to a group of 100.000 people. Reproduced from (29).

	All Solid Cancers		Leukemia	
	Male	Female	Male	Female
Excess cases	800	1,300	100	70
Number cases without dose	45,500	36,900	830	590
Excess deaths	410	610	70	50
Number deaths without dose	22,100	17,500	710	530

Several experiences with animals irradiated full body with lethal doses has proved that the organism may recover, but the animals die sooner than controls. Other studies on the effects of low dose radiation, with particularly detailed autopsies, showed that life shortening in animals is due to an excess of neoplasia (17).

All these findings, among several others, obtained from several scientific epidemiological studies and fundamental research undertaken throughout the 20th century contributed to improve the state-of-the-art on the biological effects of ionizing radiation and the perception of the radiological risk associated to the exposure to ionizing radiation. These effects can be categorizes as:

- Stochastic Effects, that may result from the lesion from one or several cells, without a defined threshold; the increase of radiation dose implies the increase of frequency of the effect and not its severity; cancer and genetic effects fall in in this category .
- Deterministic Effects on the other hand, are those effects whose severity depends on the number of cells or the tissue damaged; the higher the radiation dose, more severe will be the injury. These effects are produced above the threshold dose value. Cataracts and cardiovascular diseases are examples of deterministic effects caused by exposure to ionizing radiation.

As stated by the UNSCEAR 1993 Report, "Deterministic effects of ionizing radiation in humans depend on the dose and can be expected to have thresholds below which the radiation effects are too small to impair function of the irradiated tissue or organ. In children, tissues are actively growing, and a radiation induced deterministic damage in a tissue or organ will often be more severe than in adults." Many researches on deterministic effects can't conclude precisely the dose levels at which body damages appear, although the past studies on the follow-up of children treated for tumours revealed much information concerning this subject (37).

4.6 INFLUENCE ON RADIOSENSITIVITY

Radiosensitivity is gender-dependent, females tolerating doses 5% to 10% higher than males, as confirmed by experimental data. Besides gender, the other main factor that greatly influences radiosensitivity is age. This aspect is consistent with Bergonie and Tribondeau's Law; radiosensitivity through age can be described in figure 4.5:

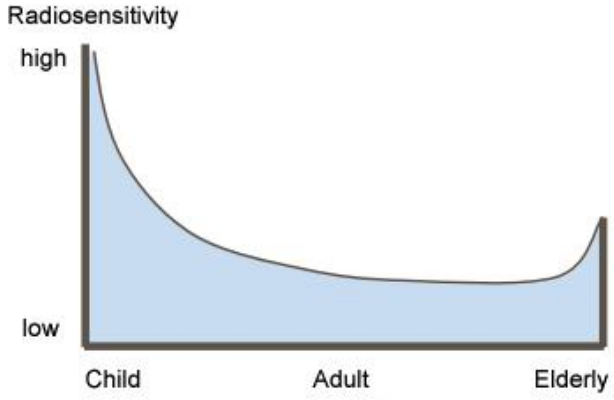


Figure 4. 8 - Radiosensitivity dependency with age. Adapted from (12).

A developing organism is a highly dynamic system, characterized by a high and quick cell differentiation and proliferation, from which it's possible to conclude how radio-sensible an embryo is. Its response to radiation depends highly on its development stage, the total dose and the type of radiation.

The three stages of the fetus development – preimplantation, organogenesis major and fetal – demonstrate different effects to the same amount of radiation, as it was studied on the descendants of the survivors of the atomic bombs. The most commons diseases include microcephaly (incidence of 3%), mental and growth retardation. In the preimplantation stage, which occurs from the beginning until the 9th day, the blastocyst is formed. In this stage, consequences of irradiation include death or the "all-or-nothing" kind of response: if the embryo recovers, the damaged cells are repaired, so no abnormality will be developed in the future. The repair ability, deddiferentiation, hypoxic state contribute to the relatively high cell resistance; the most critic exposure moments are when the two pronuclei join together, two hours after conception, and when the first divisions occur, 30 to 60 hours after conception.

From animal studies, doses of 50 to 100 mGy may cause spontaneous abortion, although, after implantation, it's needed around 250 mGy to cause neonatal death. It's in the Organogenesis phase that the highest incidence of congenital anomalies is observed. Usually, if the embryo is irradiated early in this stage, it may have the most severe mental retardation, as shown by the atomic bomb survivors: *in-uterus* irradiation of more than 100 mGy lead to an increased incidence of microcephaly (since the human Central Nervous System, CNS, has a long gestation period, it has a higher probability of being affected by radiation). In the final stage, from 8 weeks until birth, the anomalies mostly verified are in the CNS and senses organs, although its probability is very low. Of course the damage caused in this stage can only manifest a few years later, in the form of cancer, behavior changes or decrease of IQ (12). Figure 4.6 represents a resume of the possible effects of radiation on the three stages:

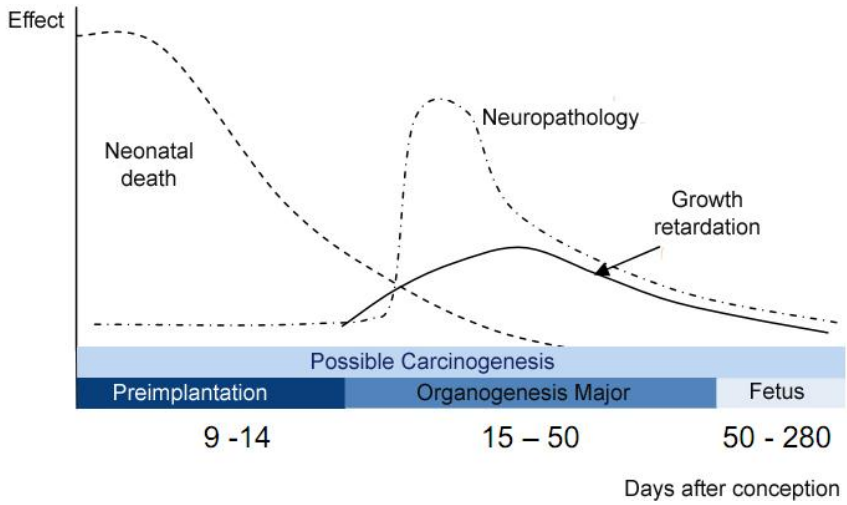


Figure 4. 9 - Possible effects of radiation in the gestational period. Adapted from (12).

5. STATISTICAL STUDY

In order to assess several aspects related directly with pediatric CT exposure, mostly the effective dose to which pediatric patients are exposed, a survey was accomplished in two pediatric hospitals in Portugal, one having a *Siemens Somaton Plus 4* CT-equipment and the other a *Siemens Somaton Definition AS* CT-equipment. In the first hospital visited, which will be referred to as "Hospital A", both pediatric and adult data were gathered in order to make a comparison. In the other pediatric hospital that will be referred to as "Hospital B", only pediatric data was made available. Since the values obtained in the two hospitals refer to different equipment and also to different time intervals, the data analysis was performed separately for Hospital A and Hospital B.

5.1 HOSPITAL A

For Hospital A, data records corresponding to examinations performed during the period of one year from 2010-2011 were collected, and whenever possible, for each examination the following factors were registered:

- date,
- type of exam,
- patient's age,
- patient´s sex,
- mA and kV,
- $CTDI_w$,
- scan length,
- pitch,
- protocol followed,

Data records for which not all these parameters could be retrieved were considered as "Invalid data".

The amount of collected data is displayed in table 5.1:

Table 5. 1- General information on the collected data.

Data	**Amount**	**Percentage**
Pediatric	1179	68,0 %
Adult	475	27,4 %
Invalid data	81	4,7 %
Total	1735	100 %

Since the Hospital does not have an electronic recording/logging system, all the data is handwritten in monthly logbooks, being difficult to keep a precise and complete record of all the exams performed; as it's possible to see by table 1, the number of invalid data is quite considerable.

The types of exams performed in this hospital include cranial, abdominal, abdominal-pelvic, thorax, ears, paranasal sinuses (referred as "sinuses" in this thesis) and others, with a very low frequency, such as mandible, legs, orbits, lumbar spine, face, renal, elbow, hip joint, pelvis, sternoclavicular joint, shoulder and wrist. The relative frequency (in percent) of these types of examinations is displayed in Figure 5.1.

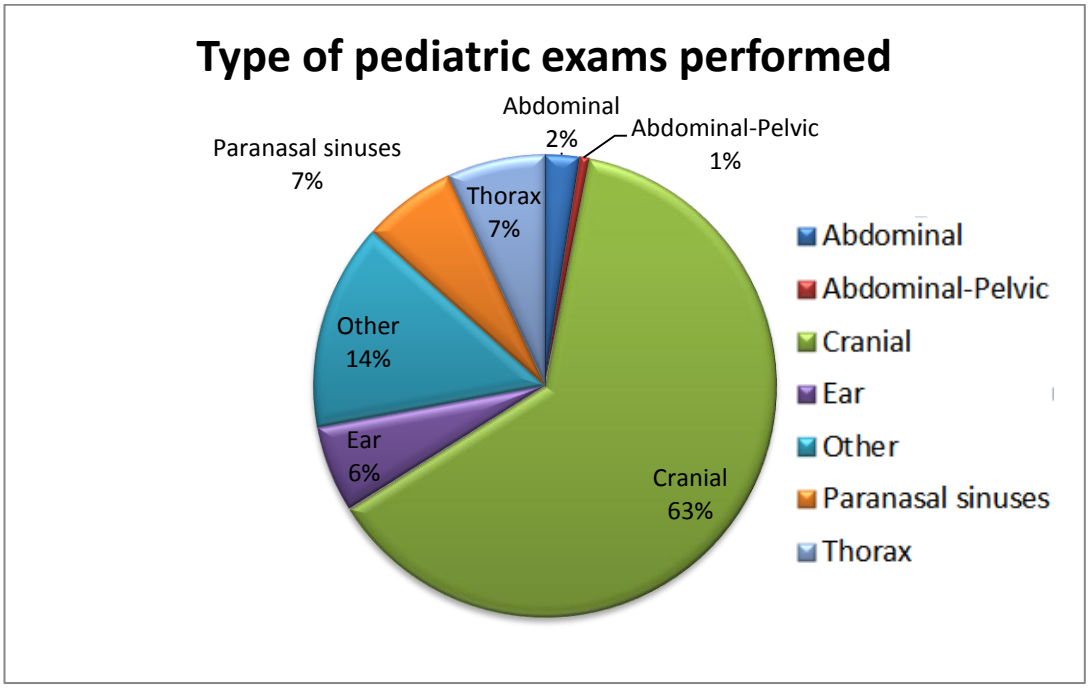


Figure 5. 1 - Percentage of pediatric exams performed in approximately 11 months, representing the most common types of exams; the Category "Other" includes the types referred above (2% of the total number of examinations), and each one was performed less than 10 times over this period of time.

The most common type of pediatric examinations is undoubtedly cranial, followed by sinuses and ears, which are mostly head exams. Since the number of abdominal-pelvic exams is very low for the period of time under study, only the abdominal were considered in the following analysis. In the pediatric exams, 45,3% were performed to females and 54,7% to males.

In the case of adult exams (displayed in Figure 5.2), the relative frequency of exams presents a different perspective:

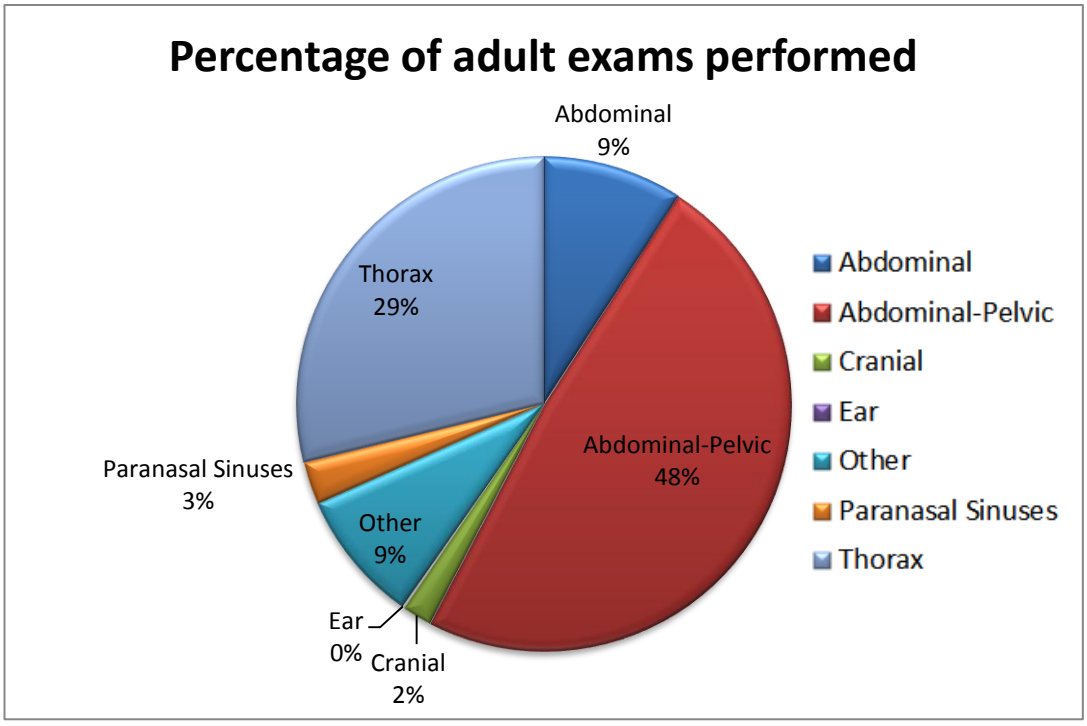


Figure 5. 2– Percentage of adult exams performed in 11 months.

Since the hospital is specialized also in gynecology and obstetrics, it is not surprising that the most executed exams are abdominal-pelvic, abdominal and thorax, which are performed to detect breast cancer or any kind of the female reproductive system cancer. Therefore, it is logical that during this period about 96,6% of the examinations were perform to women and only 3,4% to men.

5.1.1 Analysis of the Pediatric Data

Figure 5.3 provides a general idea of the number of pediatric examinations as a function of age. Age bins of one year width were considered.

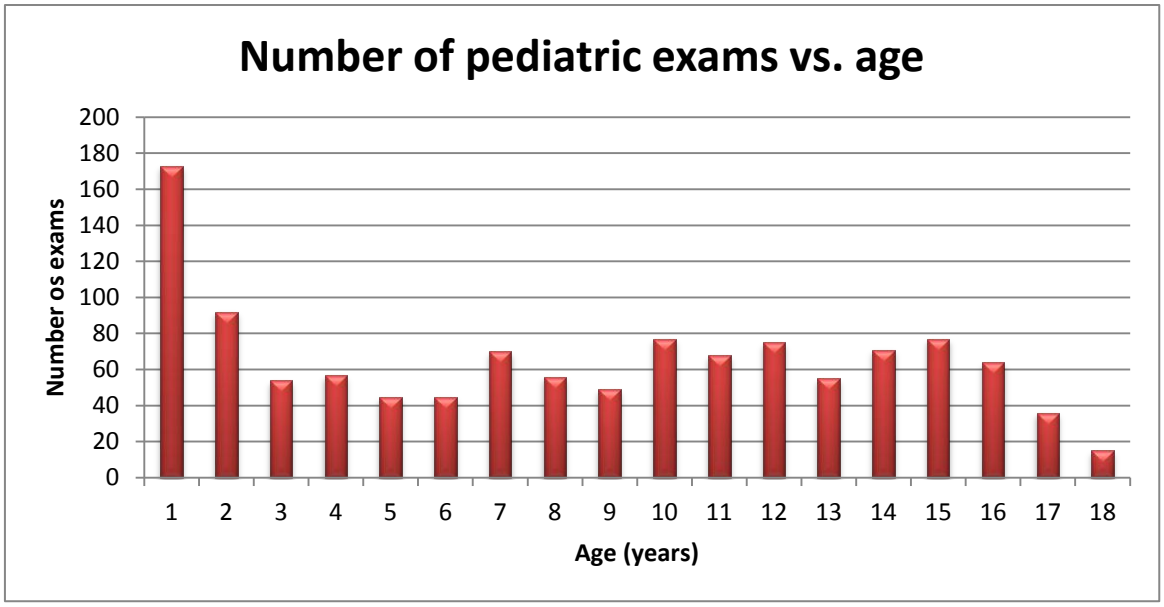


Figure 5. 3 – Number of pediatric CT-exams performed for the different ages.

From the perspective of the radiosensitive issues discussed in this thesis, it is interesting to note that the age group from the birth to 1 year exhibits the highest number of examinations performed.

Due to the different radiosensitivity of the tissues in every stage of the pediatric individuals´ life, it is necessary to consider new age groups and to regroup the data sets accordingly. The new age groups were suggested by a neuro-radiologist of the Hospital A, as follows:

- Birth – 3 months
- 3 months – 12 months
- 1 year – 2 years
- 2 years – 6 years
- 6 years – 8 years
- 8 years – 12 years
- 12 years – 18 years
- Adult

Figure 5.4 depicts the percentage of each type of examinations performed per age group, considering the new age group division. It may be concluded that since birth and until 3 months old, the most common examinations is cranial followed by thorax, but as the age increases, the frequency of ear examinations also increases.

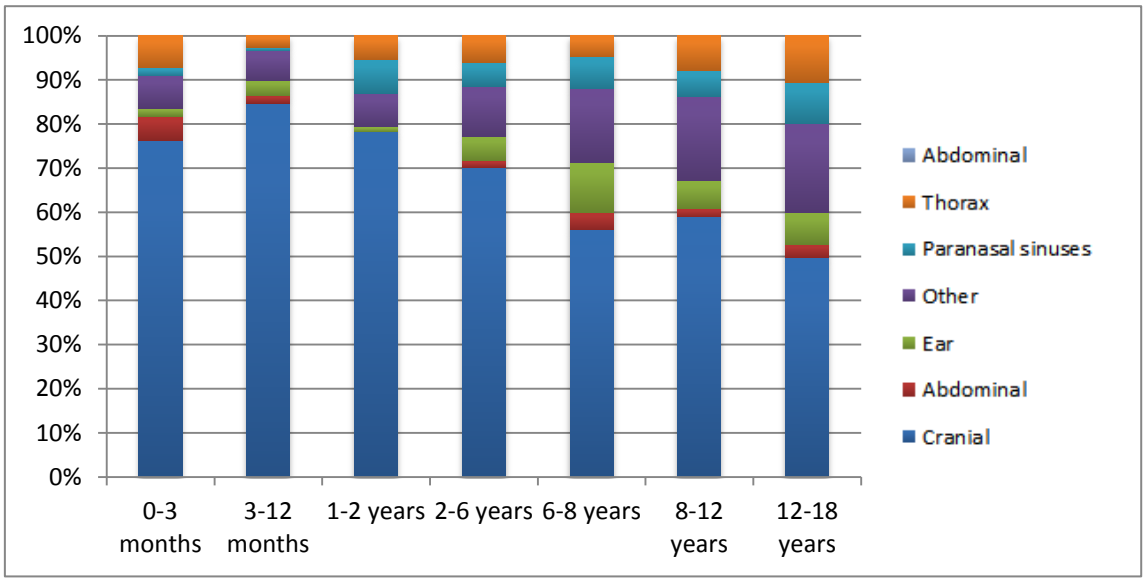


Figure 5. 4 – Quantity of types of pediatric exams by age group.*

One of the most common examinations performed in the first months of a children's life are cranial exams. This happens mainly due to a sensory acquired pathology and malformation that can develop in early stages and lead to deafness. The adequate age group to control, to prevent and diminish this kind of events is from 3 to 6 months, as during this period the brain still has the flexibility to adapt to an alternative learning throughout life. After this age, starts the sustenance period, where the main goal is to prevent any aggravation of the disease; cranial exams are also performed in order to control the possibility of development of neurologic, neurosurgery or traumatic intracranial pathologies, such as hematomas, epilepsy or ventricular widening, since birth.

Figure 5.5 shows the variation of the average mAs for the most common types of examinations performed.

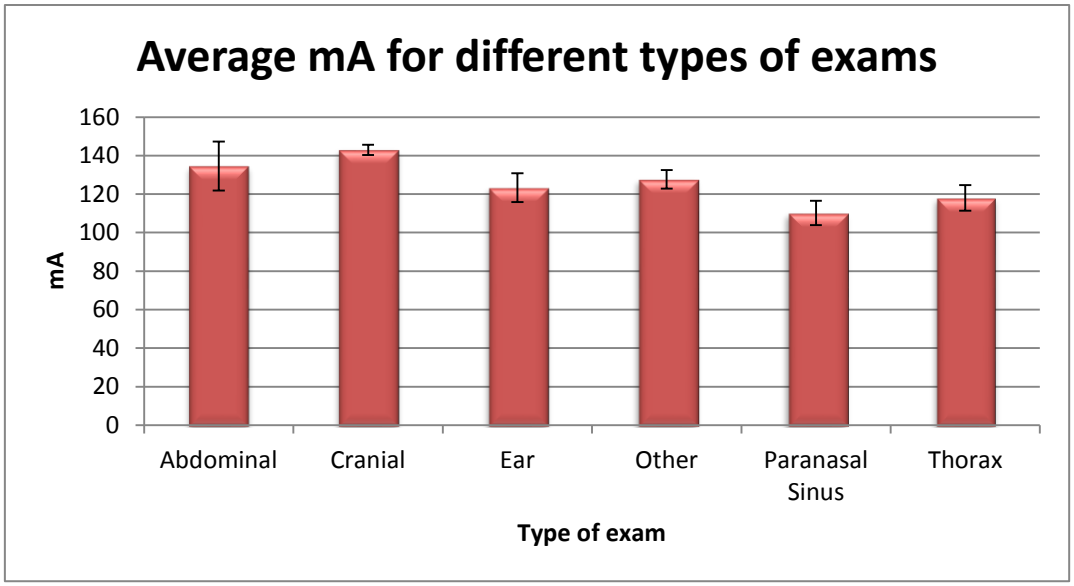


Figure 5. 5 – Average mAs for different pediatric exams.

The values of mAs increase for high density structures and with the need of better resolution, in areas such as ears, paranasal sinuses and posterior cranial fossa, (since there is a big difference in density between bone and the cerebral parenchyma below the supratentorial region). It is also noticeable the difference between thorax and abdomen (high mAs); both have high density structures (bone from the spinal cord), but the abdomen may have also a high density contribution from the pelvis, hip joints and the possible administration of intravenous or *per os* contrast, while the thorax has a major area mostly of negative density, the air filled lungs.

A parameter given by the equipment is the $CTDI_w$ (defined in Chapter 2), which provides useful quantitative dosimetric on the patient´s exposure. With this parameter, it is possible to calculate the $CTDI_{vol}$, (also defined in Chapter 2) multiplying the $CTDI_w$ by the pitch, which is easily known through the used protocol. The average value of the $CTDI_{vol}$ per age group, for the different types of exams considered, is shown in Figure 5.6.

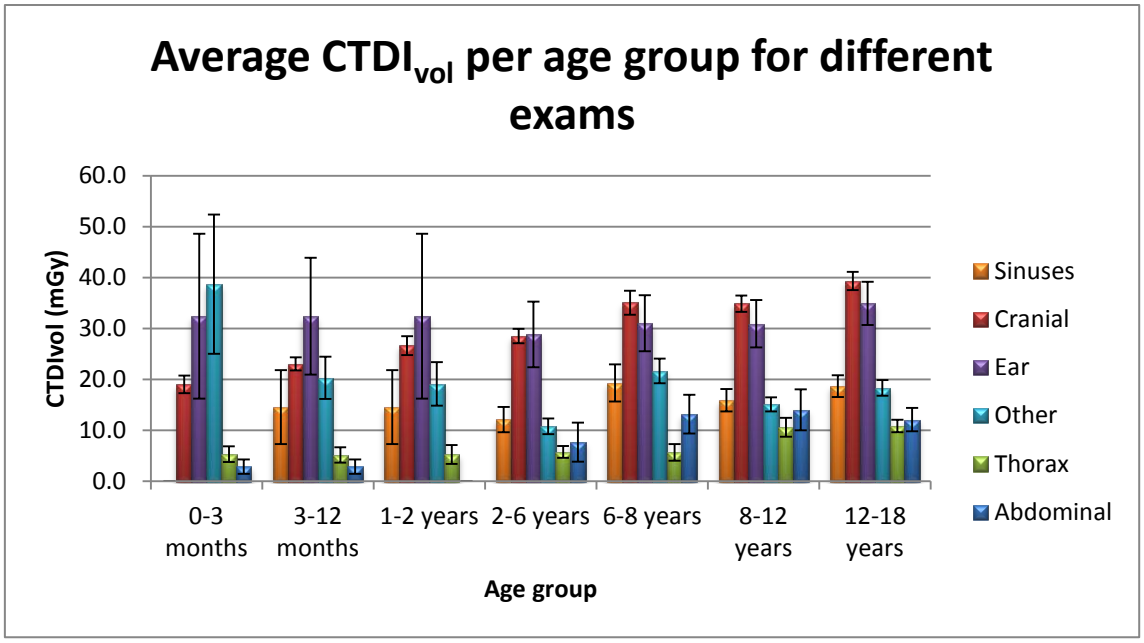


Figure 5. 6 – Average value of $CTDI_{vol}$ per age group and for the different types of pediatric exams (larger display in appendix).

From Figure 5.6, it's possible to conclude that the average $CTDI_{vol}$ for ear exams does not vary significantly for the different age groups. Other types of exams, such as cranial and thorax, exhibit a wider variation in $CTDI_{vol}$. It is also important to take in account that the phantoms used to simulate the patient's body while measuring the standard $CTDI_{vol}$ are very simplified. The internal organs and tissues generate a non-uniform dose distribution across the body, which is what is simulated by the phantom – therefore, the $CTDI_{vol}$ is not extremely accurate with reality, although accepted by the scientific community as a method to infer CT parameters.

In order to assess the hospital's practice while setting the $CTDI_{vol}$ values (and consequently DLP) and other examination parameters, the collected data was compared with a 2010 Diagnostic Reference Levels Swiss study (22).

The study entitled "*Diagnose Reference Levels (DRL) in CT Scan*" was conducted by the Unity of Direction of Consumers' Protection, from the Internal Federal Department of the *Swiss Confederation*. The DRL's obtained are based on the 75th percentile of adults and children's data collected from studies and from real data acquired in Switzerland. The type of equipment and parameters such as kV, mA, pitch, collimation, etc. are not displayed.

Using the data obtained in that study, a comparison was performed between the 75th percentile values of $CTDI_{vol}$ and DLP (for cranial, abdominal, thorax and paranasal sinuses exams) obtained in the present study and the Diagnose Reference Levels for CT determined in the Swiss study. (Note: the DRL values of this study are displayed in the appendix). Even though in this study there was no data for certain age groups, Figure 5.7 displays the comparison results for abdominal examinations, Figure

5.8 displays the comparison results for cranial examinations, Figure 5.9 displays the comparison results for cranial examinations and Figure 5.10 displays the comparison results for paranasal sinuses examinations;

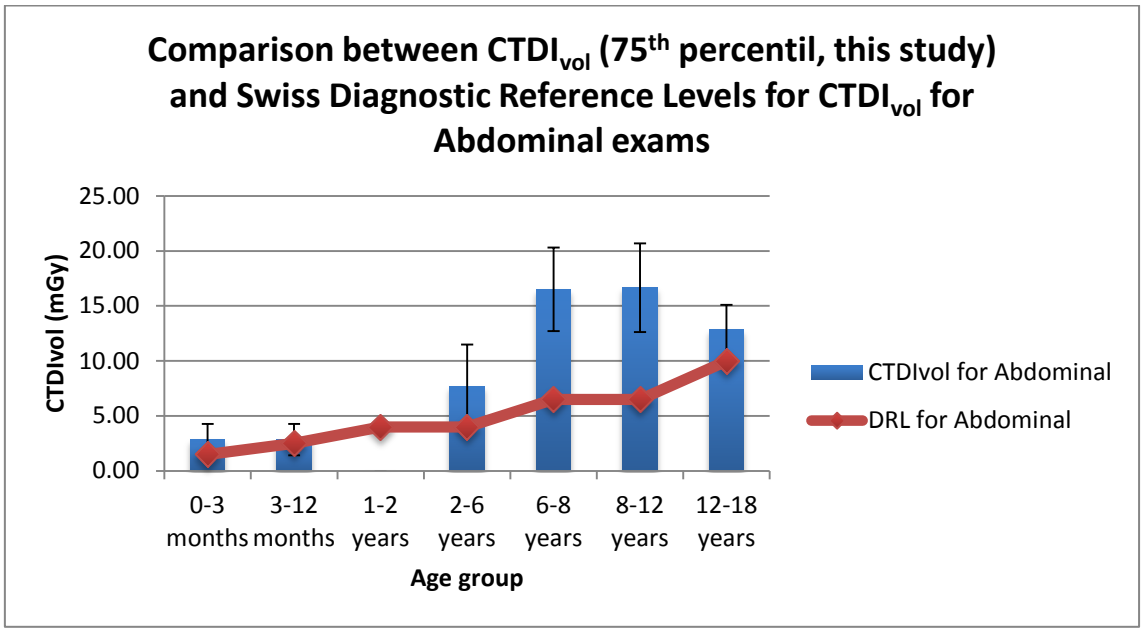


Figure 5. 7 – Abdominal exams: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study and the Swiss $CTDI_{vol}$ diagnostic reference levels.

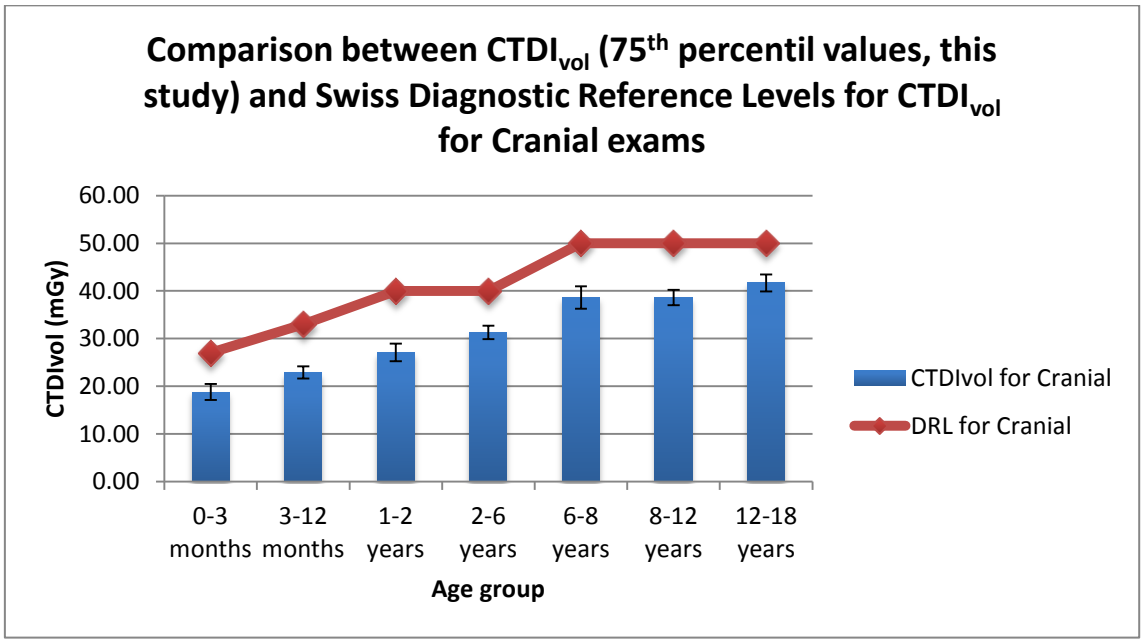


Figure 5. 8 – Cranial exams: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study and the Swiss $CTDI_{vol}$ diagnostic reference levels.

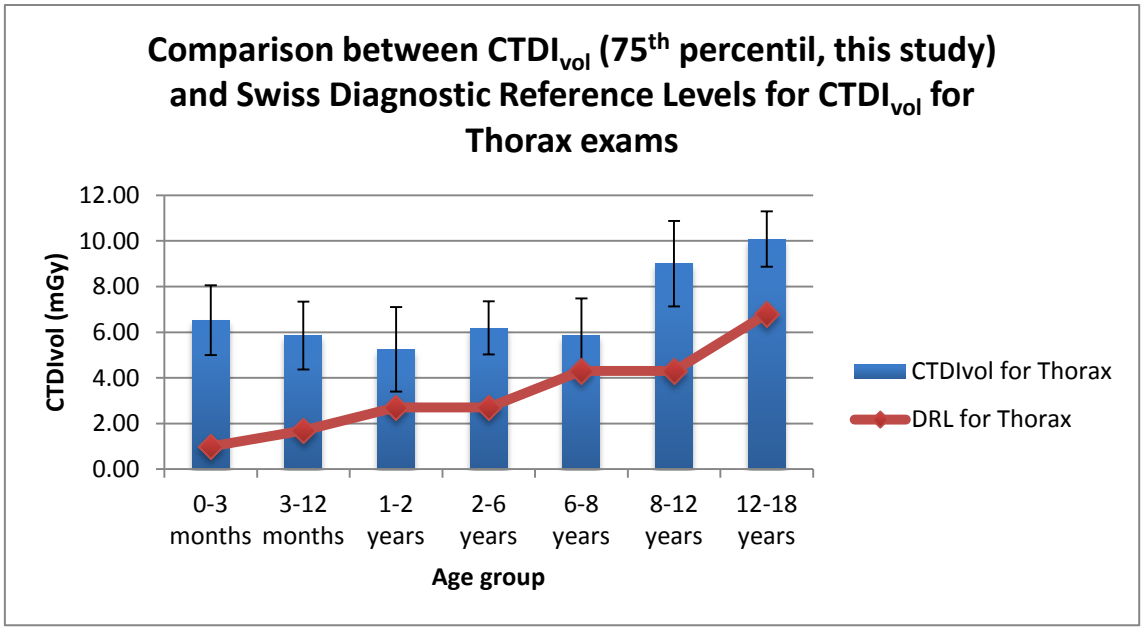


Figure 5. 9 – Thorax examinations: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study and the Swiss $CTDI_{vol}$ diagnostic reference levels.

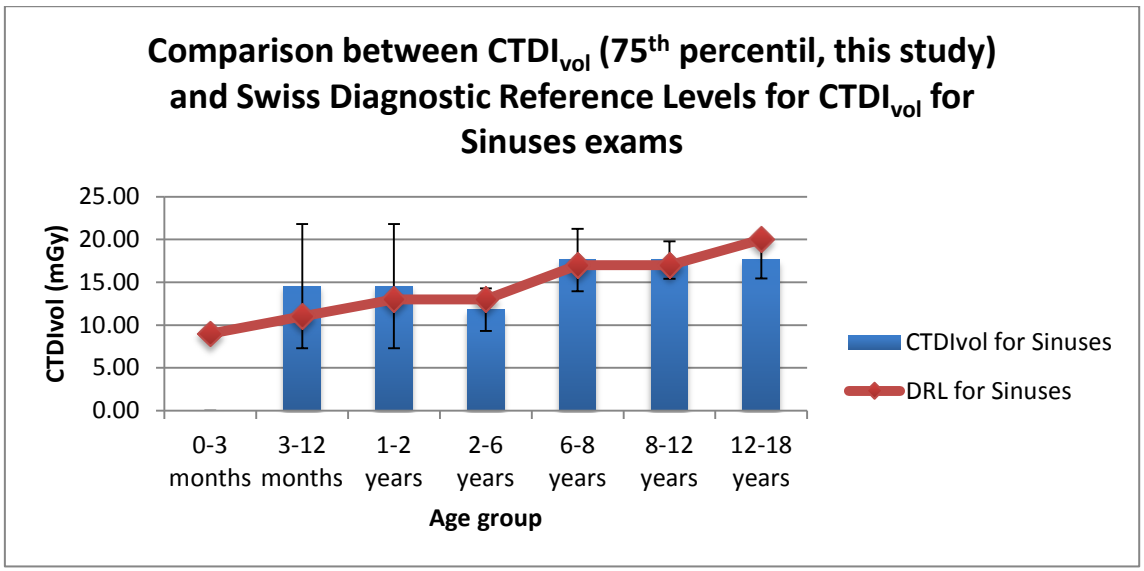


Figure 5. 10 – Comparison established between the 75th percentile values for $CTDI_{vol}$ obtained in the gathered data and the Swiss $CTDI_{vol}$ diagnostic reference levels for paranasal sinuses exams.

Unfortunately, for some age groups, the data collected was non-existent (the age group of 1 to 2 years in Figure 5.7 and the age group of birth until 3 months in Figure 5.10) For cranial examinations, the more frequently performed, it is clear that the $CTDI_{vol}$ results obtained in this study exhibit a "trend" similar to the one observed in the Swiss DRLs study but are always significantly lower.

It is worth mention the significant discrepancies between the data "patterns" and the sizable numerical differences for practically all age groups in thorax, and for

some in abdominal and sinuses, between the data values of this study and the Swiss DRL data.

When analyzing the scan lengths of cranial examinations in order to calculate the Dose Length Product, DLP, it was clear that many of them were representative of the sum of the scan lengths of the examination with and without contrast (the value was therefore doubled), since most of them were too high (as seen before, all the data is handwritten, and there is no requirement to specify each acquisition performed to the same patient in one examination). In order to correct this aspect, the exam lengths were decreased to half in the following cases:

- 0 to 3 months - exams with more than 10 cm were reduced to half;
- 3 to 12 months - exams with more than 14 cm were reduced to half;
- 1 to 2 years - exams with more than 14 cm were reduced to half;
- 2 to 8 years - exams with more than 15 cm were reduced to half;
- 8 to 12 years: exams with more than 17 cm were reduced to half.

Figure 5.11 represents the average DLP for each age group, for the different types of examinations,

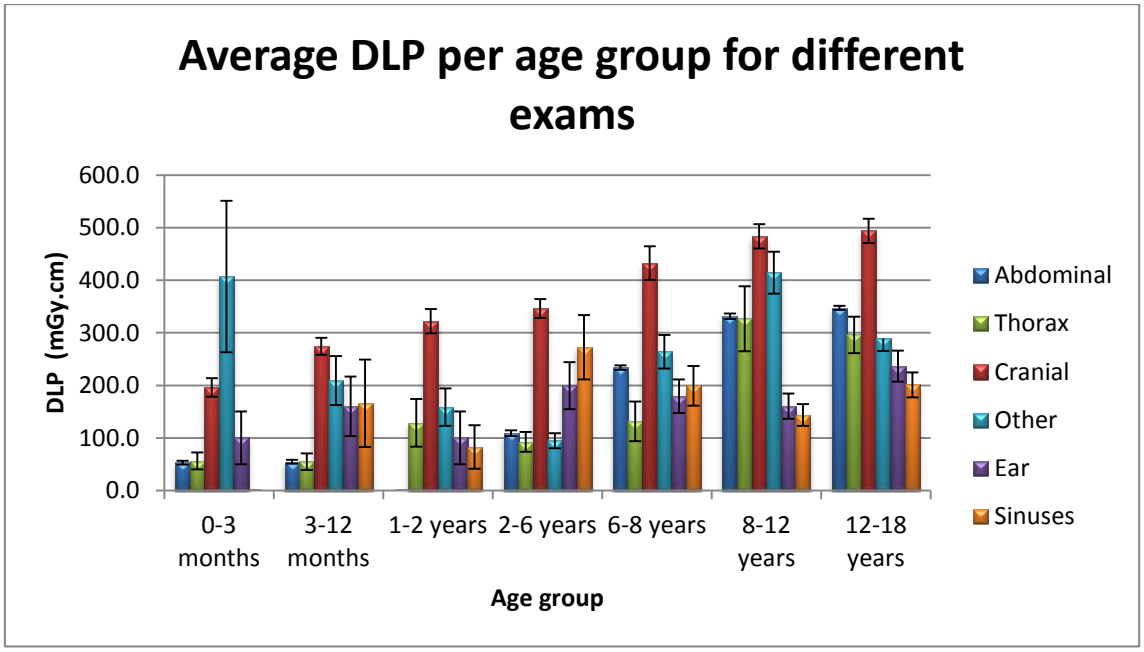


Figure 5. 11 – DLP per age group for the different types of pediatric examinations (larger display in appendix).

Since the DLP is the product between the scan length of the examination and the $CTDI_{vol}$, the highest values of DLP are for cranial (which have a high $CTDI_{vol}$) and other types; for cranial exams, since many children don't cooperate, and in order to avoid using anesthesia some slices need to be repeated, which may lead to higher

values. It can also be due a complementary study, with thinner slices or a repetition of the exam with intravenous contrast.

As previously done, the average DLP values obtained in this study were compared with the Diagnose Reference Levels on the Swiss study previously mentioned. The results are displayed in the following Figures.

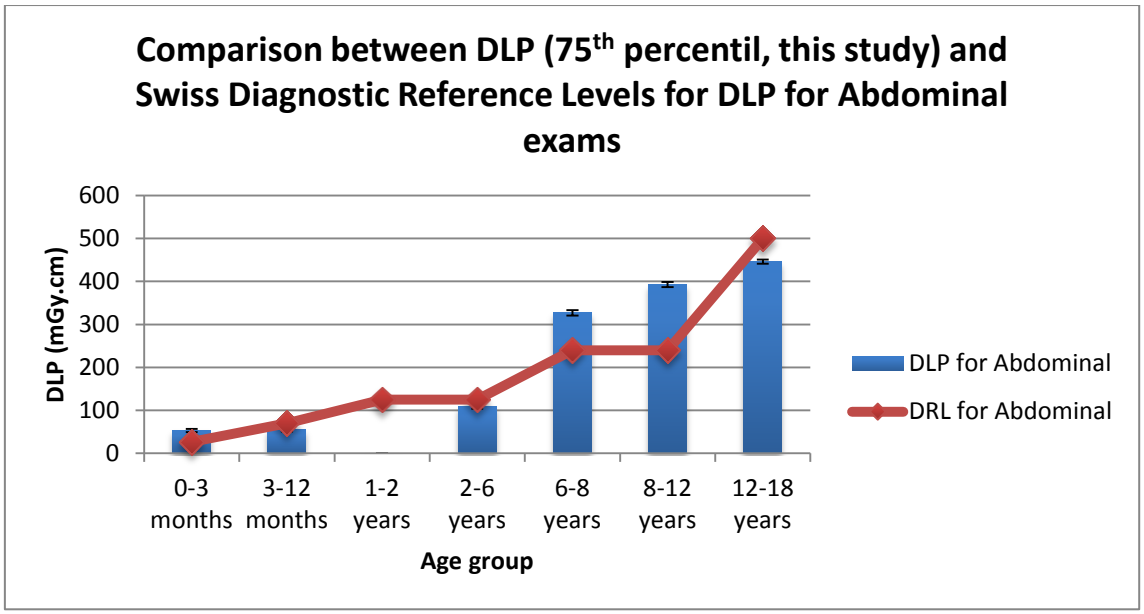


Figure 5. 12 – Abdominal examinations: comparison between the 75th percentile values for DLP obtained in this study and the Swiss DLP diagnostic reference levels.

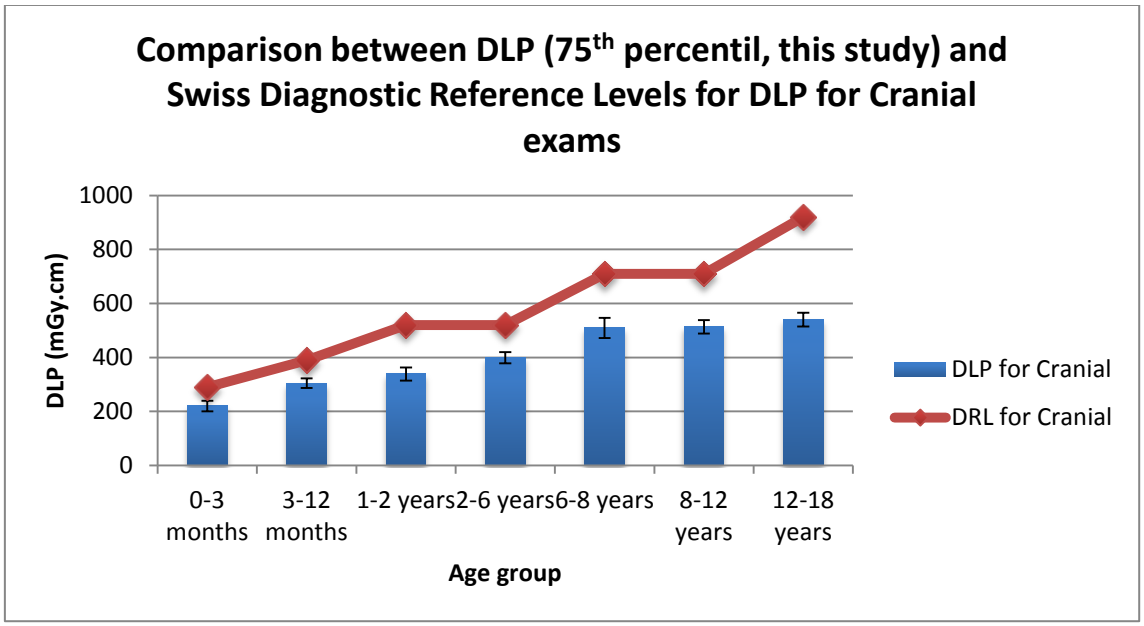


Figure 5. 13 – Cranial examinations: comparison between the 75th percentile values for DLP obtained in this study and the Swiss DLP diagnostic reference levels.

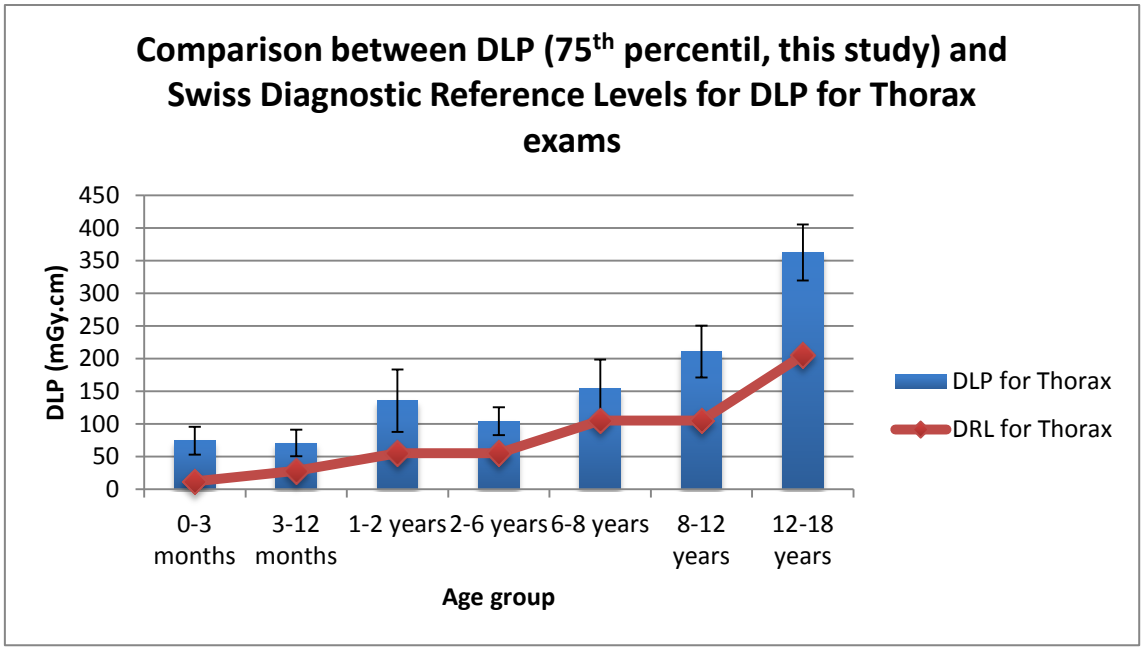


Figure 5. 14 – Thorax examinations: comparison between the 75th percentile values for DLP obtained in this study and the Swiss DLP diagnostic reference levels.

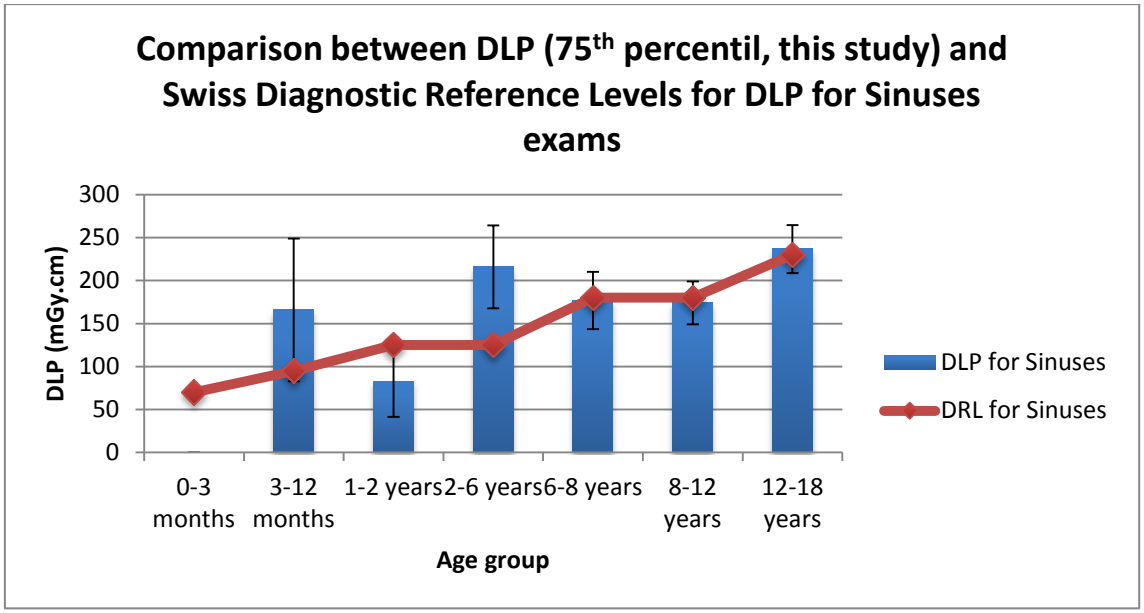


Figure 5. 15 – Paranasal sinuses examinations; comparison between the 75th percentile values for DLP obtained in this study and the Swiss DLP diagnostic reference levels for.

In DLP analysis some of the values exceed the recommended diagnose reference levels, especially in thorax exams.

For abdominal and especially for cranial examinations, the DLP mean values obtained in this study are lower, for the majority of the age groups, than the Swiss DRLs. The discrepancies are sizable for some age groups.

As for paranasal sinuses examinations, there is no clear trend in the data obtained in this study. The discrepancies are significant for some age groups. Overall, the average DLP values obtained in this study are in most age intervals (but not all) above the Swiss DRLs. It may also happen in very specific situations that a higher area needs to be scanned to detect secondary lesions; as an example, in thorax exams to evaluate carcinogenesis, the examination usually covers all the thorax area, neck and head until the paranasal sinuses, to detect eventual metastases.

The two final Figures on pediatric data of hospital A intend to represent the effective dose received for every age group considered, and also related with the type of exam. As explained in a previous Chapter 3, the effective dose was calculated taking in account the conversion coefficients of DLP into effective doses (k-values) displayed in Table 5.2, for the different body region and age group.

Table 5. 2 – Conversion factors K according to body region and age group **(39)**.

Body Region	k (mSv mGy^{-1} cm^{-1})				
	0 year	1 year	5 year	10 year	Adult
Head	0,011	0,0067	0,0040	0,0032	0,0021
Chest	0,039	0,026	0,018	0,013	0,014
Abdomen and pelvis	0,049	0,030	0,020	0,015	0,015
Trunk	0,044	0,028	0,019	0,014	0,015

The effective dose values for four different types of examinations are displayed in Figure 5.16:

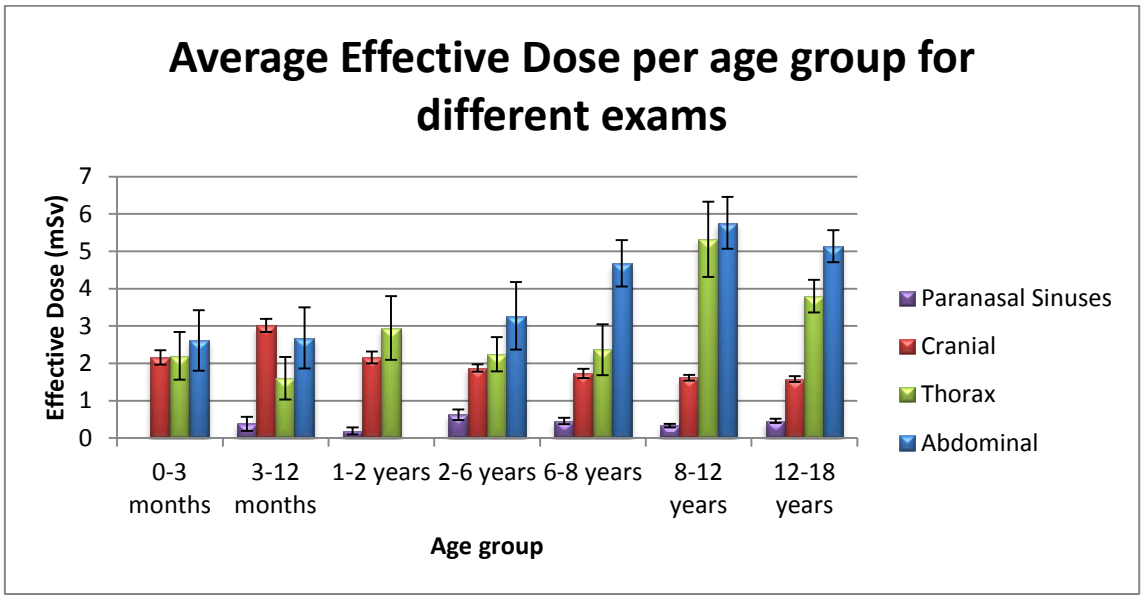


Figure 5. 16 – Effective dose per age group and for three types of pediatric exams.

In Figure 5.16 it is noticeable how abdominal exams performed in children older than 6 years translate into significant effective dose values. Cranial exams are performed in every age, with resulting effective dose that does not significantly vary, ranging between 1,5 mSv and 3 mSv. Considering that the standard values of adult effective doses are 2 mSv for cranial exams, 3 mSv for thorax and 5 mSv for abdominal (discussed ahead with further detail), the data analyzed in this study paves the way to the conclusion that the pediatric exposures in cranial and abdominal CT-examinations needs to be justified and optimized, in light of the Radiation Protection principles.

An interesting approach to assess the differences in gender is to consider the effective dose for the group of 12 to 18 years, since this age group is the one where children start to develop physically; the following chart clarifies the differences in effective dose between girls and boys, in thorax and abdomen CT. The effective doses are clearly lower for girls, since most of the times there is a higher awareness for reduction of the exam length and the number of slices in women.

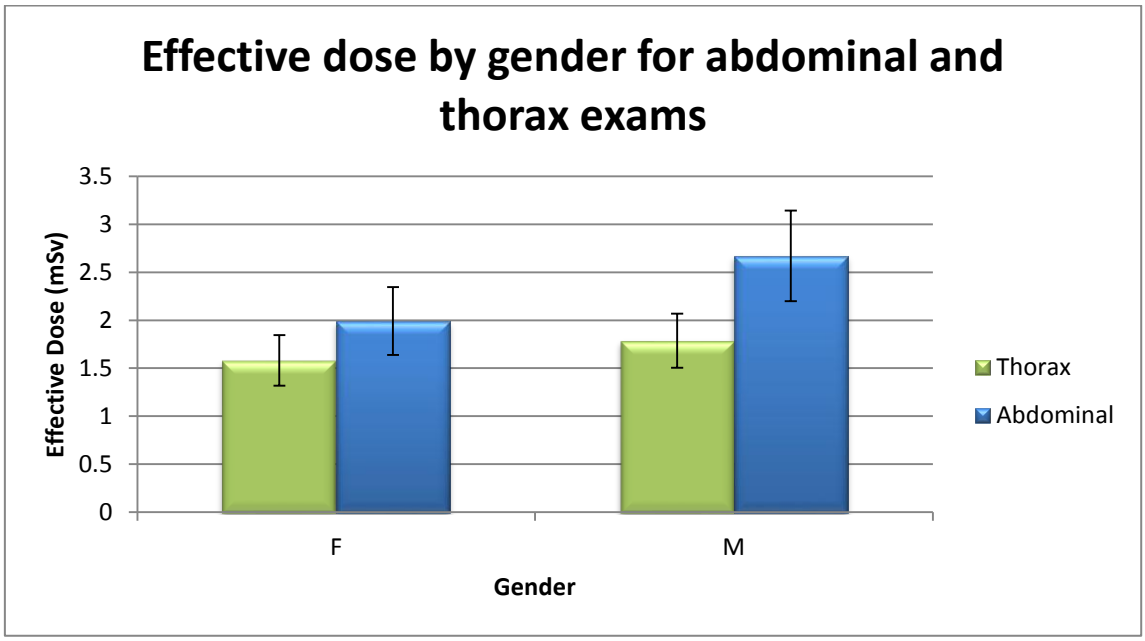


Figure 5. 17 – Effective dose by gender for thorax and abdominal examinations, for the age group of 12 to 18 years old.

The main purpose of the studies on the use of ionizing radiation in both pediatric and adult CT examinations is to assess the corresponding lifetime risk of inducing a fatal cancer.

These values led to a study, published in *The British Journal of Radiology*, concluding that for paediatric chest examination there is a risk of 2.0 fatalities per million examinations and for abdominal examination the risk is of 2.8 fatalities per million examinations (39).

5.1.2 Analysis of the Non-Pediatric (Adults) Data

As for the adult's data, the most frequent type of CT-examination is abdominal-pelvic, with higher incidence in the age groups from 40 to 80 years old as can be seen in Figure 5.18.

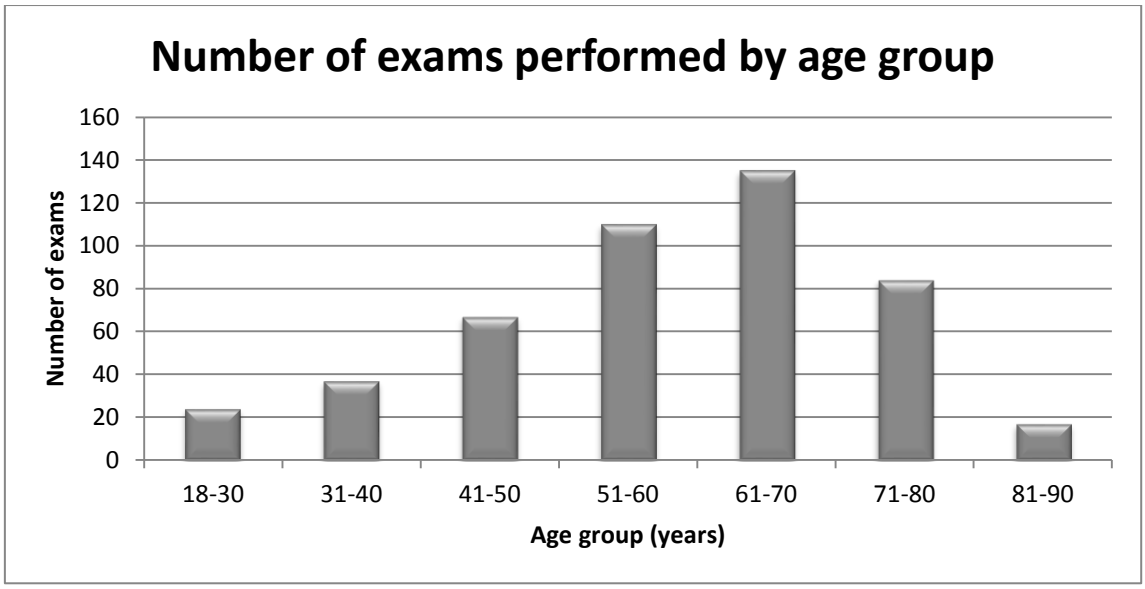


Figure 5. 18 – Number of adult exams performed by age group.

This is partly explained by the fact that 50 years old is the age from which most women start to have hormonal changes and enter menopause, a period that requires more tumor control.

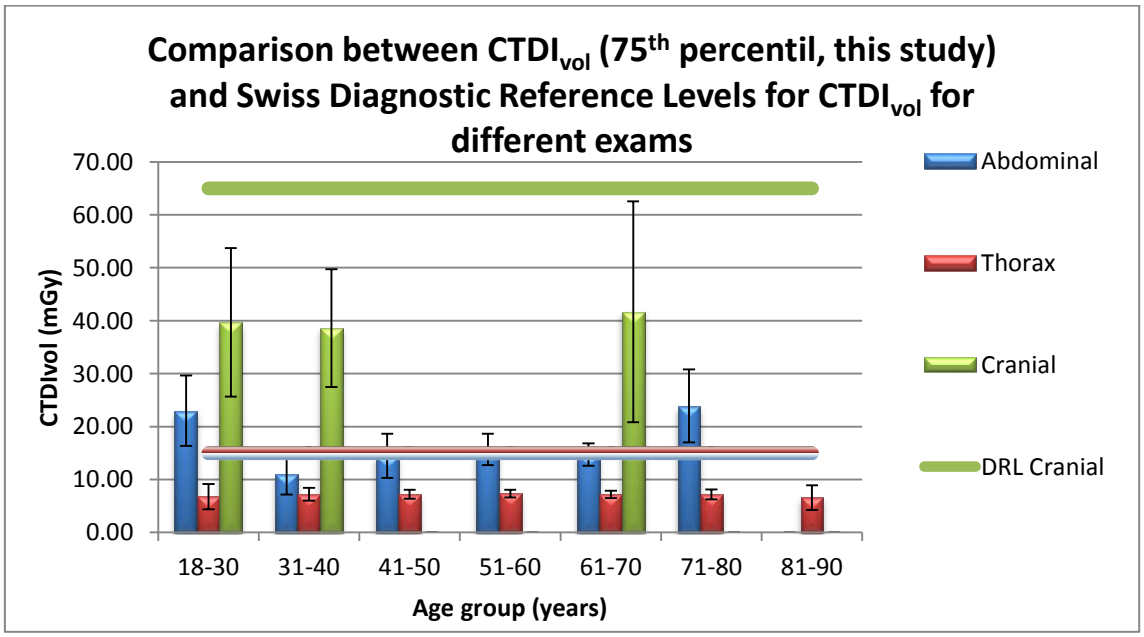


Figure 5. 19 – Adult examinations: comparison established between the $CTDI_{vol}$ values obtained in this study and the Swiss $CTDI_{vol}$ diagnostic reference levels for different exams.

Comparing the three main types of examinations with the Swiss Diagnose Reference Levels, Figure 5.19 was obtained.

Similarly to pediatric examinations, cranial is the examination with higher $CTDI_{vol}$ in adults, in order to have more detailed images (although it's performed only 2% of the times and only for 3 age groups). For this type of exam, similarly to what happened before in the pediatric data, the number of exams is so low that the uncertainties are extremely high. For cranial and thorax exams, the $CTDI_{vol}$ values are below the Swiss DRLs, proposed by the "Diagnose Reference Levels (DRL) in the CT Scan" Swiss study.

Figure 5.20 displays the comparison between the mean value of the DLP values obtained in this study for the three main types of examinations and the corresponding values of the Swiss Diagnose Reference Levels.

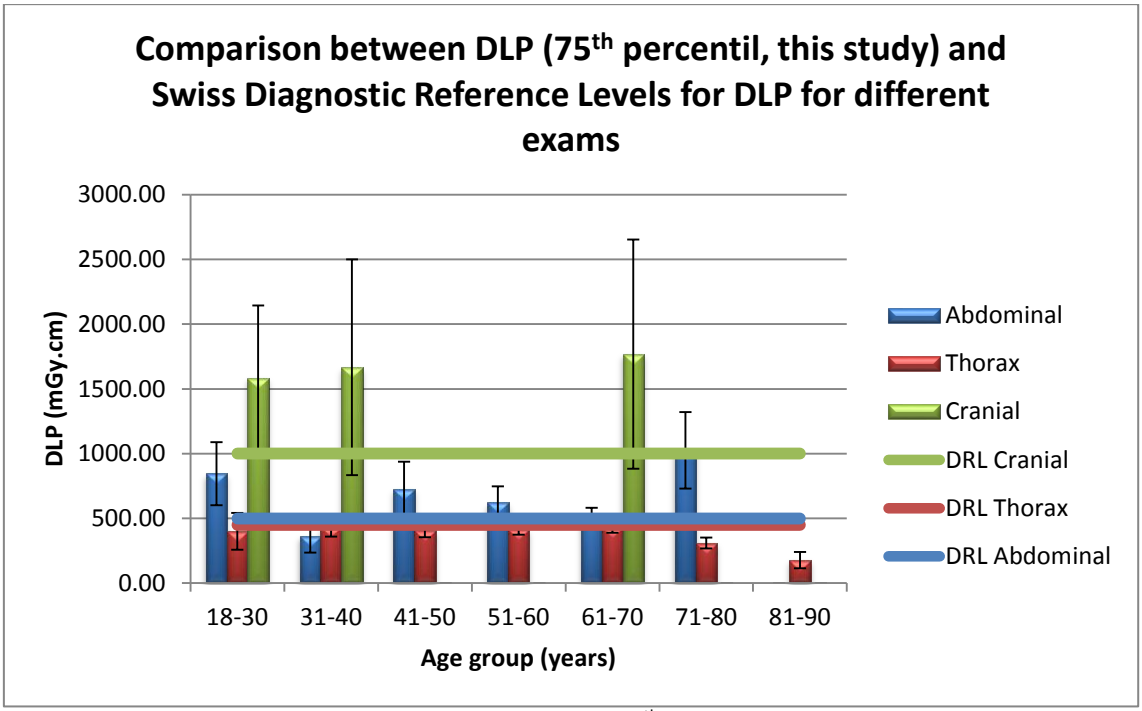


Figure 5. 20 – Comparison established between the 75th percentile values for DLP obtained in the gathered data and the DLP diagnostic reference levels for different exams.

Following the same methodology that was used for the pediatric data, the effective dose per age group for the main types of examinations, was obtained for the adults data sets and the results are displayed Figure 5.21:

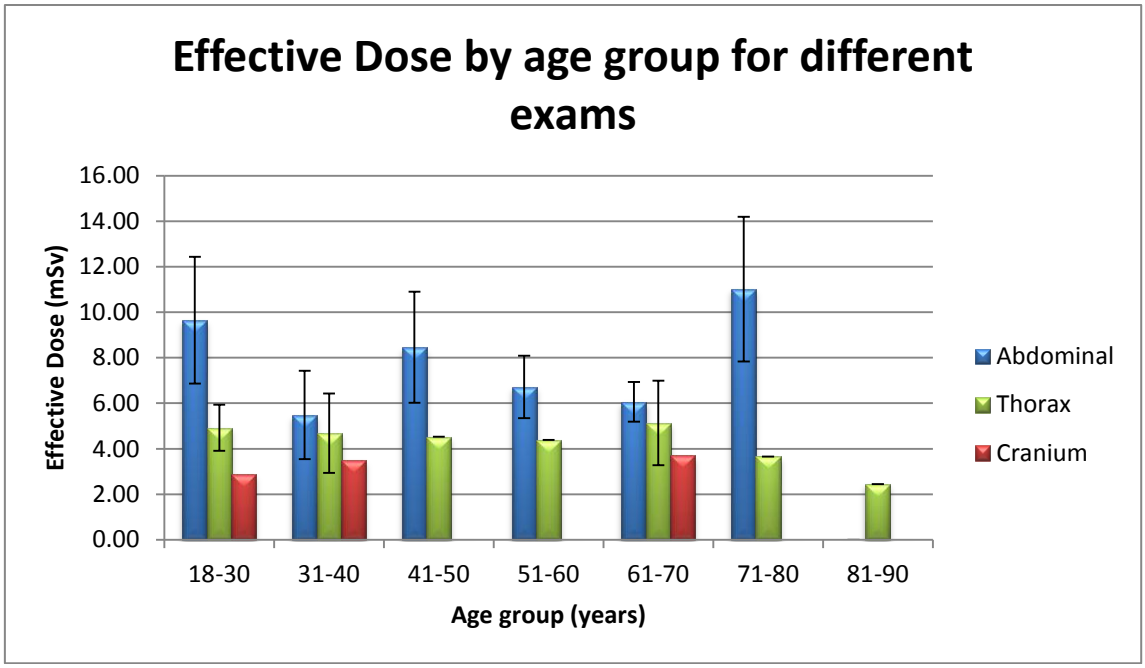


Figure 5. 21 – Average effective dose per age group for different adult exams.

The National Academy of Sciences (NAS) published the BEIR VII report in 2005, on the Biological Effects of Ionizing Radiation, being the most important guidelines for radiation protection and risk estimation on the USA. The following chart was published in this report, and jointly with table 5.3 allows a comparison between the CT exposure analysed in hospital A and the sources of exposure the human being can be submitted to:

Table 5. 3 -Typical effective doses for exposures to natural and medical sources of ionizing radiation (41).

Source of exposure	**Effective Dose (mSv)**
Natural Radiation	
• External terrestrial	0.48
• Cosmic	0.39
• Inhalation (Rn and Th)	1.26
• Ingestion (^{40}K, U and Th series)	0.29
○ Worldwide exposure for natural radiation	2.4 – 2.8
Artificial Radiation	
• Chest X-ray	0.01
• Head CT	2
• Chest CT	3
• Abdominal CT	5
• Angiography or venography	11 - 33
• CT guided intervention	11 - 17

For example, the abdominal CT exams give to the patient a dose of 6 to 10 mSv, in hospital A, which can be the double of a regular abdominal CT, or almost the dose given in an angiography or a CT guided intervention, according to Table 5.3.

5.2 HOSPITAL B

Hospital B is a recent facility with a CT equipment still undergoing tests and protocol optimization. The gathered data correspond to a period of 4 months, consisting of 464 pediatric exams. The parameters recorded in the PACS include the date, patient's age and gender, type of exam, the mA and reference mA, $CTDI_{vol}$, DLP and slice thickness.

From the total 464 exams, 40,5 % are performed in girls and 59,5% in boys, and the most common types of exams are represented in Figure 5.22:

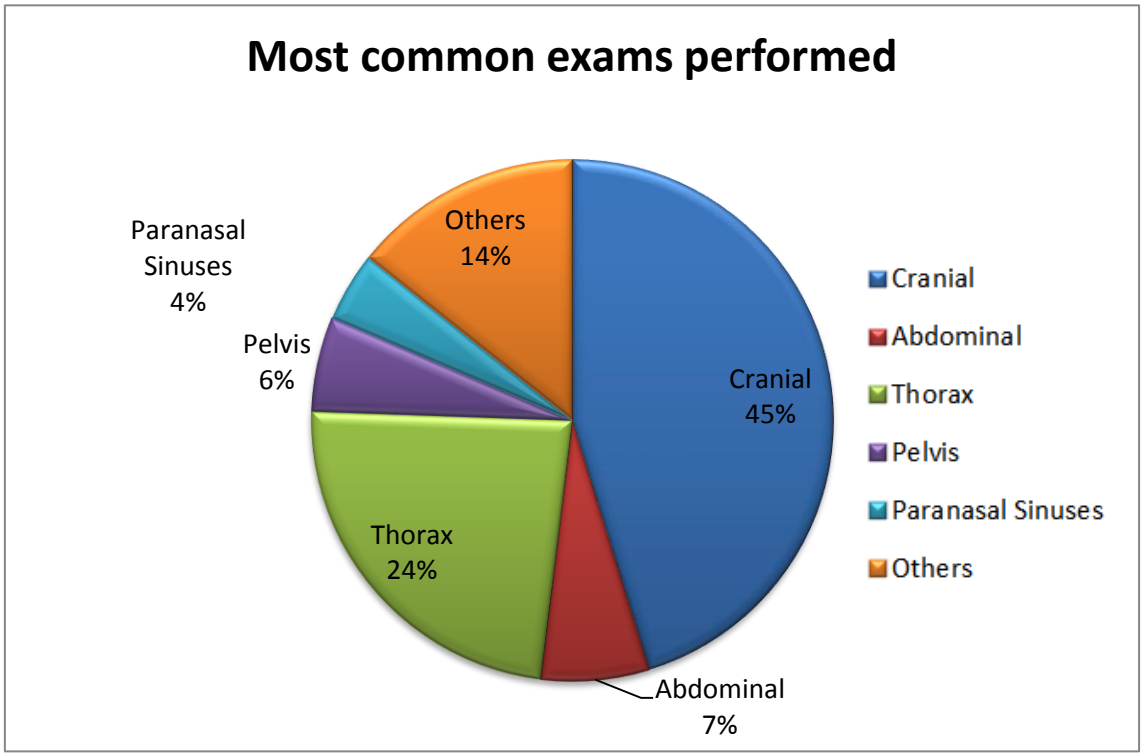


Figure 5. 22 –Most common types of examinations in hospital B.

The category "others" includes extremities, ears, neck, column and orbits, examinations which are less frequently performed.

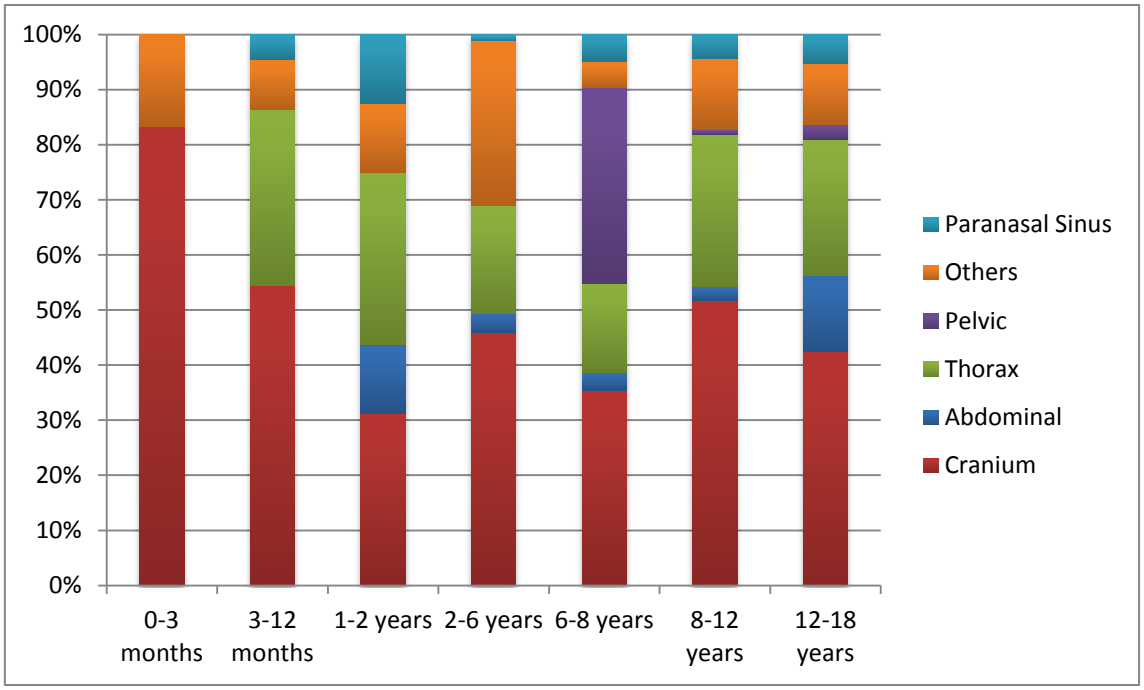


Figure 5. 23 – Percentage of the most common exam types in hospital B, by age group.

Like in hospital A, the most common types are cranial exams for all the age groups. It is also the evident the frequency of paranasal sinuses examinations during the first years of life to detect malformations.

The $CTDI_{vol}$ is a parameter given directly by the equipment, and its distribution per age group for the different types of examinations is given by Figure 5.24:

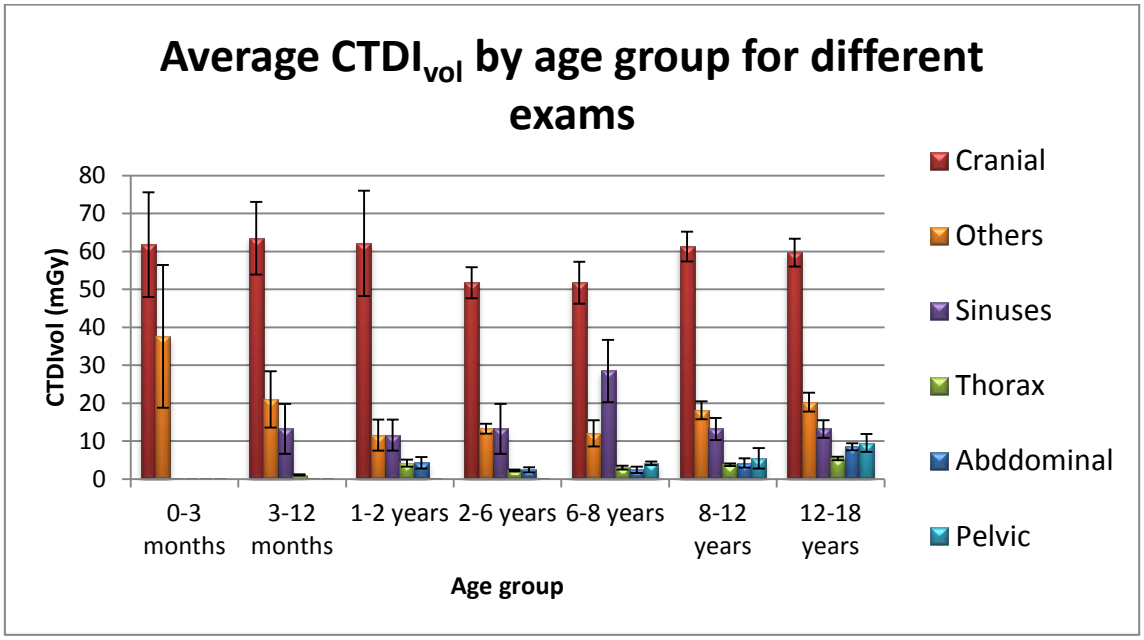


Figure 5. 24 – Average value of $CTDI_{vol}$ per age group and for the different types of pediatric exams (larger display in appendix).

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In cranial examinations the $CTDI_{vol}$ is high, similarly to the examinations grouped as type "others", which include ear examinations that also required a high $CTDI_{vol}$. A comparison is performed in the following four charts with the "Diagnose Reference Levels (DRL) in CT Scan" published by the Internal Federal Department of the Swiss Confederation (17).

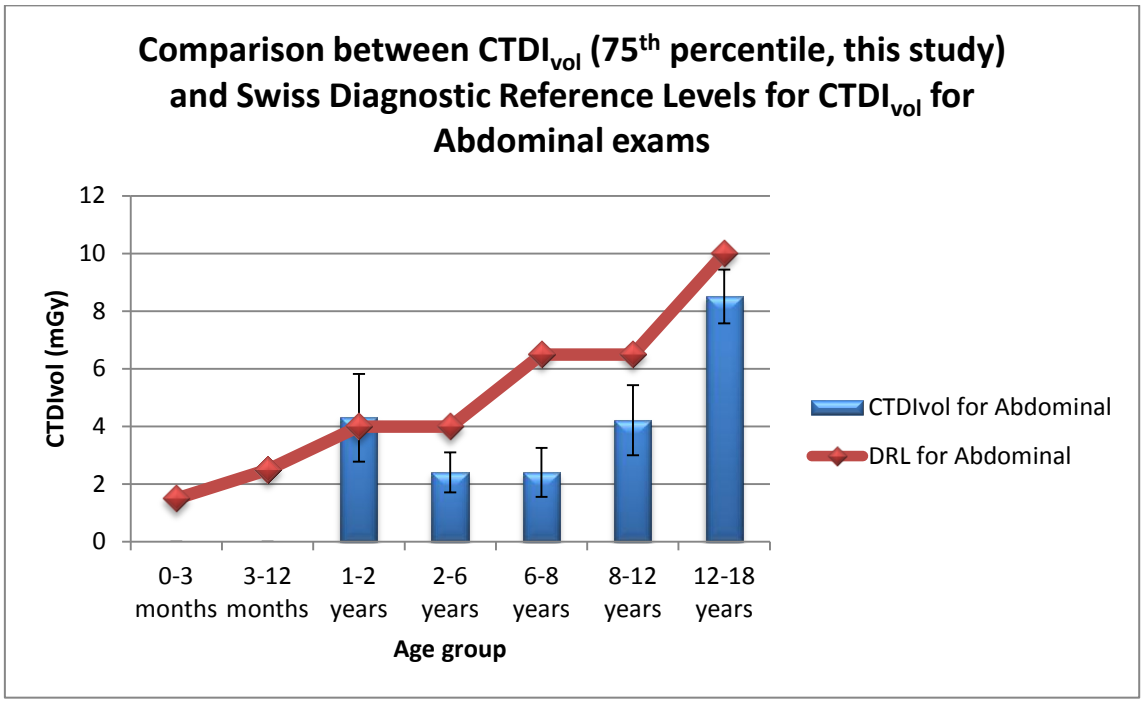


Figure 5. 25 – Abdominal examinations: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL)for $CTDI_{vol}$.

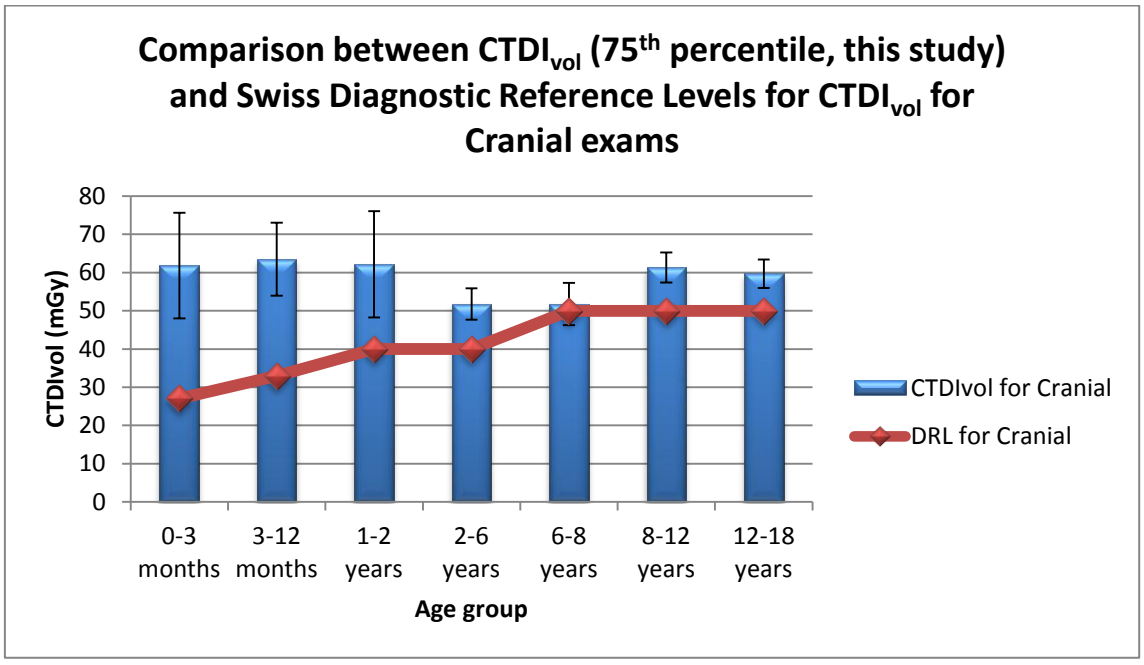


Figure 5. 26 – Cranial examinations: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study (Hospital B data) and the corresponding Swiss diagnostic reference levels (DRL) for $CTDI_{vol}$.

The $CTDI_{vol}$ values determined in this study show little variation amongst the different age groups, contrary to the trend of the Swiss DRLs which feature an increase of the DRLs with increasing age, as could be expected based on radiosensitivity-related considerations.

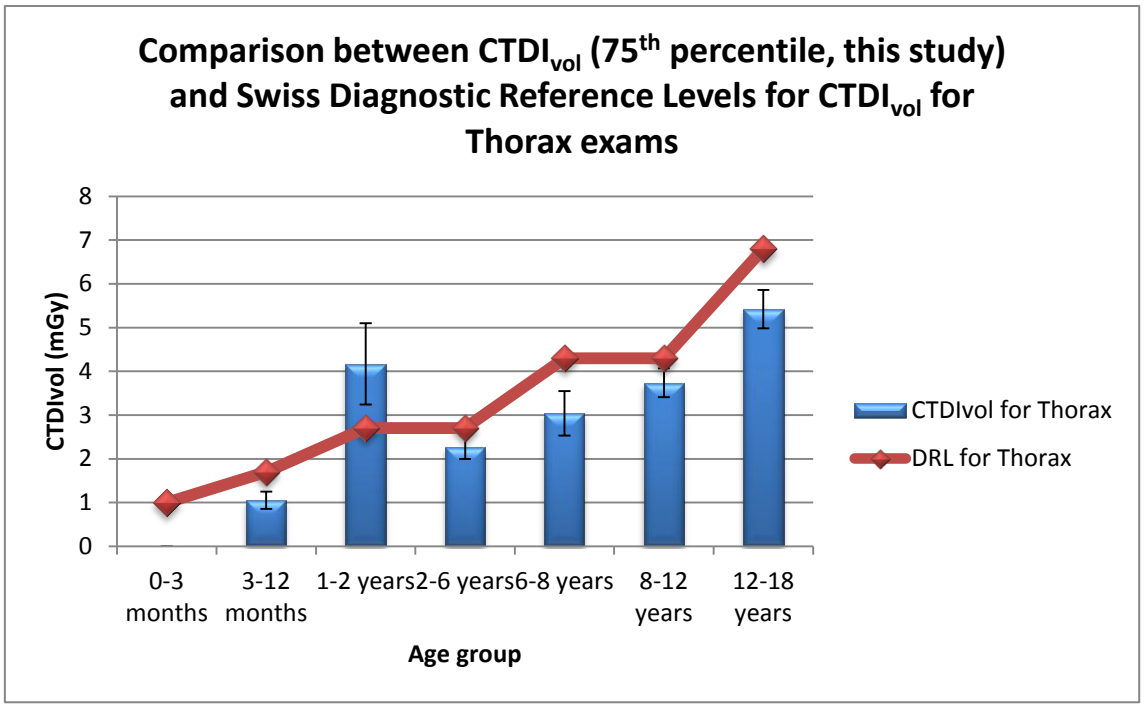


Figure 5. 27 – Thorax examinations: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for $CTDI_{vol}$.

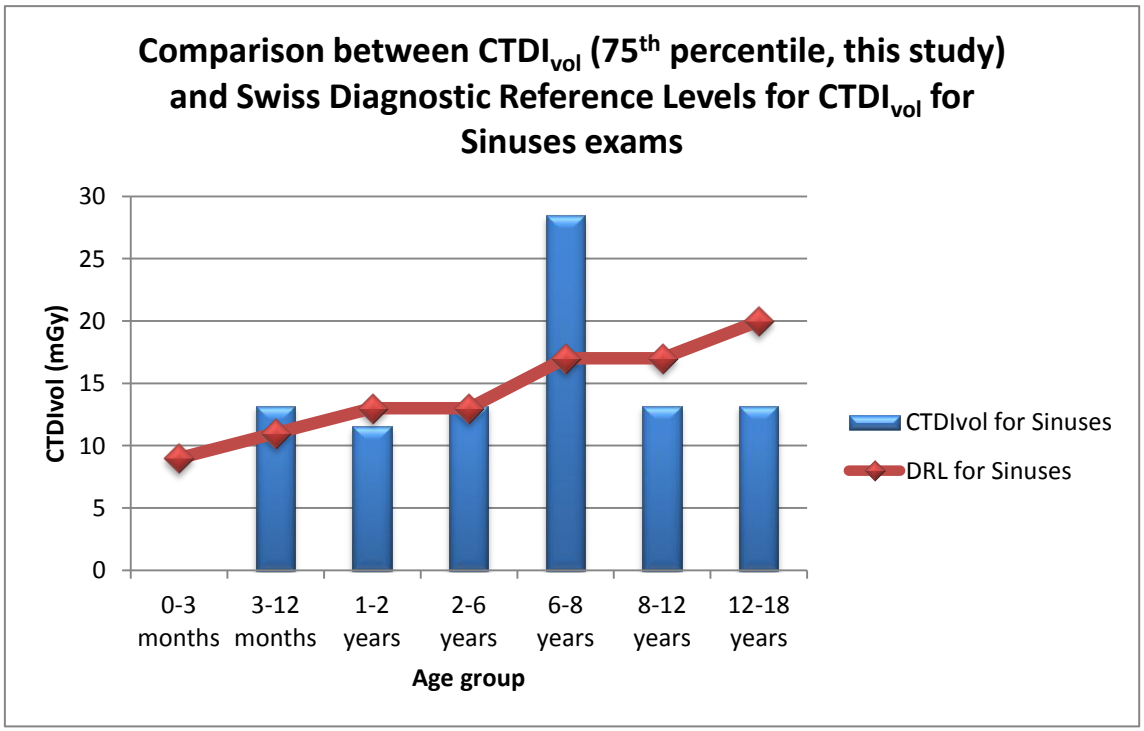


Figure 5. 28 – Paranasal sinuses examinations: comparison between the 75th percentile values for $CTDI_{vol}$ obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for $CTDI_{vol}$.

In each examination type there is at least one age group that doesn't accomplish the settings of the diagnostic reference levels. A big discrepancy was observed in the cranial exams, especially for younger ages, and an outlier was detected and eliminated.

In Paranasal Sinuses examination the dose index is also quite elevated for 3 to 12 months and 6 o 8 year olds, which also may be critic if the eye crystalline is not appropriately protected.

The same analysis was performed for the DLP values also given by the equipment. The general view is shown in Figure 5.29:

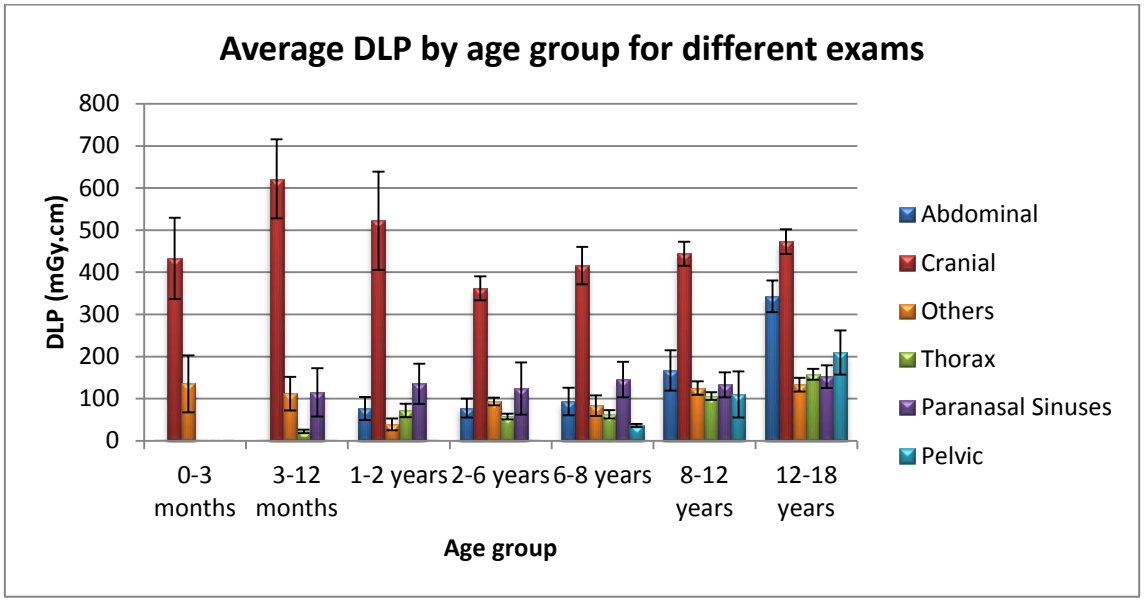


Figure 5. 29 – DLP values obtained by age group for different examinations (larger display in appendix).

As previously performed for the $CTDI_{vol}$, the following Figures display the comparisons with the Swiss diagnostic reference levels for DLP, for the four main types of examinations:

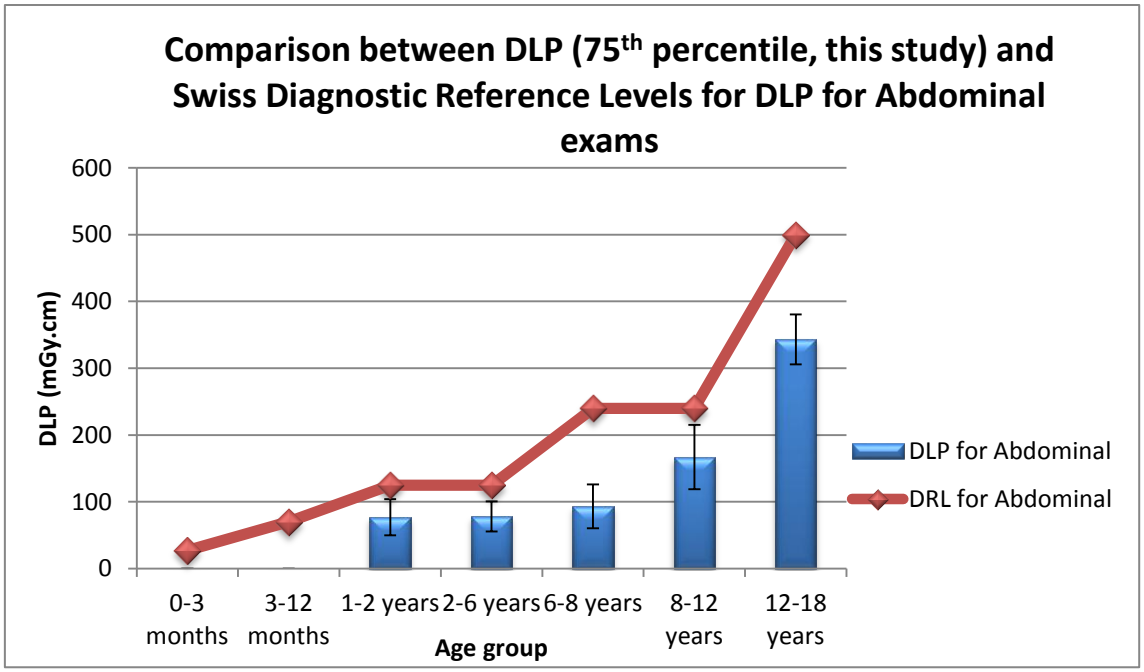


Figure 5. 30 – Abdominal examinations: comparison between the 75th percentile values for DLP obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for DLP.

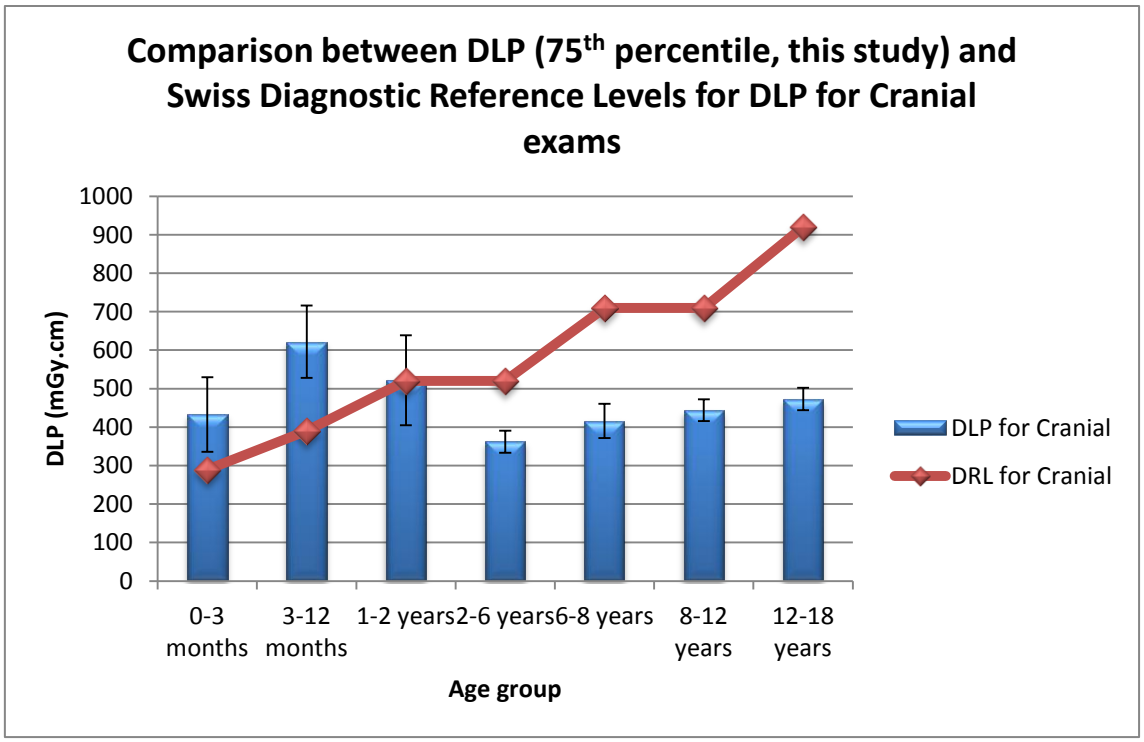


Figure 5. 31 – Cranial examinations: comparison between the 75th percentile values for DLP obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for DLP.

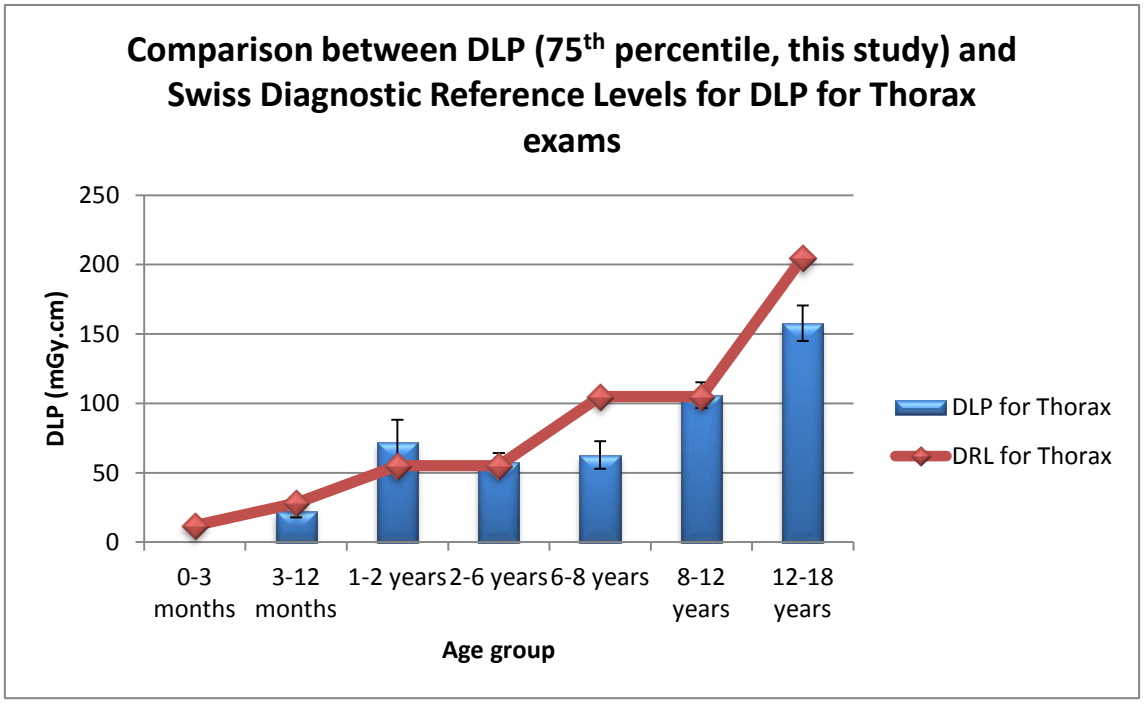


Figure 5. 32 – Thorax examinations: comparison between the 75th percentile values for DLP obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for DLP.

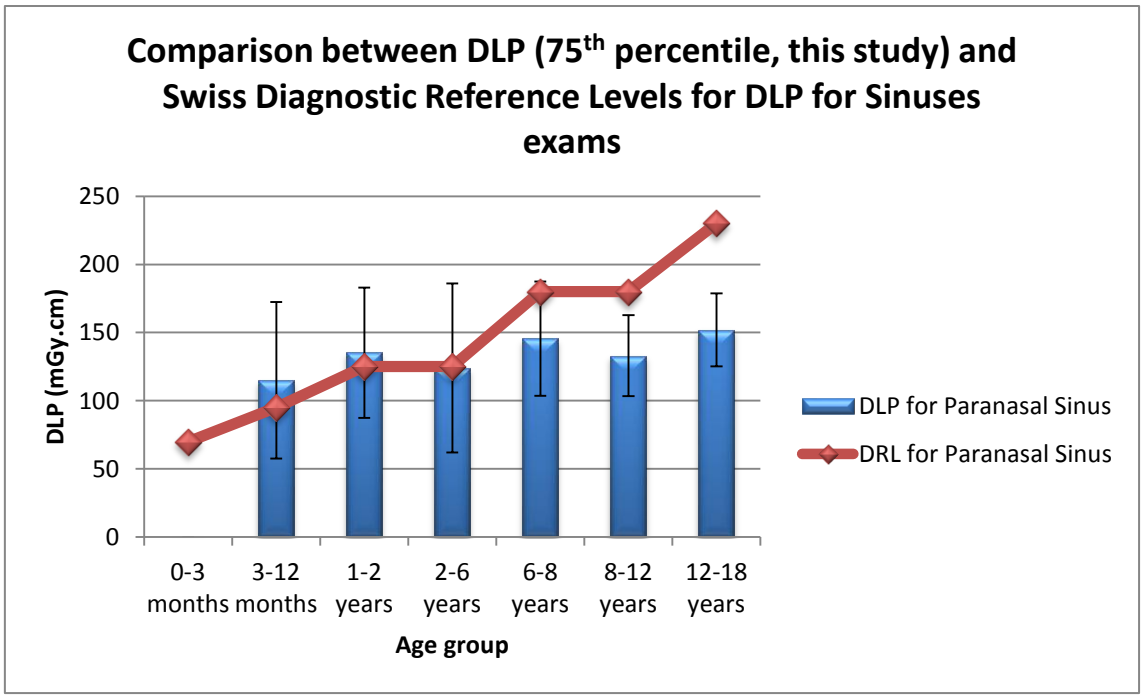


Figure 5. 33 – Paranasal sinuses examinations: Comparison between the 75th percentile values for DLP obtained in this study (Hospital B data) and the Swiss diagnostic reference levels (DRL) for DLP.

Surprisingly, for cranial examinations, the values reported in this study show that the highest (by far) 75th percentile values of DLP are obtained for the first year of life!

The most sizable differences also occur for cranial examinations and for the age groups “0-3 months” and “3-12 months”, for which the obtained DLP values in this study are significantly higher than the Swiss DRL values. Since the equipment is still undergoing tests, protocols still need further optimization in order to adequately incorporate the patient age, size, in view of radiosentivity-related considerations.

Finally, the effective dose was calculated with K conversion values, and the following Figure was obtained:

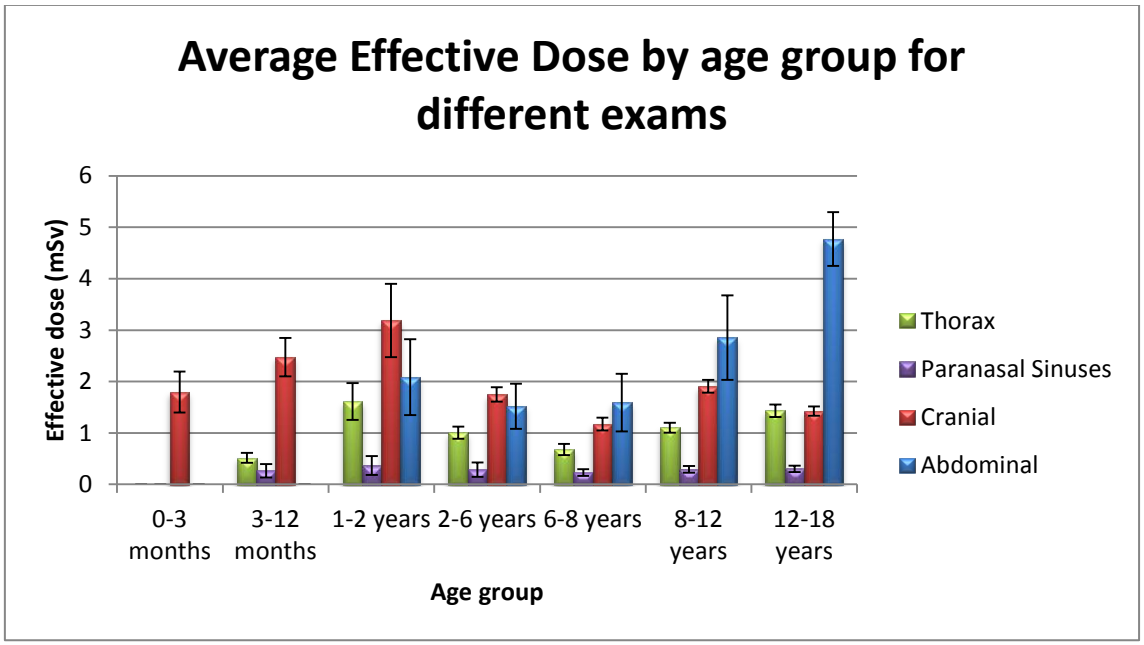


Figure 5. 34 – Average Effective dose by age group for different exams.

In terms of effective dose, there is also some lack of data for the first age groups. Comparing with Table 5.3, it’s possible to verify how high the abdominal doses are for teenagers and early adolescents, almost the same as an abdominal adult CT (5 mSv).

6. CT EXPERIMENTAL STUDY

In this chapter, the results of an experimental study undertaken using several CT-equipments in 3 different hospitals are reported. The study aimed at performing the assessment of the image quality and the corresponding patient's exposure in a common CT examination, taking in account different protocols and the variation of several equipment parameters, mainly the tube voltage and current intensity.

The different acquisition parameters must be chosen carefully by the radiographer according to the patient's age or size, the anatomic region being examined, the clinical symptoms and the image resolution required. The X-ray tube voltage selected defines the image resolution; for good resolution of very detailed areas, it's necessary that the X-ray beam strongly penetrates the organs, tissues and other anatomical structures, with the least possible attenuation.

Weight		Minimum mA	Maximum mA	kV
0-9 Kg	Routine Exam	65	130	80
	Low-dose Exam	80	160	100
9,1-27,2 Kg	Routine Exam	50	100	80
	Low-dose Exam	60	120	100

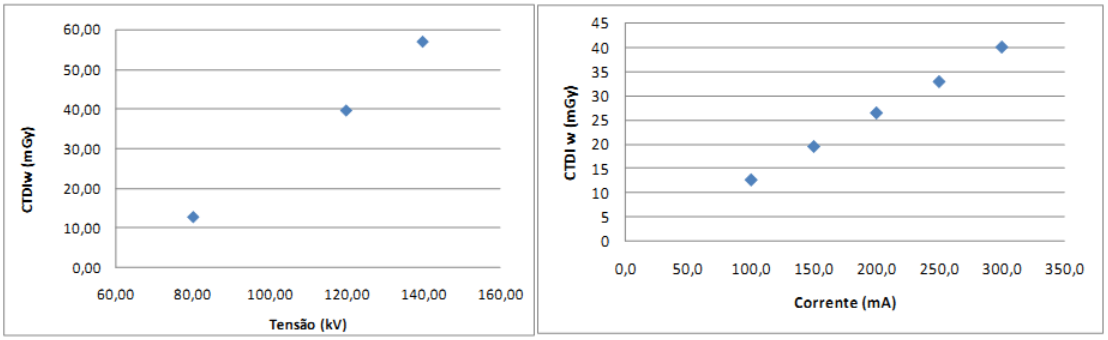
Figure 6. 1 – Relation between child's weigh and CT parameters. Reproduced from (30).

Due to the small size of children, it's possible to reduce this parameter, keeping image quality, but with a significant reduction in dose. As seen in Figure 6.1, routine examinations can be performed selecting tube voltages from 80 kV to 100kV, especially for children with less than 45 kg. Moreover, lower tube voltage values also translate in less diffuse radiation.

It is generally accepted that the dose to the patient varies linearly with the X-ray tube current intensity: for lower mA values, lower is the dose received, although the image noise also increases. Thus, provided that the image noise doesn't jeopardize the aimed quality of diagnostic, the reduction of the mA is allowed and recommended.

A study recently performed in Portugal entitled "Measurement of the diagnostic reference levels in CT for head and neck" (11), also establishes the linearity

between $CTDI_{vol}$ and tube current intensity and voltage; for measurements performed using a head phantom keeping a pitch of 1, 1 second of rotation, either the voltage or the current intensity were kept constant while the other was varied (keeping in mind, from formula (3.5), for a pitch of 1, the $CTDI_w$ is identical to $CTDI_{vol}$); the obtained results are displayed in the following Figures:



(a) (b)

Figure 6. 2 – Variation of $CTDI_w$ with a) tube voltage (kV) and b) tube current intensity (mA).

In the present study, a standard adult cranium phantom, of PMMA, cylindrical, and a PTW pencil-shaped ionization chamber of 16 cm were used to perform measurements of the DPI (Dose Profile Integral) in several tomographs. All the measurements took place with the help of a radiographer of the hospital, specialized in the equipment being operated. Figure 6.3 represents the experimental setup, used for all the measurements performed.

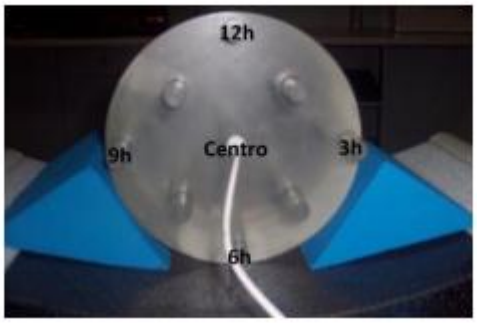


Figure 6. 3 – Adult cranium PMMA phantom with the five possible positions for the ionization chamber.

In the sequence, the measurements performed and the analysed results are described.

Hospital A

In the first hospital visited, the measurements were performed in a *Siemens Somaton Plus 4* single slice CT; initially, the phantom was centered with the laser positioning system, the ionization chamber's pencil was positioned in the center of the

phantom (according to Figure 6.4.a)), and a scout with 120 kV, 50 mA and 128 mm of length was acquired. Afterwards, the pencil was positioned at 12h. (Figure 6.4. b)).

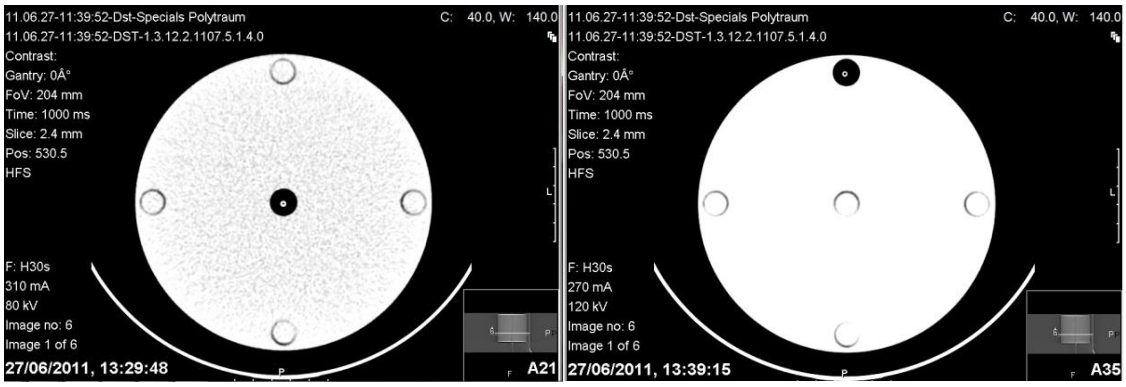


Figure 6. 4 - Phantom measurements: a) Center; b) Periphery.

In these measurements, two different protocols often used in this hospital were tested: 5/5 and 5/5/8 (the first number represents the table headway per 360ª of gantry rotation, in mm, and the second number is the slice thickness, from which the pitch of 1 is obtained), FOV of 175 mm, one single slice of 5 mm was acquired in 1 second.

Table 6.1 represents the kV and mA values tested in this equipment for two different pediatric protocols, each one with a different exam length: for protocol 5/5, one series of 15 cm; for protocol 5/5/8, two series were performed, one with 7 cm followed by the other with 5 cm. The expected $CTDI_{vol}$ given by the equipment is also displayed in Table 6.1, to establish a comparison.

Table 6. 1 - CT parameters and measurements performed in hospital A.

Kv	mA	Equipment's $CTDI_{vol}$ (mGy)	Measured DPI	Protocol	Length (cm)	Ionization chamber position
80	75	3.1	4.16	5/5	15	Center
120	70	9.7	15.72			
120	90	12.5	20.38			
120	110	15.3	25.3			
140	77	15.5	25.32			
80	75	3.1	4.08	5/5/8	7+5	
120	70	9.7	15.82			
120	90	12.5	20.26			
120	110	15.3	25.03			
140	77	15.5	25.18			

80	75	3.1	5.26	5/5	15	12h
120	70	9.7	18.86			
120	90	12.5	23.32			
120	110	15.3	29.9			
140	77	15.5	29.28			
80	75	3.1	5.08	5/5/8	7+5	
120	70	9.7	17.46			
120	90	12.5	24.08			
120	110	15.3	30.26			
140	77	15.5	29.58			

As a first remark, as expected, the DPI values are higher for the periphery position (12h) then for the center.

Hospital A was the hospital in which more data and a wider variety of parameters could be tested. To obtain the $CTDI_w$ values from the DPI measured in the ionization chamber, DPI was divided by the slice thickness and by the number of slices (1 slice in all measurements) of each acquisition. Afterwards, with formula (3.4), $CTDI_{vol}$ was obtained, since for the same kV and mA, both center and periphery (12h) measures were acquired. With the exam length, the DLP was also calculated for both protocols. The obtained results are displayed in Table 6.2.

Table 6. 2 – Calculated $CTDI_{vol}$ and DLP from the measurements performed in hospital A.

kV	mA	Equipment's $CTDI_{vol}$ (mGy)	DPI	Calculated $CTDI_{vol}$ (mGy)	DLP (mGy.cm)	Protocol
80	75	3.1	4.2	9.79	147	5/5
120	70	9.7	15.7	35.63	534	
120	90	12.5	20.4	44.68	670	
120	110	15.3	25.3	56.73	851	
140	77	15.5	25.3	55.92	839	
80	75	3.1	4.08	9.49	114	5/5/8
120	70	9.7	15.82	33.83	406	
120	90	12.5	20.26	45.61	547	
120	110	15.3	25.03	57.03	684	
140	77	15.5	25.18	56.23	675	

The calculated $CTDI_{vol}$ is proportional to the equipment's predicted $CTDI_{vol}$, although considerably higher. The values of $CTDI_{vol}$ and DLP obtained in this study were compared to the corresponding values of cranial examinations from the Swiss study "Diagnostic Reference Levels (DRL) in CT Scan" (22) already mentioned in chapter 5. The results of the comparison can be summarized as follows:

- For $CTDI_{vol}$, since birth and until 15 years old, the Swiss $CTDI_{vol}$ values range from 27 to 50 mGy and the 75th percentile values obtained in the previous chapter (Chapter 5 – Statistical Study) for $CTDI_{vol}$ in cranial exams range from 20 to 40 mGy until 18 years old. Therefore, the grey values in Table 6.2, corresponding to 120 kV and 110 mA, 140kV and 77 mA, 120 kV and 110 mA, and finally 140 kV and 77 mA exceed the Swiss $CTDI_{vol}$ and the experimental data gathered in 2010 in that CT equipment, suggesting the use, whenever possible and without compromising the aimed image quality, of lower tube voltage and/or tube current intensity values.
- As for the DLP values calculated in Table 6.2 they lie within the interval of the Swiss DLP values from new-born to 15 years old: from 290 to 920 mGy.cm, although the grey ones are not situated in the range of the 75th percentile values for DLP in cranial exams obtained in the previous chapter: 200 to 550 mGy.cm.

Hospital B

The second set of measurements was performed in hospital B, in a *GE Brightspeed* 16 slices equipment installed in 2010, and currently fully operational. The scanning time was 1s, with a slice thickness of 5mm and the pitch was considered 1; the remaining parameters are unknown. Table 6.3 displays the measurements performed:

Table 6. 3 – CT parameters obtained in hospital B, for the first equipment tested.

kV	mA	Measured DPI	Protocol	Position
80	120	1.3	0 to 18 months Protocol	Pediatric 12h
100	120	2.36		
120	100	2.98		
120	**120**	**3.54**		
120	140	4.12		
80	120	1	0 to 18 months Protocol	Pediatric Center
100	120	1.96		
120	100	2.58		
120	**120**	**3.1**		
120	140	3.62		
80	70	1.3	Defined by the operator	Cranium 12h Adult
120	70	2.08		
120	90	2.72		
120	110	3.3		
120	230	7.76		
140	70	2.88	Low-dose Cranium Protocol	

140	220	10.34	Routine Cranium Protocol	
80	70	0.6	Defined by the operator	Cranium Center Adult
120	70	1.8		
120	90	4.16		
120	110	7.02		
120	230	6.8		
140	70	2.58	Low-dose Cranium Protocol	
140	220	20.48	Routine Adult Cranium Protocol	

The bold values, 120 kV and 120 mA, correspond to the technical parameters of the standard protocol used in this hospital for the ages from 0 to 18 months.

As could be anticipated all the values of DPI for the 12h position are larger, both for children and adult protocols, since the radiation dose in this area is higher than the one at the center of the phantom. The same methodology applied for hospital A measurements was used to calculate $CTDI_{vol}$: the measured DPI is divided by the slice thickness and by the number of slices, and then, the center and periphery values are combined using formula (3.4):

Table 6. 4 - Calculated $CTDI_{vol}$ for the parameters used and measurements performed in hospital B for the first equipment.

kV	mA	Measured DPI	Calculated $CTDI_{vol}$ (mGy)	Protocol
80	120	1.30	2.40	0 to 18 months Protocol
100	120	2.36	4.45	
120	100	2.98	5.69	
120	120	3.54	6.79	
120	140	4.12	7.91	
80	70	1.30	2.13	Adult Protocol
120	70	2.08	3.97	
120	90	2.72	6.40	
120	110	3.30	9.08	
120	230	7.76	14.88	
140	70	2.88	5.56	
140	220	10.34	27.44	

For the pediatric cranium protocol, from 0 to 18 months, the $CTDI_{vol}$ value from the Swiss DRL study is 33 mGy. For adults, for cranial standard exams, metastases research and assessment of cerebral abscesses, the $CTDI_{vol}$ value from the Swiss DRL study is 65 mGy.

A similar study was performed in the same hospital, but with a GE VCT 64 slices equipment installed in 2011. A scanning time of 1s was used to perform each measurement, with 2.5 mm slices and a pitch of 1 (the remaining CT parameters are unknown). The ionization chamber was positioned firstly in the center of the phantom and afterwards at the "12h" position to test the exposure near the surface. A pediatric protocol for cranium was used, and both the tube voltage and tube current intensity were varied; the measured DPI values are displayed in table 6.5:

Table 6. 5 – CT parameters measured in hospital B, for the second equipment used.

kV	mA	Measured DPI	Protocol	Position
80	70	1.7	Pediatric Cranium	Center
100	70	3.3		
120	70	5.2		
120	90	6.6		
120	100	7.4		
120	110	8.1		
80	70	2.1	Pediatric Cranium	12h
100	70	3.8		
120	70	5.9		
120	90	7.5		
120	100	8.4		
120	110	9.1		

The methodology previously described, used for the other measurements, was applied to calculate $CTDI_{vol}$ and the corresponding values are displayed in Table 6.6

Table 6. 6 - Calculated $CTDI_{vol}$ from the measurements performed in hospital B for the second equipment used.

kV	mA	Measured DPI	Calculated $CTDI_{vol}$ (mGy)	Protocol
80	70	1.70	7.87	Pediatric Cranium
100	70	3.30	14.35	
120	70	5.20	22.67	
120	90	6.60	28.80	
120	100	7.40	32.27	
120	110	8.10	35.07	

As seen before, the $CTDI_{vol}$ values for cranial examinations and for pediatric exposures in the Swiss study are below 50 mGy.

CONCLUSIONS AND DISCUSSION

Currently, almost 11.000 children undergo a CT examination per day in the United States. This widespread dissemination of the use of Computed Tomography stems from the fact that it has proven to be a powerful tool in trauma and cancer diagnostic. However, CT-examinations translate in much higher radiation doses to the patients than conventional radiography (20).

In this thesis, internationally available scientific data and reports are used to provide compelling evidence about the concern that radiobiology- and radiosensitivity-related issues raise when pediatric exposure to ionizing radiation is considered. Such data indicates a much higher radiosensitivity to ionizing radiation of organs and tissues of newborns, babies, children and adolescents and translates into a much higher lifetime cancer risk for these individuals if exposed to ionizing radiation during CT-examinations.

Bearing this in mind, the study described in this thesis was undertaken, which main objective consisted of assessing the clinical practice of pediatric CT in Portugal, analysing data from CT- examinations performed in two major pediatric hospitals in the country.

In the first part of the study, for the two hospitals considered, the $CTDI_{vol}$ and DLP were calculated from the analysed data, for different pediatric age groups and for certain types of CT-examinations. For some age groups and for some types of examinations these CT-dosimetric quantities were found to be higher than the corresponding Diagnostic Reference Levels from the Swiss study "Diagnostic Reference Levels in CT" (22). The following general conclusions were extracted from Chapter 5 – Statistical Study:

- For the more frequent examinations, such as cranial, abdominal and thorax, it is possible to establish a semi-quantitative comparison with the Swiss diagnostic reference levels; it is clear that there is room for optimization in order to reduce the exposure of pediatric patients, especially, for some types of examinations, for the age groups corresponding to new-borns and babies, due to their higher radiosensitivity.

- For several types of examinations the analysed data needs a reappraisal of the protocols especially in terms of the kV and mA necessary, which leads to unnecessarily higher doses. In most of the exams evaluated, a voltage of 120 kV is used, when probably the same image quality can be obtained by a lower voltage.

- The need to increase the awareness of the medical staff (medical doctors and radiographers) on the radiological risk and radiosensitivity issues associated with the exposure of pediatric patients (namely young infants and children) in CT examinations must be highlighted.

- Sometimes the protocols used in hospitals don't follow the evolution of the equipment and the new advances in knowledge and technology, becoming obsolete. Therefore, in order to adequate the dose to highly sensitive pediatric patients, extreme care, awareness and knowledge are required on the operation of the CT equipment, with the purpose of obtaining an acceptable relationship between image quality and dose to the patient.

The second part of this study included a set of measurements performed using a PMMA phantom to simulate a pediatric examination. Firstly, the $CTDI_{vol}$ was measured for the recommended parameters used in the hospital's pediatric protocols, and secondly, both kV and mA varied in a certain range, according to the radiographers experience. The main conclusions and findings of Chapter 6 – CT Experimental Study, can be summarized as follows:

- $CTDI_{vol}$ can be reduced acting (reducing) the parameters kV and mA. These findings are corroborated by a recent study entitled "Low-Radiation CT Scans Match Regular X-Rays in Image Quality" (43) from 2010, which assessed the image quality produced with a 40 slice MDCT for X-ray tube voltages of 80 kV, 120kV and 140 kV and current intensity varying from 35 mAs to 350 mAs. The images obtained were evaluated by two experienced radiologists; for the different voltage values, no big difference between the images was found while examining osseous structures, and even proved to deliver a lower dose to the patient then conventional radiography (44)

- Despite the adequacy of the existing protocols, the adjustment (by the radiographer) of the X-ray tube parameters (kV, mA) to take in account the patient's size and age is one of the most effective ways to reduce the patient´s exposure. This issue has also been addressed in another study entitled "Optimal tube potential in pediatric CT for radiation dose reduction: principle, clinical implementation and pitfalls" (44).

- For some pediatric examinations, the parameter mAs can be reduced in a factor of 4 to 5 compared to the values used for adult. As for the tube voltage (kV) reduction from the traditional 120 kV (for adults) to 100 kV or even 80 kV, can be accommodated for pediatric examinations.

- In order to achieve dose reduction to the patient, the interplay between kV, mAs, pitch, rotation time, etc. has to be assessed always having in mind that the image quality needed to perform an accurate diagnostic cannot be jeopardized.

- In addition to the technical parameters of the examination, a careful assessment of the patient's characteristics, the possible existence of high attenuation structures, which can lead to the presence of image artifacts must also be taken into consideration. The variation of the image quality as the dose decreases is displayed in Figure 7.1 (43).

Figure 7. 1 - A simulation of low dose exam; a) original dose; b) 70% dose; c) 50% dose; d) 25% dose. Reproduced from (32).

Therefore, most of the protocols tested in this chapter are adequate for children examinations, although in most of the cases CT performance can be done with the low dose protocols established without jeopardizing the image quality necessary for a good diagnostic. Considering the high radiosensitivity of younger children, whenever possible, the X-ray tube tension should be set to 80 kV or 100 kV and mAs adjusted to the quality required, but always taking in account the equipment's signal/noise relation, the possible X-ray beam attenuation or artifacts that may prevent, for example, to detect trauma situations, especially ones a few cm from the body surface.

In a recent study (33) it was established that many times there are no attempts by the medical professionals to adapt the standard protocols provided by the manufacturers with the CT-equipments, in order to lower radiation exposure, for fear of losing image quality.

These standard protocols are often established with the objective to obtain best image quality, disregarding to a great extent how much dose the patient is exposed to. Even though the CT parameters are set according to the X-ray tube limitations, a considerable dose reduction can be achieved in examinations of high contrast structures. Therefore, the knowledge and expertise of radiographers about their equipment´s technical and dosimetric performance is essential for a good radiological performance.

More and more often awareness campaigns are being promoted worldwide, with the main goal to promote a safe radiological environment for children undertaking CT and other types of radiological examinations, taking especially in account two of the three main radiological protection principles applied to the medical exposures: justification (of the examination) and optimization (of the protection, always maintaining dose as low as reasonably achievable).

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