MODERN RADIOLOGY eBook

Conventional X-Ray Imaging

常规 X线成像

EUROPEAN SOCIETY OF RADIOLOGY

Preface

Modern Radiology is a free educational resource for radiology published online by the European Society of Radiology (ESR). The title of this second, rebranded version reflects the novel didactic concept of the *ESR eBook* with its unique blend of text, images, and schematics in the form of succinct pages, supplemented by clinical imaging cases, Q&A sections and hyperlinks allowing to switch quickly between the different sections of organ-based and more technical chapters, summaries and references.

Its chapters are based on the contributions of over 100 recognised European experts, referring to both general technical and organ-based clinical imaging topics. The new graphical look showing Asklepios with fashionable glasses, symbolises the combination of classical medical teaching with contemporary style education.

Although the initial version of the *ESR eBook* was created to provide basic knowledge for medical students and teachers of undergraduate courses, it has gradually expanded its scope to include more advanced knowledge for readers who wish to 'dig deeper'. As a result, *Modern Radiology* covers also topics of the postgraduate levels of the *European Training Curriculum for Radiology*, thus addressing postgraduate educational needs of residents. In addition, it reflects feedback from medical professionals worldwide who wish to update their knowledge in specific areas of medical imaging and who have already appreciated the depth and clarity of the *ESR eBook* across the basic and more advanced educational levels.

I would like to express my heartfelt thanks to all authors who contributed their time and expertise to this voluntary, non-profit endeavour as well as Carlo Catalano, Andrea Laghi and András Palkó, who had the initial idea to create an *ESR eBook*, and - finally - to the ESR Office for their technical and administrative support.

Modern Radiology embodies a collaborative spirit and unwavering commitment to this fascinating medical discipline which is indispensable for modern patient care. I hope that this *educational* tool may encourage curiosity and critical thinking, contributing to the appreciation of the art and science of radiology across Europe and beyond.

Minerva Becker, Editor
Professor of Radiology, University of Geneva, Switzerland

X-Ray Imaging

CHAPTER OUTLINE:

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章节大纲：

前言

*《现代放射学》*是由欧洲放射学协会 (European Society of Radiology, ESR) 在线发布的免费放射学教育资源。第二版（更名版）标题反映了 ***ESR 电子书***新颖的教学概念，它以简洁页面的形式巧妙地融合文本、图像和示意图，并辅以临床影像学案例、问答部分和内容超链接，使读者能够在各基于器官的部分、更具技术性的章节、摘要以及参考文献之间快速切换浏览。

其章节以 100 多名公认欧洲专家的优秀稿件为根基，涉及各类一般技术和基于器官的临床影像学主题。同时采用了全新的图形外观，展示了佩戴时尚眼镜的 Asklepios，象征着传统医学教学与现代风格教育的结合。

虽然初版 ***ESR 电子书***旨在为医学生和本科生教师提供医学基础知识，但现已逐渐扩充其知识领域，为希望"深入挖掘"的读者提供了更多高阶技术知识。因此，*《现代放射学》*还涵盖了***欧洲放射学培训课程***研究生水平的各类主题，旨在解决住院医师的研究生教育需求。此外，书中还囊括了全球医疗专业人士的反馈，他们希望更新自己在医学影像特定领域的知识，并对 ***ESR 电子书***在基础和高等教育水平上的深度和清晰度表示高度赞赏。

我要衷心感谢所有为这项非营利活动自愿贡献时间和专业知识的作者，以及最初提出创作 ***ESR 电子书***的 Carlo Catalano、Andrea Laghi 和 András Palkó，最后还要感谢 ESR 办公室所提供的技术和行政支持。

*《现代放射学》*充分体现了医者的协作精神和对这门热门医学学科坚定不移的承诺，这是现代患者护理必须具备的优秀精神品质。我希望这款***教育***工具能够激励各位始终保持好奇心和批判性思维，从而促进整个欧洲乃至欧洲以外地区对放射学艺术和科学的认识。

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NOTE FROM THE COORDINATORS:
Thank you to Chinese radiology experts for bridging languages and open the world-class English resource by ESR to every Mandarin-speaking student, fueling global radiology talent with a single click

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/ X-Ray Imaging

CHAPTER OUTLINE:

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章节大纲：

/ 翻译致谢

本章节为《现代放射学电子书》的部分译文。

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常规 X 线成像

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译者寄语：
感谢中国放射学专家们的倾力奉献！你们跨越了语言的鸿沟，将欧洲放射学会 (ESR) 的世界级学术宝库呈献给广大中文学子。如今，前沿智慧一键即达，为全球放射学人才的蓬勃发展注入了强劲动力。

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Based on the ESR Curriculum for Undergraduate Radiological Education

Conventional X-Ray Imaging

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X-Ray Imaging

CHAPTER OUTLINE:

X 线成像

基于 ESR 课程的本科放射学教育

章节大纲：

常规 X 线成像

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Principles of X-Ray Imaging

X-Ray Imaging

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章节大纲：

X 线成像的原理

/ Principles of X-Ray Imaging

X-ray imaging is a major diagnostic technique based on the interactions of X-rays in a body to produce images of organs and tissues.

Three main X-ray imaging modalities are used:

/ projection radiography
/ fluoroscopy
/ computed tomography (CT)

As shown in Fig. 1, these three imaging techniques are based on the:

/ production of X-rays in an X-ray tube
/ transmission of an X-ray beam through a patient
/ detection of the transmitted X-rays on a detector
/ image processing

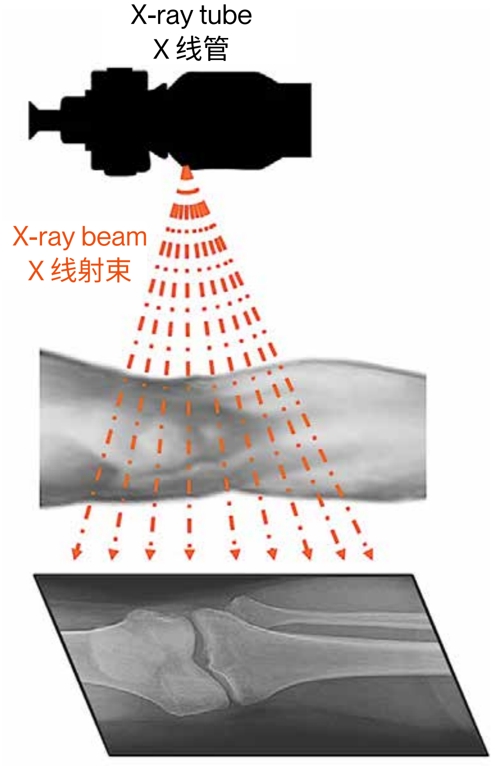

FIGURE 1

Principle of X-ray imaging.

/ X-Ray Imaging

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/ X 线成像

章节大纲：

/ X 线成像的原理

X 线成像是一种重要的诊断技术，其原理是利用 X 线在体内的相互作用来生成器官与组织的图像。

主要有 3 种 X 线成像模式：

/ 投影放射摄影
/ 荧光透视检查
/ 计算机断层扫描 (computed tomography，CT)

如图 1 所示，这三种成像技术基于：

/ 在 X 线管中产生 X 线
/ X 线射束对患者进行透射
/ 在探测器上探测透过的 X 线
/ 图像处理

图 1

X 线成像的原理

X-ray imaging modalities provide two-dimensional projections or slices of the attenuating properties of the tissues traversed by X-rays.

/ Radiography gives a single static projection acquired on an X-ray flash (Fig. 2B).

/ Fluoroscopy produces temporal series of projections at an adjustable image rate (0.5-30 images per second) and gives access to dynamic imaging.

/ Computed tomography (CT) acquires single projections at many angles over 360° around the patient to reconstruct slices of the anatomy (Fig. 2C) and volume rendering (Fig. 2D).

This chapter explains the principle of projection X-ray imaging, also called “conventional X-ray imaging”.

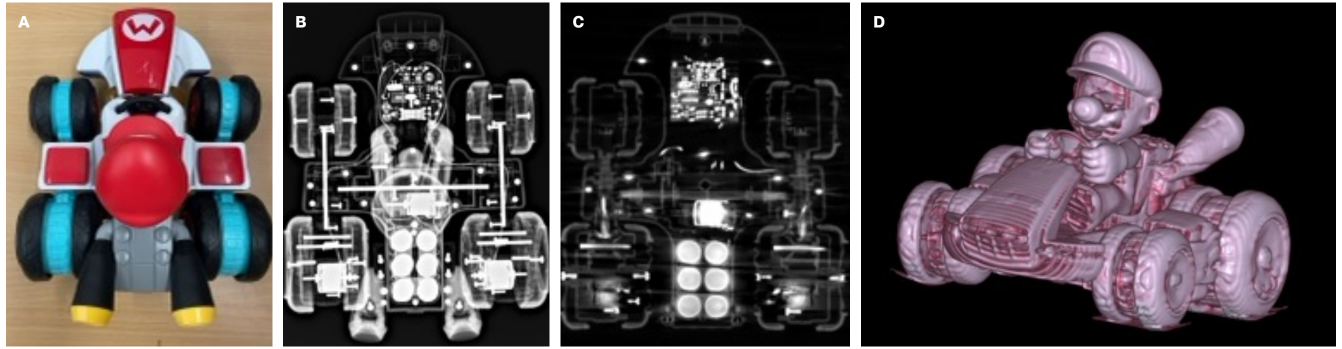

FIGURE 2

Difference between an X-ray projection (B) and a CT slice (C) of an imaged object (A). D illustrates a 3 dimensional reconstruction from the CT slices. Figure courtesy Davide Cabral, Department of Radiology, Geneva University Hospitals.

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X 线成像模式提供 X 线所穿过的组织的衰减特性的二维投影或切片。

/ 放射摄影通过一次短时 X 线曝光获得单幅静态投影（图 2B）。

/ 荧光透视以可调节的图像速率（每秒 0.5～30 幅图像）产生时间系列投影，并提供动态成像。

/ 计算机断层扫描 (computed tomography，CT) 在患者周围 360°内的多个角度采集单个投影，来重建解剖结构的二维图像（图 2C）并实现三维体绘制（图 2D）。

本章介绍投影 X 线成像（也称为“常规 X 线成像”）的原理。

图 2

X 线投影 (B) 与成像对象 (A) 的 CT 图像 (C) 之间的差异。D 显示了基于 CT 图像的三维重建。图片由日内瓦大学医院放射科 Davide Cabral 提供。

/ Production of X-Rays

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/ X 线的产生

/ The X-Ray Tube

<!> ATTENTION

X-rays are high-frequency electromagnetic waves produced in an X-ray tube when highly energetic electrons interact with matter.

Major tube components are (Fig. 3) :

1. Cathode: Negative electrode comprised of an electron emitter and a focusing cup.
2. Anode: Metal target electrode at a positive potential difference relative to the cathode.
3. Rotor/stator.
4. Glass or metal envelope.
5. Tube housing comprising a lead shielding.

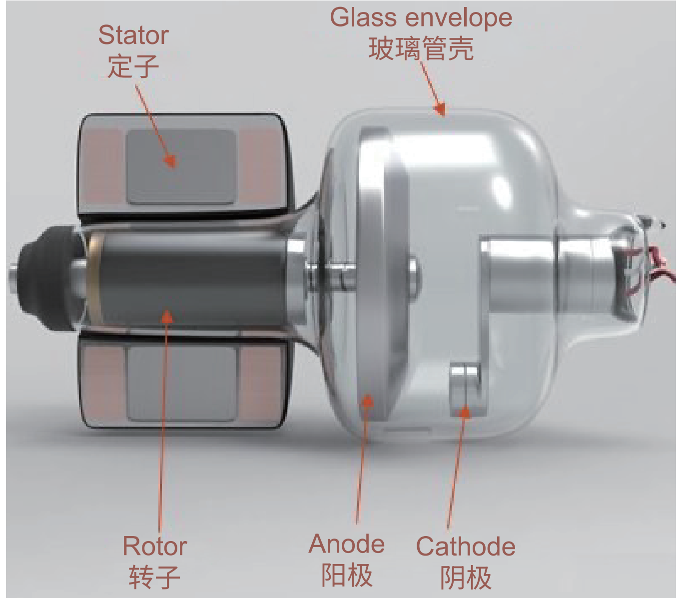

FIGURE 3

X-ray tube.

/ X-Ray Imaging

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/ X 线成像

章节大纲：

/ X 线管

<!> 注意

X 线是高能电子与物质相互作用时在 X 线管中产生的高频电磁波。

X 线管的主要组成包括（图 3）：

1. 阴极：负电极由电子发射器和聚焦杯组成。
2. 阳极：金属靶电极处于相对于阴极的正电位差。
3. 转子/定子。
4. 玻璃或金属外壳。
5. 带铅屏蔽的管套。

图 3

X 线管。

Cathode (Fig. 4):

- The cathode usually contains tungsten **filaments** electrically connected to the X-ray generator.
- Most X-ray tubes are referred to as dual-focus tubes because they have two filaments: a large filament and a small filament.
- The small or the large filament can be manually or automatically selected, depending on the **voltage (kV) and time-current product (mAs).**
- The filament is heated by an electrical resistance.
- A static electron cloud is formed around the filament.
- When voltage is applied, electrons from the filament are accelerated toward the anode.
- The electrons flux corresponds to the X-ray tube current.

Anode (Fig. 4):

The anode is a metal target electrode maintained at a positive potential difference relative to the cathode.

- **Tungsten** is the most widely used anode material because of its high melting point (3,000° C) and high atomic number (Z = 74) which provides high X-ray production.
- The anode area impacted by the electrons is the **focal spot**.
- Dental x-ray units, mobile x-ray machines and mobile fluoroscopy systems use fixed-anodes.
- Rotating anodes allow higher x-ray output by spreading the heat over a larger surface.
- The **actual focal spot size** is the area on the anode struck by electrons, determined by the size of the filament selected in the cathode.
- The **effective focal spot size** is the projection of the actual focal spot size on the image plane, determined by the anode angle.

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阴极（图 4）：

- 阴极通常包含由钨丝构成的发射组件，该发射组件与 X 线发生器相连。
- 大多数 X 线管被称为双焦管，因为它们具有两个灯丝：大灯丝和小灯丝。
- 可根据**电压 (kV) 和电流-时间乘积 (mAs)** 手动或自动选择小灯丝或大灯丝。
- 灯丝通过电阻加热。
- 灯丝周围形成静态电子云。
- 当施加电压时，来自灯丝的电子加速朝向阳极。
- 电子通量对应于 X 线管电流。

阳极（图 4）：

阳极是相对于阴极保持在正电位差下的金属靶电极。

- **钨**是应用最广泛的阳极材料，因为它的熔点高 (3,000°C) 且原子序数高 (Z = 74)，可产生大量 X 线。
- 被电子轰击的阳极区域称为**焦点**。
- 牙科 X 线设备、移动 X 线机和移动荧光透视系统使用固定阳极。
- 旋转阳极通过将热负荷分散至更大表面，从而实现更高的 X 线输出。
- **实际焦斑尺寸**是阳极上被电子撞击的面积，由阴极中选择的灯丝的尺寸决定。
- **有效焦斑尺寸**是实际焦斑尺寸在图像平面上的投影，由阳极角决定。

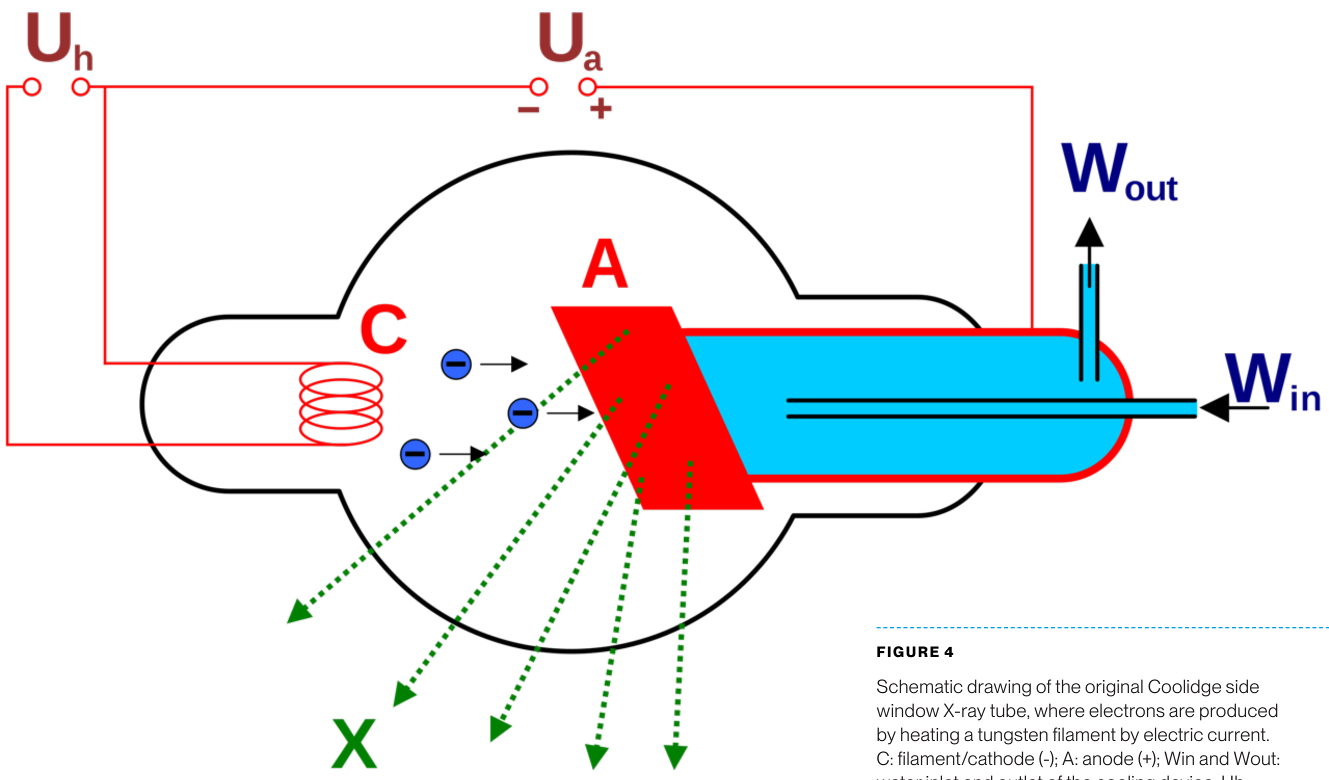

FIGURE 4

Schematic drawing of the original Coolidge side window X-ray tube, where electrons are produced by heating a tungsten filament by electric current. C: filament/cathode (-); A: anode (+); Win and Wout: water inlet and outlet of the cooling device. Uh: voltage potential for heating the cathode; Ua: voltage potential between anode and cathode. The electrons produced by the cathode are accelerated in the vacuum tube towards the anode. X: X-rays produced by the anode. Image reproduced from: https://commons.wikimedia.org/wiki/File:WaterCooledXrayTube.svg

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图 4

原始 Coolidge 侧窗 X 线管的示意图，其中电子通过电流加热钨丝产生。C：灯丝/阴极 (-)；A：阳极 (+)；Win 和 Wout：冷却装置进出水口。Uh：加热阴极的电势；Ua：阳极和阴极之间的电势。阴极产生的电子在真空管中向阳极加速。X：阳极产生的 X 线。影像来源：https://commons.wikimedia.org/wiki/File:WaterCooledXrayTube.svg

/ X-Ray Spectra

/ X-rays are produced through two processes: **braking** and **characteristic radiations**.

/ **Braking X-rays** are emitted from the anode in a continuous range of energies, the maximum energy being determined by the tube voltage (Fig. 5).

/ Electrons can **eject** other electrons from the inner shells of the atoms in the anode. These vacancies are filled when electrons descend from higher energy levels and emit **characteristic X-rays** (Fig. 4).

/ **Characteristic X-rays** have well-defined energies determined by the difference between the atomic energy levels of the atoms of the anode.

/ A **filtration in aluminum** placed at the tube output cuts off low-energy X-rays which would increase the patient dose but would never reach the patient exit nor the detector.

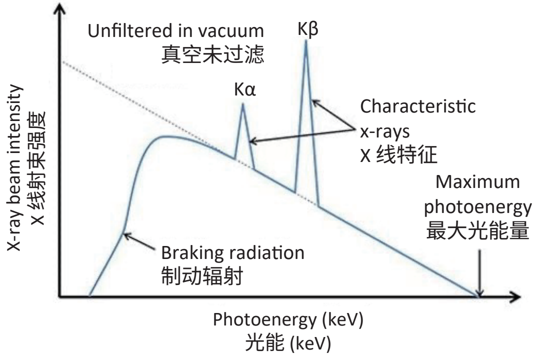

FIGURE 5

Typical X-ray spectrum.

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章节大纲：

/ X 线谱

/ X 线通过两个过程产生：**制动和特征辐射**。

/ **制动 X 线**从阳极以连续的能量范围发射，最大能量由管电压决定（图 5）。

/ 电子可以从阳极原子的内壳中**射出**其他电子。当电子从较高的能级下降并发射出**特征 X 线**时，这些空位就会被填满（图 4）。

/ **特征 X 线**具有明确的能量，该能量由阳极原子的原子能级之间的差异决定。

/ 置于球管输出口的**铝滤过装置**可去除低能量 X 线，这些射线可能会增加患者剂量，但不会到达患者出口或探测器。

图 5

典型的 X 线谱。

/ Parameter Setting

<!> ATTENTION

Focus size (Fig. 6)

- A small focus size (small cathode filament) helps reducing geometric blur (penumbra) when magnification is employed.
- A large focus size helps reducing motion blurring when high exposure rate (high mA) is needed for shortest exposure times.

Voltage (kV)

- X-ray tube high voltage is applied between the cathode and the anode.
- The mean energy of the X-ray spectrum and the quantity of X-rays produced increases with the tube voltage.
- The tube high voltage is set between:
  - 40 and 150 kV in standard radiography and fluoroscopy.
  - 23 and 40 kV in mammography.

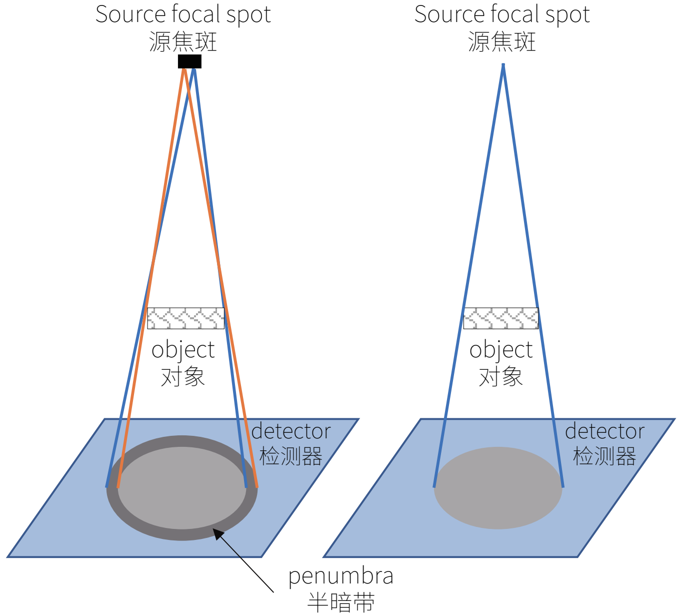

FIGURE 6

Geometric blurring.

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CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 参数设置

<!> 注意

焦点尺寸（图 6）

- 当采用放大倍数时，小焦点尺寸（小阴极灯丝）有助于减少几何模糊（半影）。
- 在需要高曝光率（高 mA）以实现最短曝光时间的情况下，大焦点尺寸有助于减少运动模糊。

电压 (kV)

- 在阴极和阳极之间施加高管电压。
- X 线谱的平均能量和产生的 X 线量随管电压的增加而增加。
- 高管电压设置为：
  - 标准放射摄影和荧光透视为 40～150 kV。
  - 乳腺 X 线摄影为 23～40 kV。

图 6

几何模糊。

Current time product

/ The electrical current in the X-ray tube is the charge of electrons per unit time (mA).

/ The current time product represents the electrical charge going from the cathode to the anode during the exposure time (mAs).

Filtration

/ X-ray tube filtration absorbs the low-energy X-rays as they only produce an irradiation to the patient and do not reach the detector.

/ **Inherent filtration** results from the composition of the tube and housing.

/ **Additional filtration** consists of aluminium or copper plates of different thicknesses placed between the window and the collimator which can be inserted or removed depending on the imaging protocol.

/ **Total filtration** is the sum of all filtrations.

<!> ATTENTION

The total filtration is expressed in equivalent millimeters of aluminium and must be at least 2.5 mm of aluminium.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

电流时间乘积

/ X 线管中的电流为单位时间内通过的电荷量 (mA)。

/ 电流时间乘积表示曝光时间内从阴极到阳极的电荷 (mAs)。

滤过

/ X 线管的滤过可吸收低能量 X 线，因为它们只会增加患者受照剂量而不会到达探测器。

/ 固有滤过由管道和外壳的组成。

/ 附加滤过包括置于视窗和准直器之间的不同厚度的铝板或铜板，可根据成像方案插入或移除。

/ 总滤过量是所有滤过量的总和。

<!> 注意

总滤过量以等效毫米铝表示，必须至少为 2.5 mm 铝。

/ X-Ray Beam

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ X 线射束

/ Interaction of X-Rays with Matter

There are 3 outcomes of the passage of X-rays through matter (Fig. 7):

- / T: Transmission (no interaction)
- / A: Absorption
- / S: Scatter

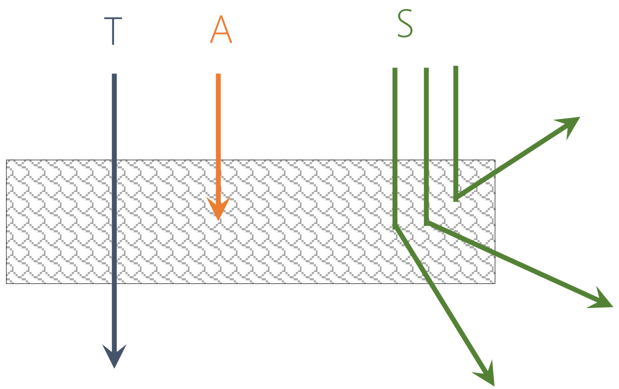

FIGURE 7

Interactions of X-rays with matter.

<!> ATTENTION

- / The absorption of X-rays is caused by the **photoelectric effect**.
- / The photoelectric effect produces the contrast in the radiological image.
- / It constitutes the basis of X-ray imaging.
- / There are two mechanisms for producing **scattered radiation**:
  - / Incoherent scattering: Compton effect
  - / Coherent scattering: Rayleigh effect
- / Scattered radiation does not produce contrast in the radiological image. It is an "unwanted effect".

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ X 线与物质的相互作用

X 线穿过物质有 3 种结果（图 7）：

- / T：透射（无相互作用）
- / A：吸收
- / S：散射

<!> 注意

- / X 线的吸收是由**光电效应**引起的。
- / 光电效应在放射影像中产生对比度。
- / 它是 X 线成像的基础。
- / 产生**散射辐射**的机制有两种：
  - / 非相干散射：康普顿效应
  - / 相干散射：瑞利效应
- / 散射辐射不会在放射影像中产生对比度。这是一种“不需要的效应”。

图 7

X 线与物质的相互作用

In the photoelectric effect (absorption) (Fig. 8)

/ An X-ray hits an electron, which is ejected from the atom (photoelectron).

/ The X-ray stops and the atom is ionised, with an inner-shell electron vacancy.

/ The electron vacancy is filled with an electron resulting from a cascade from outer to inner shells.

/ The difference in binding energy is released as either characteristic X-rays or Auger electrons.

The probability of a photoelectric effect :

/ Decreases with the beam energy, which explains why image contrast decreases with X-ray energy E.

/ Increases in materials of high atomic number Z.

/ Is approximately proportional to Z^3/E^3.

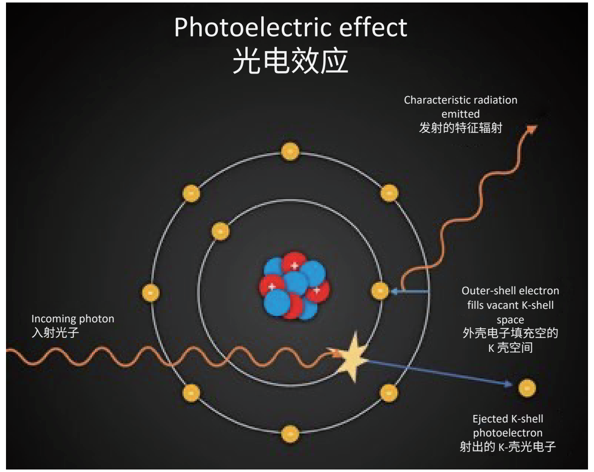

FIGURE 8

Photoelectric interaction
Case courtesy of Frank Gaillard, https://radiopaedia.org/articles/photoelectric-effect

>▪< FURTHER KNOWLEDGE

If the photon energies are doubled, the probability of photoelectric interaction is decreased eightfold: $(½)^3 = 1/8$.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

在光电效应（吸收）中（图 8）

/ X 线与束缚电子相互作用，电子被击出原子（光电子）。

/ 入射 X 线光子被完全吸收，原子电离并产生内层空位。

/ 该空位由外层电子经级联跃迁填充。

/ 结合能的差异以特征 X 线或俄歇电子的形式释放。

光电效应的概率：

/ 随着射束能量增加而降低，这就解释了图像对比度为何随 X 线能量 E 增加而降低。

/ 随材料原子序数 Z 升高而增加。

/ 与 Z^3/E^3 近似成比例。

图 8

光电相互作用
由 Frank Gaillard 提供，https://radiopaedia.org/articles/photoelectric-effect

>▪< 进阶知识

如果光子能量翻倍，则光电相互作用的概率会降至 1/8：$(½)^3 = 1/8$。

In Compton scattering (inelastic scattering) (Fig. 9)

- / An X-ray hits an electron which is ejected from the atom (atom ionized).
- / A scattered X-ray is emitted at a different angle with respect to the incident photon.
- / The scattered X-ray has a reduced energy due to the transfer of energy to the electron.
- / The scattered X-ray may undergo subsequent interactions such as Compton or Rayleigh scattering, or photoelectric absorption.
- / Compton scattering is the main interaction of X-rays with soft tissues in the diagnostic energy range.

<!> ATTENTION

Scattered X-rays degrade image contrast and signal-to-noise ratio.

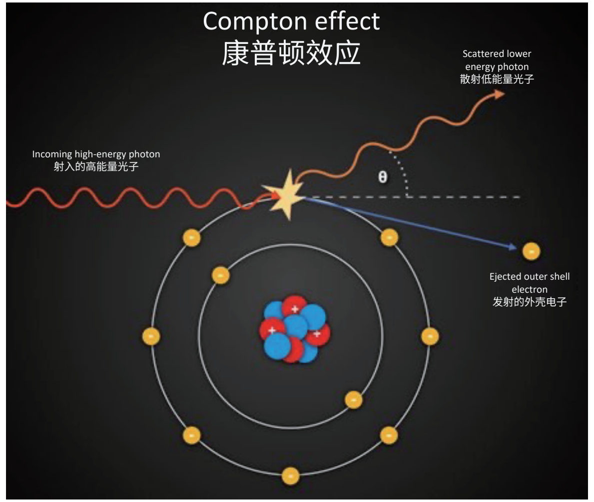

FIGURE 9

Compton interaction
Case courtesy of Frank Gaillard,
https://radiopaedia.org/articles/compton-effect

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

在康普顿散射（非弹性散射）中（图 9）

- / X 线与近似自由电子碰撞，电子被击出原子（原子被电离）。
- / 散射 X 线以相对于入射光子的不同角度发射。
- / 由于能量传递到电子，散射 X 线的能量降低。
- / 散射 X 线可以发生后续的相互作用，例如康普顿或瑞利散射或光电吸收。
- / 在诊断能量范围内，康普顿散射是 X 线与软组织的主要相互作用。

<!> 注意

散射 X 线会降低图像对比度和信噪比。

图 9

康普顿相互作用
由 Frank Gaillard 提供，
https://radiopaedia.org/articles/compton-effect

In Compton scattering (inelastic scattering)

/ At the X-ray energies used in diagnostic imaging (15-150 keV), the incident X-ray energy is mainly transmitted to the scattered X-ray.

/ The average scattering angle decreases as the X-ray energy increases (Fig. 10).

/ The scattering angle of the ejected electron cannot exceed 90°, whereas that of the scattered X-ray can be any value including a 180° backscatter.

/ In contrast to the scattered X-ray, the ejected electron is usually reabsorbed near the scattering site.

<!> ATTENTION

The probability of Compton scattering is

/ nearly independent of Z,

/ approximately proportional to the density of the material.

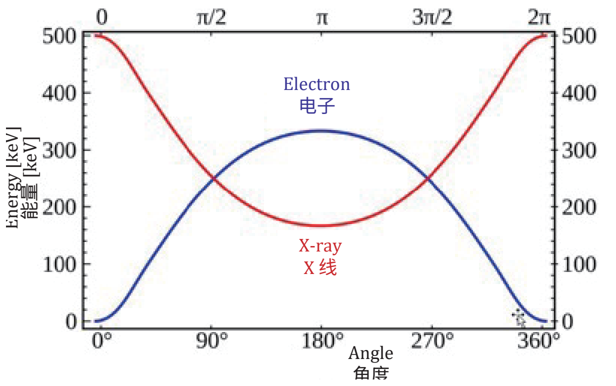

FIGURE 10

Deviation angle of the scattered X-ray and the emitted electron as a function of the incident X-ray energy
Case courtesy:
https://en.wikipedia.org/wiki/Compton_scattering

X-Ray Imaging

CHAPTER OUTLINE:

X 线成像

章节大纲：

在康普顿散射（非弹性散射）中

/ 在用于诊断成像的 X 线能量下 (15~150 keV)，入射 X 线能量主要传递到散射 X 线。

/ 平均散射角随着 X 线能量的增加而减小（图 10）。

/ 射出电子的散射角不能超过 90°，而散射 X 线的散射角可以是包括 180° 背向散射在内的任何值。

/ 与散射 X 线不同，射出的电子通常在散射位置附近被重新吸收。

<!> 注意

康普顿散射的概率

/ 几乎与 Z 无关，

/ 与材料的密度近似成比例。

图 10

散射 X 线和发射电子的偏差角作为入射 X 线能量的函数
来源：
https://en.wikipedia.org/wiki/Compton_scattering

In Rayleigh scattering (elastic scattering)

/ The incident X-ray excites the total atom, as opposed to Compton scattering or photoelectric effect.

/ Electrons are not ejected, and no ionisation occurs.

/ This interaction occurs mainly with low energy X-rays, such as those used in mammography (15-30 keV).

/ The atom's electron cloud in the scattering atom oscillates in phase and immediately radiates this energy, emitting a scattered X-ray of the same energy but in a slightly different direction (Fig. 14).

/ The average scattering angle decreases as the X-ray energy increases.

>=< FURTHER KNOWLEDGE

Rayleigh scattering accounts for only 10% of interactions in mammography and 5% in standard radiography.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

在瑞利散射（弹性散射）中

/ 与康普顿散射或光电效应相反，入射光子使原子整体发生相干振荡（不发生电离）。

/ 电子不会射出，也不会发生电离。

/ 这种相互作用主要见于低能量 X 线，例如乳腺 X 线摄影中使用的 X 线 (15～30 keV)。

/ 散射原子中的原子电子云同相振荡，并立即辐射该能量，发射相同能量但方向略有不同的散射 X 线（图 14）。

/ 平均散射角随着 X 线能量的增加而减小。

>=< 进阶知识

瑞利散射仅占乳腺 X 线摄影中相互作用的 10%，标准放射摄影中相互作用的 5%。

/ Attenuation of X-Rays

/ X-rays are attenuated in matter due to absorption and scattering.

/ Due to X-ray absorption, the quantity of X-rays decreases exponentially. X-ray absorption depends on matter thickness:

$$N(x) = N_0 \cdot e^{-\mu x}$$

Where N and N_0 are the number of X-rays at depth x and at the surface (depth zero) of the traversed matter, and μ is the linear attenuation coefficient, which gives the probability of interaction per unit length of matter in (cm^{-1}) (Fig. 11).

/ Most of X-ray attenuation in the diagnostic energy range is due to the photoelectric effect and is proportional to $(Z/E)^3$.

/ The linear attenuation coefficient depends on each material and:

- / Increases with the atomic number of matter.
- / Decreases with the energy of X-rays.

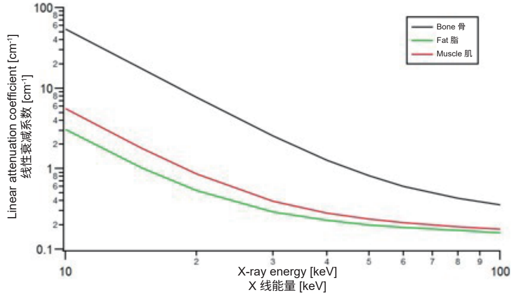

FIGURE 11

Linear attenuation coefficient of bone, fat and muscle for X-rays between 10 and 100 keV.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ X 线衰减

/ X 线在物质中由于吸收和散射而衰减。

/ 由于 X 线吸收，X 线量呈指数下降。X 线吸收取决于物质厚度：

$$N(x) = N_0 \cdot e^{-\mu x}$$

其中 N 和 N_0 是穿过物质的深度 x 处和表面（零深度）的 X 线量，μ 是线性衰减系数，表示每单位长度物质的相互作用概率 (cm^{-1})（图 11）。

/ 诊断能量范围内的大多数 X 线衰减是由于光电效应所致，与 $(Z/E)^3$ 成比例。

/ 线性衰减系数取决于每种材料，并且：

- / 随物质的原子序数增加而增大。
- / 随 X 线能量的增加而减小。

图 11

10–100 keV X 线在骨骼、脂肪与肌肉中的线性衰减系数。

Half Value Layer (HVL)

/ The HVL of an X-ray beam is the thickness of absorbing material that is needed to reduce the beam intensity by half of its initial value (Fig. 12).

/ HVL is an indirect measure of the mean beam energy, and is inversely proportional to the linear attenuation coefficient μ:

$$HVL = \frac{ln(2)}{\mu}$$

<!> ATTENTION

/ Low energy X-rays are stopped faster than high-energy X-rays, causing the mean beam energy of polyenergetic beams to increase in the depth of the traversed material. This effect is called **beam hardening**.

/ Beam hardening causes X-rays to decay in the depth of the traversed matter less rapidly than exponentially.

/ The HVL of polyenergetic X–ray beams defines the effective attenuation coefficient:

$$\mu_{eff} = ln(2)/HVL$$

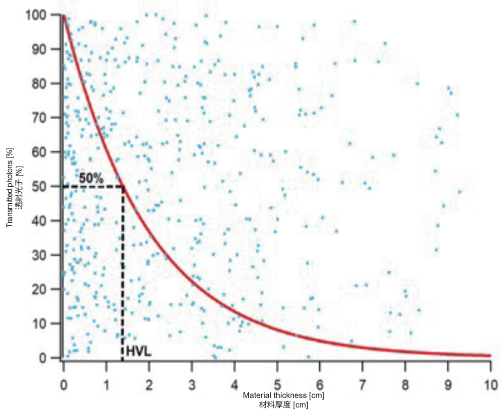

FIGURE 12

Half value layer.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

半值层 (Half Value Layer，HVL)

/ X 线射束的 HVL 是将射束强度降低其初始值的一半所需的吸收材料的厚度（图 12）。

/ HVL 是平均射束能量的间接测量，与线性衰减系数 成反比：

$$HVL = \frac{ln(2)}{\mu}$$

<!> 注意

/ 低能 X 光子优先被吸收，使多能 X 线射束的平均能量沿深度方向升高。这种效应称为**射束硬化**。

/ 射束硬化使 X 线射束在被穿透介质中的随深度衰减较理想的指数规律更为缓慢。

/ 多能 X 线的 HVL 决定有效衰减系数：

$$\mu_{eff} = ln(2)/HVL$$

图 12

半值层。

/ Scatter Fraction

- / The amount of scatter detected in an image is characterised by the scatter-to-primary ratio (SPR) or the scatter fraction (SF), which is expressed as a percentage.
- / The SF increases with the volume of tissue irradiated by the X-ray beam:
  - / with the beam size (field of view)
  - / with the thickness of the patient
- / For a typical 30 × 30 cm² abdominal irradiation in a 25-cm-thick patient, the SF is about 80% (Fig. 13).

<!> ATTENTION

The contrast in the image is inversely proportional to the SF, and a scatter rejection technique must be used.

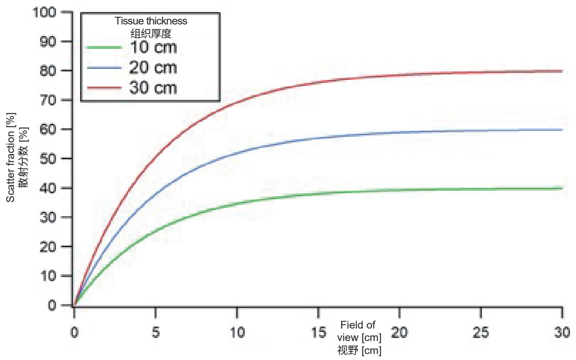

FIGURE 13

Scatter fraction of X-ray beams for different field of view and three patient tissue thicknesses.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 散射分数

- / 在图像中探测到的散射量通过散射源射比 (scatter-to-primary ratio，SPR) 或散射分数 (scatter fraction，SF) 表征，以百分比表示。
- / SF 随着 X 线射束辐射的组织体积增加而增加：
  - / 随射束尺寸（视野）增加
  - / 随患者厚度增加
- / 对于在 25 cm 厚的患者中典型的 30 × 30 cm² 腹部照射，SF 约为 80%（图 13）。

<!> 注意

图像中的对比度与 SF 成反比，必须使用散射抑制技术。

图 13

不同视野和三种患者厚度条件下 X 线射束的散射分数。

Radiological Image Formation

X-Ray Imaging

X 线成像

CHAPTER OUTLINE:

章节大纲：

放射学图像形成

Scattered Radiation Rejection

/ Rejection of X-rays scattered in the patient is based on their oblique orientation relative to primary X-rays.

/ Rejection of scatter is important for **enhancing contrast** in projection radiography.

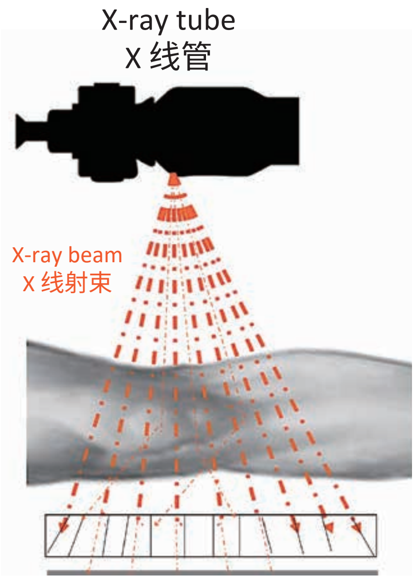

FIGURE 14

Scatter rejection in front of the detector.

Anti-Scatter Grid (Fig. 14)

/ The anti-scatter grid, placed between the patient and the detector, is the most widely used technology for reducing scatter in radiography, fluoroscopy and mammography.

/ Grids are typically manufactured with lead strips oriented along one dimension separated by a low attenuating interspace material such as carbon fiber or aluminum.

/ Parallel grids have lead strips that are focused to infinity.

/ Focused grids have lead strips oriented towards the focal point of the grid, located at the focal distance of the grid.

/ Typical focal distances are 100, 150 and 180 cm.

X-Ray Imaging

CHAPTER OUTLINE:

X 线成像

章节大纲：

散射辐射抑制

/ 在患者体内散射的 X 线的抑制基于其相对于原始 X 线的倾斜方向。

/ 散射抑制对于投影放射摄影中**增强对比度**至关重要。

防散射滤线栅（图 14）

/ 防散射滤线栅放置在患者和探测器之间，是使用最广泛的用于减少放射摄影、荧光透视和乳腺 X 线摄影中散射的技术。

/ 滤线栅通常由铅条制成，这些铅条沿着一个方向排列，由低衰减空隙材料（例如碳纤维或铝）隔开。

/ 平行滤线栅具有聚焦到无穷远的铅条。

/ 聚焦滤线栅具有朝向滤线栅的焦点定向的铅条，位于滤线栅的焦距处。

/ 典型的焦距为 100、150 和 180 cm。

图 14

探测器前的散射抑制。

Anti-Scatter Grid (Fig. 14)

/ The grid attenuates some of the primary X-rays that are incident directly on the lead strips.

/ The transmission of primary X-rays through the grid is the primary transmission (T_p).

/ The grid allows transmission of some scattered X-rays that have a small scattering angle, or scatter in a direction parallel to the lead strips.

/ The transmission of scattered X-rays through the grid is the scatter transmission (T_s).

/ The primary and scatter transmissions of the grid determine the grid efficiency, quantified by the grid selectivity Σ.

<!> ATTENTION

Grids are characterised by the parameters (Fig. 15):

/ **Grid ratio r:** the ratio between the height of the lead strip to the interspace distance

/ **Grid frequency f:** the number of grid lines per cm

/ **Grid focal distance:** The distance to the focal point

$$\Sigma = \frac{T_p}{T_s} \qquad r = \frac{h}{D} \qquad f = \frac{1}{t + D}$$

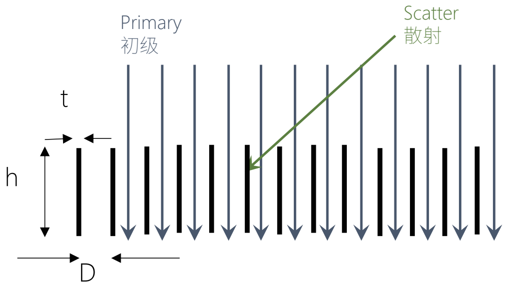

FIGURE 15

Grid characteristics.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

防散射滤线栅（图 14）

/ 滤线栅会直接衰减一部分入射到铅条上的原发 X 线。

/ 原始 X 线通过滤线栅的透射是主要透射 (T_p)。

/ 滤线栅允许具有小散射角的一些散射 X 线的透射，或在平行于铅条的方向上散射。

/ 散射 X 线通过滤线栅的透射是散射透射 (T_s)。

/ 滤线栅的主要透射和散射透射决定滤线栅效率，通过滤线栅选择性 Σ 进行量化。

<!> 注意

滤线栅通过参数表征（图 15）：

/ **滤线栅比值 r：**铅条高度与空隙距离之间的比值

/ **滤线栅频率 f：**每厘米的滤线栅线条数量

/ **滤线栅焦距：**至焦点距离

$$\Sigma = \frac{T_p}{T_s} \qquad r = \frac{h}{D} \qquad f = \frac{1}{t + D}$$

图 15

滤线栅特征。

Anti-Scatter Grid (Fig. 14)

- The total transmission (T_t) of the grid depends on T_p, T_s and the scatter fraction (SF).
- The grid factor or bucky factor, the inverse of T_t, is the increase in patient dose when using a grid compared to not using a grid to match the same detector dose.
- A grid with a higher grid ratio has a lower T_s, due to a more limited transmission angle, but also a lower T_p, and a high contrast improvement factor (Fig. 16).
- The focal range is an indicator of the flexibility of grid positioning distance from the focal spot, and is a function of the grid ratio and frequency.

<!> ATTENTION

Grid artifacts arise from bad grid positioning:

- Tilting the grid to the incident X-ray beam.
- Bad centering to the beam central axis.
- Using a focused grid outside the specified focal range.

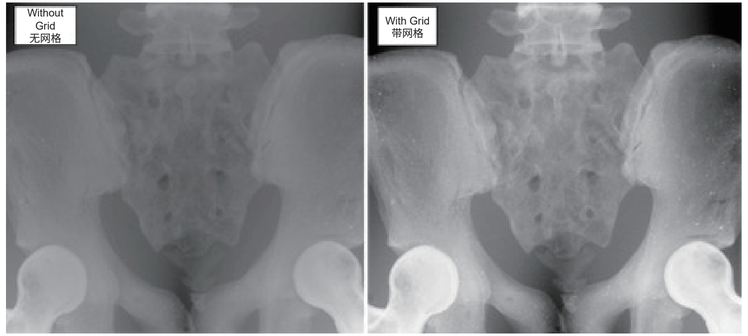

FIGURE 16

Contrast improvement due to the grid.

X-Ray Imaging

CHAPTER OUTLINE:

X-Ray Imaging

章节大纲：

防散射滤线栅（图 14）

- 滤线栅的总透射 (T_t) 取决于 T_p、T_s 和散射分数 (scatter fraction，SF)。
- 滤线栅因子或巴克因数是 T_t 的倒数，是指为达到相同探测器剂量，使用滤线栅时患者剂量相对于不使用滤线栅的增加倍数。
- 具有较高滤线栅比值的滤线栅由于透射角度更有限而具有较低的 T_s，但也具有较低的 T_p 和高对比度改善因子（图 16）。
- 焦距范围是离焦斑的滤线栅定位距离的灵活性指标，是滤线栅比值和频率的函数。

<!> 注意

滤线栅伪影由错误的滤线栅定位引起：

- 滤线栅向入射 X 线射束倾斜。
- 射束中心轴居中不佳。
- 使用指定聚焦范围外的聚焦滤线栅。

图 16

滤线栅使对比度得到改善。

Air Gap (Fig. 17)

/ An air gap distance between the patient and the detector lets the X-rays scatter out of the image field of view.

/ The scattered X-ray intensity decreases with the air gap distance.

/ Practical factors limit the use of the air gap:

  / Magnification of the patient anatomy.

  / Increased geometrical blurring due to the focal spot size.

  / May require extending the focus-to-detector distance to decrease magnification, while increasing exposure time and motion blur.

/ The advantages of the air gap over the grid:

  / A primary transmission at 100%.

  / A lower increase in patient dose.

  / A higher efficiency (selectivity) for median scatter fractions.

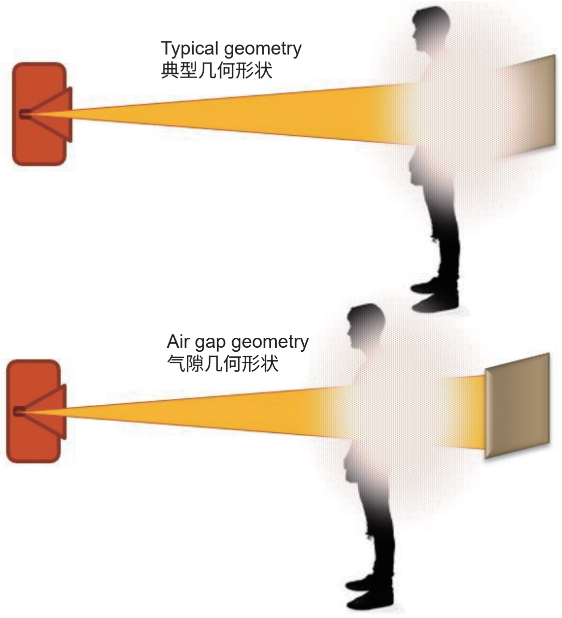

FIGURE 17

Principle of the air gap.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

气隙（图 17）

/ 在受检者与探测器之间设置空气间隙，可使散射 X 线偏离成像视野。

/ 散射的 X 线强度随着气隙距离的增加而降低。

/ 限制气隙使用的实际因素：

  / 患者解剖结构放大。

  / 焦斑尺寸导致几何模糊增加。

  / 可能需要延长焦点到探测器的距离以降低放大倍率，但会增加曝光时间和运动伪影。

/ 气隙相比于滤线栅的优点包括：

  / 100% 的主要透射。

  / 患者剂量增加幅度较小。

  / 中位散射分数的效率（选择性）更高。

图 17

气隙原理。

/ Projection

/ Conventional radiological image formation results from the projection of the differential transmission of the primary X-ray beam through the different anatomic tissues.

/ Two different processes contribute to beam attenuation: absorption and scattering.

/ The transmission characteristics of the anatomic parts are determined by their

  / thickness.

  / linear attenuation coefficient

/ The X-ray transmission T decreases exponentially with the linear attenuation coefficient μ and the thickness x of the irradiated tissue:

$$T = e^{-\mu x}$$

/ The output radiation modulation that interacts with a detector is the **latent image.**

<!> ATTENTION

Once detected, on a radiographic image (Fig. 18):

/ A strongly attenuating tissue is bright.

/ A low attenuating tissue is dark.

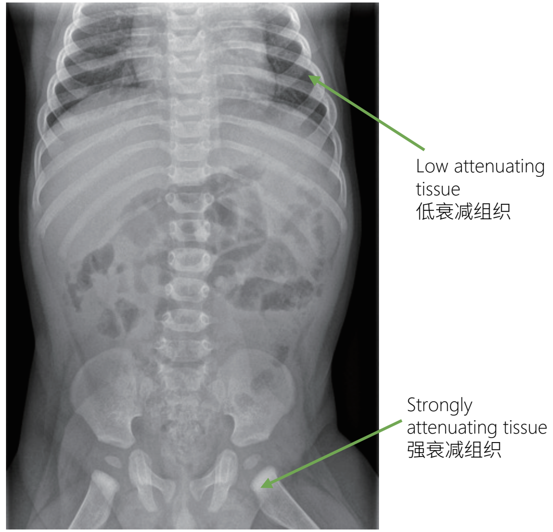

FIGURE 18

A conventional radiograph is a projection of the differential transmission of X-rays in the tissues.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 投影

/ 传统放射影像的形成，源于原发 X 线射束穿过不同解剖组织时所产生的差异性透射投影。

/ 两个不同的过程导致射束衰减：吸收和散射。

/ 解剖部位的透射特征取决于

  / 厚度。

  / 线性衰减系数

/ X 线透射 T 随着线性衰减系数 μ 和被照射组织的厚度 x 呈指数下降：

$$T = e^{-\mu x}$$

/ 与探测器相互作用的输出辐射调制为潜影。

<!> 注意

一经探测，即在 X 线摄影图像上呈现（图 18）：

/ 高衰减组织呈亮影。

/ 低衰减组织呈暗影。

图 18

常规 X 线片是组织间 X 线透射差异的投影成像。

Magnification

/ The focal spot creates a divergent beam in which X-rays travel in straight line.

/ The patient-to-detector distance in the divergent projection creates a magnification of the anatomy on the image.

/ The magnification M is defined as (Fig. 19):

$$M = \frac{Image\ size}{Object\ size} = \frac{SID}{SOD}$$

/ Low magnification occurs for:

/ a long source-to-detector distance

/ a short object-to-detector distance

<!> ATTENTION

The size of the object on projections also strongly depends on the orientation of the object relative to the detector plane!

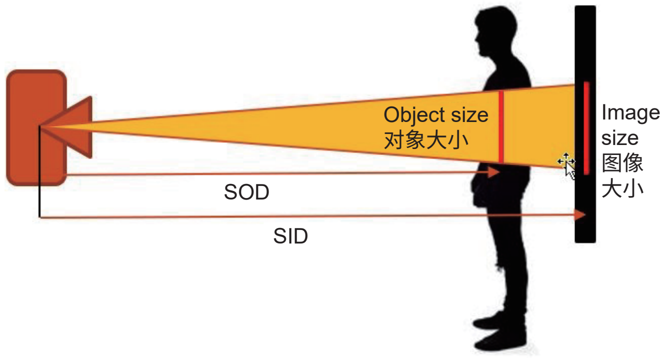

FIGURE 19

Magnification factor in conventional radiography.
SOD = Source Object Distance | SID = Source Image Distance.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

放大率

/ 焦斑会产生发散射束，X 线在该发散射束中沿直线传播。

/ 发散投影中的患者到探测器的距离使解剖结构在图像上放大。

/ 放大倍率 M 定义为（图 19）：

$$M = \frac{Image\ size}{Object\ size} = \frac{SID}{SOD}$$

/ 低放大倍率见于：

/ 放射源到探测器的距离长

/ 对象到探测器的距离短

<!> 注意

投影上的物体尺寸高度依赖于其相对于探测器平面的取向！

图 19

常规放射摄影中的放大倍数。SOD = 源对象距离 | SID = 源图像距离。

Geometric Blur

/ The finite size of the focal spot is the reason why the X-rays "are coming out" from an area and not just from a single point.

/ As the X-rays come from the whole area of the focal spot, a **penumbra** appears on the edge of objects.

/ The larger the size of the focal spot, the greater the blur will be on the detector.

/ The geometric blur depends on the size of the focal spot, and the system geometry (Fig. 20):

$$B = f \cdot \frac{OID}{SOD} = f \cdot (M - 1)$$

/ Low geometric blur occurs for:

- / a small focal spot size
- / a long source-to-detector distance
- / a short object-to-detector distance

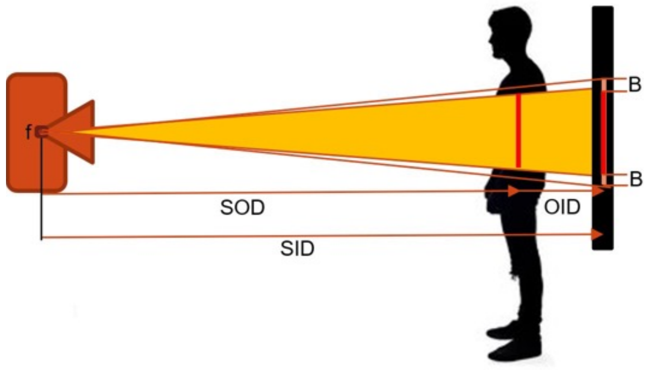

FIGURE 20

Geometric blur (B) in conventional radiography (penumbra). SOD = Source Object Distance | SID = Source Image Distance | OID = Object Image Distance

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

几何模糊

/ 焦斑的有限尺寸是 X 线从一个区域而不是仅仅从一个点"出来"的原因。

/ 当 X 线来自焦斑的整个区域时，对象的边缘会出现一个**半暗带**。

/ 焦斑的尺寸越大，探测器上的模糊程度就越高。

/ 几何模糊取决于焦斑的尺寸和系统几何形状（图 20）：

$$B = f \cdot \frac{OID}{SOD} = f \cdot (M - 1)$$

/ 低几何模糊见于：

- / 焦斑尺寸较小
- / 放射源到探测器的距离长
- / 对象到探测器的距离短

图 20

常规放射摄影中的几何模糊 (B)（半暗带）。
SOD = 源对象距离 | SID = 源图像距离 | OID = 对象图像距离

/ Digital X-Ray Detectors

/ Flat panel detectors (FPD) make an electronic conversion of X-rays to digital signal on a flat area.

/ Two technologies are used: indirect and direct detectors.

Indirect FPD

/ A scintillator converts X-rays to light.

/ The scintillator is coupled to a matrix of photodiodes made with amorphous silicon (a-Si).

/ Electric charges of the photodiodes are collected by thin-film transistors (TFT) for signal processing of each pixel.

/ Light in the scintillator is spread, which causes degradation of the spatial resolution (Fig. 21).

/ Columnar-shaped caesium iodide (CsI) scintillators have been used to reduce light spread, thus allowing to obtain ultra-high resolution images.

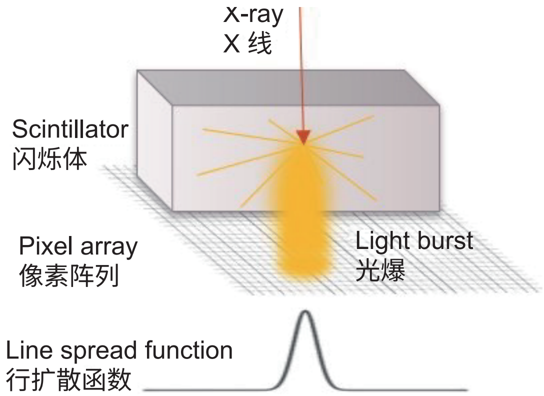

FIGURE 21

Light spread in the scintillator.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 数字 X 线探测器

/ 平板探测器 (flat panel detector，FPD) 在平坦区域上将 X 线电子转换为数字信号。

/ 使用两种技术：间接和直接探测器。

间接 FPD

/ 闪烁体将 X 线转化为光。

/ 闪烁体耦合到由非晶硅 (amorphous silicon，a-Si) 制成的光电二极管矩阵。

/ 各像素的光电二极管电荷由薄膜晶体管 (thin-film transistor，TFT) 收集，以进行信号处理。

/ 闪烁体内部光的扩散导致空间分辨率下降（图 21）。

/ 柱状碘化铯 (columnar-shaped caesium iodide，CsI) 闪烁体可抑制光的侧向扩散，实现超高分辨率成像。

图 21

闪烁体中的光扩散。

Direct FPD

/ A semiconductor in amorphous selenium (a-Se) directly converts X-rays to electrons.

/ Electric charges are collected on a capacitor matrix coupled to a TFT for signal processing of each pixel.

/ Direct conversion gives a high spatial resolution (Fig. 22).

/ The detection efficiency of a-Se (Z = 34) is low at high energy.

/ For this reason, direct conversion detectors are used mainly for mammography.

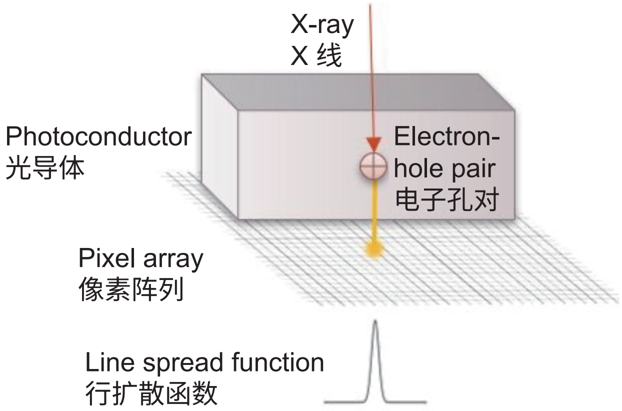

FIGURE 22

High spatial resolution of direct conversion detectors.

>■< FURTHER KNOWLEDGE

New X-ray detectors, solid-state complementary metal oxide semi-conductor (CMOS) imagers or gas electron multiplier (GEM) detectors, have paved the way for photon-counting imaging, in which each photon is detected **individually** and its energy is estimated with high efficiency and with no electronic noise.

> See eBook chapter on Computed Tomography

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

直接 FPD

/ 非晶硒 (amorphous selenium，a-Se) 半导体直接将 X 线转化为电子。

/ 在与 TFT 耦合的电容器矩阵上收集电荷，用于每个像素的信号处理。

/ 直接转换具有高空间分辨率（图 22）。

/ a-Se (Z = 34) 的探测效率在高能量下较低。

/ 因此，直接转换探测器主要用于乳腺 X 线摄影。

>■< 进阶知识

新型 X 线探测器——固态互补金属氧化物半导体 (complementary metal oxide semi-conductor，CMOS) 成像仪或气体电子倍增器 (gas electron multiplier，GEM) 探测器——开启了光子计数成像时代，在这类成像中，每个光子都被**单独**探测到，其能量被高效估算，且不受电子噪声干扰。

> 请参阅《计算机断层扫描》电子书章节

图 22

直接转换探测器的高空间分辨率。

/ Automatic Exposure Control (AEC)

- The automatic exposure control (AEC) device controls the radiation dose reaching the detector by regulating the length of exposure.
- The AEC device terminates the exposure when the detector's target dose is reached.
- Most of AEC systems consist of three or five radiation-measuring sensors, two lateral and one central, as shown in Fig. 23.
- The radiographer selects the configuration of the three AEC sensors, determining which of the three individually or in combination measures the detector dose.
- The detector's target dose of AEC devices can be adjusted using the control panel buttons numbered −2, −1, 0, +1, +2, ...
- The anatomic area of interest must cover the selected detectors, in order to avoid over or under exposition.

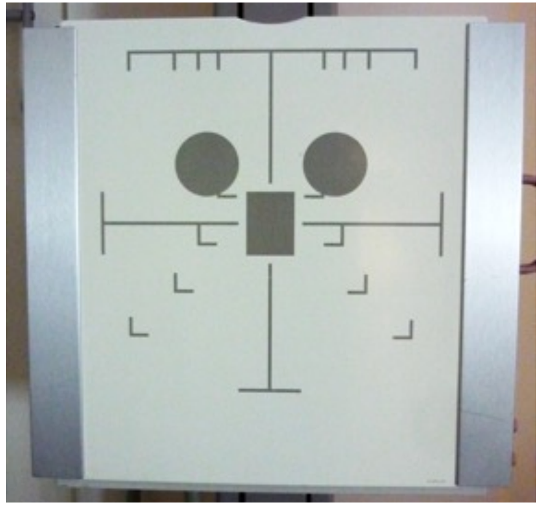

FIGURE 23

Three cells of the automatic exposure control system.
Source: Automatic exposure control - Wikipedia

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X-Ray Imaging

章节大纲：

/ 自动曝光控制 (AEC)

- 自动曝光控制 (automatic exposure control，AEC) 设备通过调节曝光长度来控制到达探测器的辐射剂量。
- 当达到探测器的目标剂量时，AEC 设备将终止曝光。
- 如图 23 所示，大多数 AEC 系统由三个或五个辐射测量传感器组成，两个在侧面，一个在中心。
- 放射技师会选择三个 AEC 传感器的配置，确定这三个传感器中的哪一个单独或组合测量探测器剂量。
- 可使用编号为 -2、-1、0、+1、+2、……的控制面板按钮调整 AEC 设备的探测器目标剂量。
- 目标解剖区域必须覆盖所选探测器，以避免曝光过度或曝光不足。

图 23

自动曝光控制系统的三个单元。来源：自动曝光控制 - 维基百科

Dosimetric Quantities

X-Ray Imaging

CHAPTER OUTLINE:

X 线成像

章节大纲：

剂量测定量

/ Exposure Index (EI)

- The exposure index gives the user feedback about the detector dose of a radiography.
- The exposure index is calculated from signals in the acquired image itself, and describes the detector dose.
- For some systems, the exposure index can scale differently to dose quantities.
- The definition of exposure index was standardised in 2008*:
  EI = 100 x detector dose in μGy
- Different combinations of patient body constitutions and exposure can result in the same detected signal and EI.
- Variation in EI can occur due to varying imaging content, even if the same exposure setting was used and patient entrance exposure was the same.

<!> ATTENTION

EI is not an equivalent for patient entrance exposure!

* Medical electrical equipment—exposure index of digital X-ray imaging systems—Part 1: definitions and requirements for general radiography. International Electrotechnical Commission (IEC), International Standard IEC 62494-1:2008-08, Geneva, Switzerland (2008).

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X-Ray Imaging

章节大纲：

/ 曝光指数 (EI)

- 曝光指数为用户提供放射摄影探测器剂量的反馈。
- 曝光指数是根据所采集图像本身的信号计算得出的，描述探测器剂量。
- 对于某些系统，曝光指数可以根据剂量不同增减。
- 2008 年对曝光指数的定义进行了标准化*：
  EI = 100 x detector dose in μGy
- 不同体型患者与不同曝光条件的组合，只要最终抵达探测器的剂量一致，即可产生相同的检测信号与曝光指数 (EI)。
- 即使曝光参数与患者入射剂量完全一致，因成像解剖内容不同，亦可导致曝光指数 (EI) 出现波动。

<!> 注意

EI 不等同于患者入口曝光！

* 医用电气设备 — 数字 X 线成像系统的曝光指数 — 第 1 部分：通用摄影的定义与要求。国际电工委员会 (IEC)，国际标准 IEC 62494-1:2008-08，瑞士日内瓦，2008 年。

/ Air Kerma in the X-Ray Beam

- / X-rays deposit energy in matter, and hence dose, through interactions with electrons, making ionisations.
- / The energy of X-rays transferred to electrons is transformed into kinetic energy.
- / These energetic electrons interact with other electrons in matter, depositing most of their energy in a very small volume.
- / The air kerma (Kinetic Energy Released in Matter) is the energy transferred from non charged particles to charged particles, divided by the mass of air in the measurement volume.
- / The air kerma unit is J/kg, called Gray (Gy).
- / The air kerma (K_a) of an X-ray beam (Fig. 24) depends on the current time product (Q), the voltage squared (U^2), the inversed square distance to the source (d^{-2}) and the X-ray tube constant C as follows:

$$K_a = C \cdot \left(\frac{U}{100}\right)^2 \cdot \frac{Q}{d^2}$$

<!> ATTENTION

The air kerma is defined at a point in the air and does not take into account scattering or beam size. The main use of air kerma is to estimate the peak skin dose in interventional radiology (see next page). It is of little interest in conventional radiology, where skin doses are below the threshold for deterministic effects.

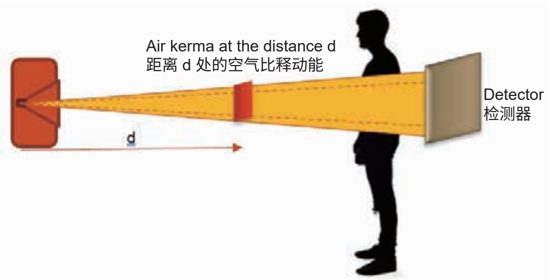

FIGURE 24

Air kerma.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ X 线射束中的空气比释动能

- / X 线通过与电子相互作用引发电离，将能量沉积于物质并形成剂量。
- / 转移至电子的 X 线能量随即转化为电子的动能。
- / 这些高能电子与物质中的其他电子相互作用，将其大部分能量积存在非常小的体积中。
- / 空气比释动能（物质中释放的动能，Kerma）是从非带电粒子传递到带电粒子的能量除以测量体积中的空气质量。
- / 空气比释动能单位为 J/kg，称为戈瑞 (Gray，Gy)。
- / X 线射束的空气比释动能 (K_a)（图 24）取决于电流时间乘积 (Q)、电压平方 (U^2)、到源距离的平方倒数 (d^{-2}) 和 X 线管常数 C，如下所示：

$$K_a = C \cdot \left(\frac{U}{100}\right)^2 \cdot \frac{Q}{d^2}$$

<!> 注意

空气比释动能在空气中的某个点确定，不考虑散射或射束尺寸。空气比释动能主要用于估计介入放射学中的峰值皮肤剂量（见下页）。在传统放射摄影中，因皮肤剂量远低于确定性效应阈值，其临床意义有限。

图 24

空气比释动能。

Entrance Skin Dose (ESD)

- The entrance skin dose (ESD) is the dose to a thin layer of skin as the X-rays reach the surface of the patient (Fig. 25).
- Backscattered radiations contribute to the ESD in addition to the primary radiation coming from the X-ray tube.
- ESD will therefore be larger by 15-30% than the air kerma at the patient surface.
- The ESD is especially important in prolonged or high dose-rate radiological examinations, such as in interventional procedures using fluoroscopy, because it is related to skin injury.
- The contribution of backscattered radiation to ESD is modelled by the backscatter factor (BSF).

$$ESD = BSF \cdot C \cdot \left(\frac{U}{100}\right)^2 \cdot \frac{Q}{FPD^2}$$

<!> ATTENTION

The BSF and the ESD depend on beam size and patient thickness.

The ESD is used in plain radiography to establish diagnostic reference levels (DRLs).

DRLs constitute a benchmark for the optimiszation of radiation protection in medical imaging using X-rays. The Nuclear Safety Agency regularly updates and publishes ESD recommendations.

> See eBook chapter on Radiation Biology and Radiation Protection

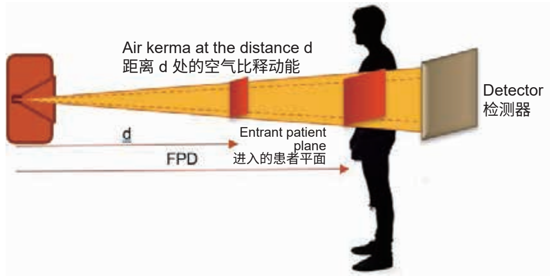

FIGURE 25

Entrance skin dose.

X-Ray Imaging

CHAPTER OUTLINE:

X 线成像

章节大纲：

入射皮肤剂量 (ESD)

- 入射皮肤剂量 (Entrance Skin Dose，ESD) 是当 X 线到达患者表面时皮肤薄层上的剂量（图 25）。
- 除了来自 X 线管的主要辐射外，背向散射辐射对 ESD 也有贡献。
- 因此，患者表面的 ESD 将比空气比释动能大 15%～30%。
- 入射皮肤剂量 (ESD) 在长时间或高剂量率的放射学检查（如透视引导的介入手术）中尤为关键，因其与皮肤损伤直接相关。
- 背向散射辐射对 ESD 的贡献可通过背向散射因子 (backscatter factor，BSF) 建模。

$$ESD = BSF \cdot C \cdot \left(\frac{U}{100}\right)^2 \cdot \frac{Q}{FPD^2}$$

<!> 注意

BSF 和 ESD 取决于射束尺寸和患者厚度。

ESD 在 X 线平片中被用于确定诊断参考水平 (diagnostic reference level，DRL)。

DRL 是使用 X 线进行医学成像时优化辐射防护的基准。核安全局定期更新和发布 ESD 建议。

> 请参阅《辐射生物学和辐射防护》电子书章节

图 25

入射皮肤剂量。

/ Dose Area Product (DAP)

/ The **dose area product (DAP)**, expressed in mGy x cm^2, is the product of the air kerma and the exposed area over a uniformly exposed area.

/ The DAP provides a good estimation of the **total radiation dose** delivered to a patient during a radiological procedure.

/ The DAP is **independent of the distance to focus**, which facilitates the comparison of measured DAP values in dose survey studies (Fig. 26).

/ The DAP is the most commonly used quantification parameter for **monitoring radiation dose** delivered to patients.

/ Radiographic and fluoroscopic systems are equipped with **DAP meters** which measure the DAP at the tube output for each radiological procedure.

<!> ATTENTION

The DAP meters at the tube output don't take into account the contribution of scattered radiation to patient dose.

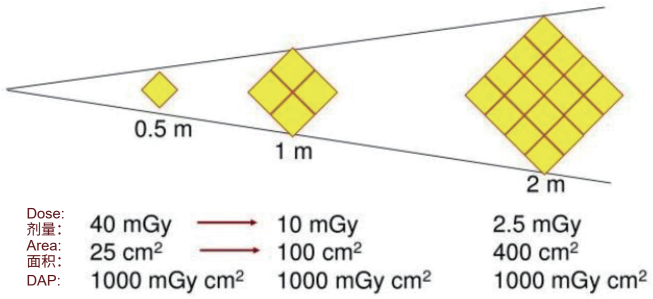

FIGURE 26

Invariance of DAP to the distance from the focus.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 剂量面积乘积 (DAP)

/ 剂量面积乘积 (Dose Area Product，DAP) 以 mGy × cm^2 表示，是空气比释动能与均匀暴露面积上暴露面积的乘积。

/ DAP 能够很好地估计放射程序期间对患者输出的**总辐射剂量**。

/ DAP **与至焦点距离无关**，有助于比较剂量调查研究中测量的 DAP 值（图 26）。

/ DAP 是**监测患者辐射剂量**最常用的定量参数。

/ 放射摄影和透视系统配有 **DAP 测量计**，可在每个放射程序的管输出处测量 DAP。

<!> 注意

管输出处的 DAP 测量计不考虑散射辐射对患者剂量的贡献。

图 26

DAP 不随焦点距离变化。

/ Diagnostic Reference Levels (DRL)

- The **dose reference level (DRL)** of a radiological examination (e.g., a chest X-ray) is the third quartile of the dose distribution determined from samples of patients (Fig. 27).
- The dose for an X-ray examination may vary depending on the **body mass index (BMI)** of the patient, the **type of detector**, the type of X-ray system and **its settings**.
- **National DRLs** have been established for standard radiology, computed tomography, and for image-guided and interventional procedures.

<!> **ATTENTION**

DRLs give an indication of the expected radiation dose received by an average-sized patient undergoing a given X-ray based imaging procedure.

DRLs are a tool to optimise medical imaging procedures using ionising radiation.

DRL are **not** dose limits.

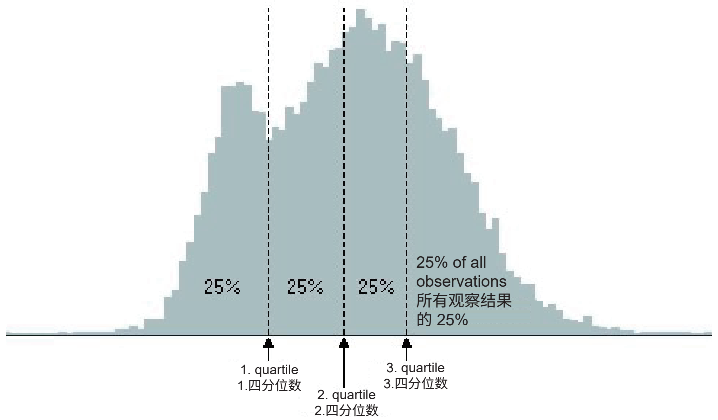

FIGURE 27

DRL is the third quartile of the dose distribution for a radiological examination obtained in a sample of patients.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 诊断参考水平 (DRL)

- 放射学检查（例如胸部 X 线检查）的剂量参考水平 (dose reference level，DRL) 是根据患者样本确定的剂量分布的第三四分位数（图 27）。
- X 线检查的剂量可能因患者的体重指数 (body mass index，BMI)、探测器类型、X 线系统类型及其设置而异。
- 已为标准放射学、计算机断层扫描以及图像引导和介入操作制定了国家 DRL。

<!> **注意**

DRL 可指示接受给定 X 线成像程序的平均体型患者所接受的预期辐射剂量。

DRL 是使用电离辐射优化医学成像程序的工具。

DRL 不是剂量限制。

图 27

DRL 是从患者样本中获得的放射学检查剂量分布的第三四分位数。

/ Image Quality

/ X-Ray Imaging

/ X 线成像

CHAPTER OUTLINE:

章节大纲：

/ 图像质量

/ Contrast

/ The contrast of a **radiological image quantifies** the difference of signal among tissues of different densities (Fig. 28).

/ The radiographic contrast of a structure is the product of two factors:

- / Difference in X-ray attenuation between tissues.
- / Difference in thickness between tissues.

/ The radiographic contrast decreases with

- / the mean energy of the X-ray beam (tube voltage, additional filtration),
- / the scatter fraction of the X-ray beam on the detector.

/ The contrast of a digital X-ray can be changed using image processing that changes the histogram of the image.

<!> ATTENTION

Display contrast can be changed by display window setting.

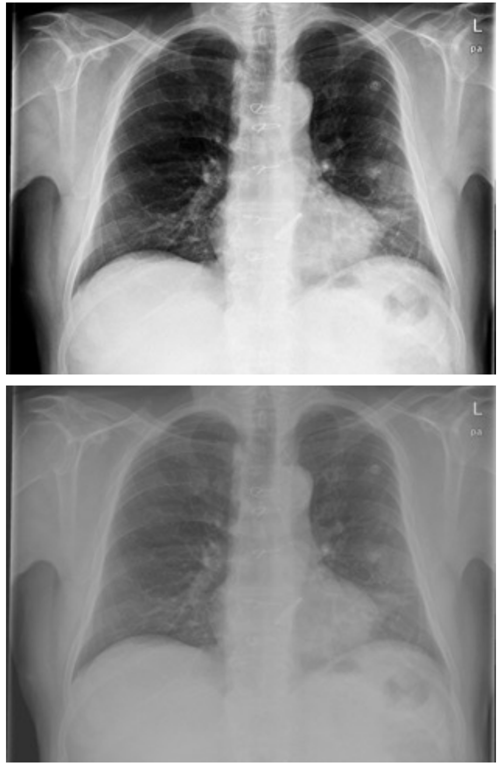

FIGURE 28

Chest X-ray. The same image. Top: high contrast. Bottom: Low contrast.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 对比度

/ 放射图像的对比度量化不同密度的组织之间的信号差异（图 28）。

/ 结构的放射摄影对比度是两个因素的乘积：

- / 组织之间的 X 线衰减差异。
- / 组织之间的厚度差异。

/ 放射摄影对比度随以下因素增加而降低

- / X 线射束的平均能量（管电压、附加过滤），
- / 探测器上 X 线射束的散射分数。

/ 数字 X 线的对比度可使用更改图像直方图的图像处理进行更改。

<!> 注意

可通过显示窗口设置更改显示对比度。

图 28

胸部 X 线检查。相同的图像。上：高对比度。下：低对比度。

/ Signal-to-Noise Ratio (SNR)

- The **signal-to-noise ratio (SNR)** of an image is the ratio between the signal and the noise.
- The **signal** is the mean pixel value, which is related to the number of X-rays converted into a signal by the detector.
- The **noise** is the level of random variations of pixel values around the mean pixel value, quantified by the standard deviation of pixel values in an homogeneous area.
- The SNR of an X-ray increases when increasing the detector dose, the pixel dose and the detective efficiency of the detector.
- The SNR can be increased using image processing that decreases the frequency bandwidth of the image.
- The SNR of an X-ray image is a compromise between
  - Patient dose (mAs and anatomical thickness).
  - Spatial resolution (pixel size and image processing).

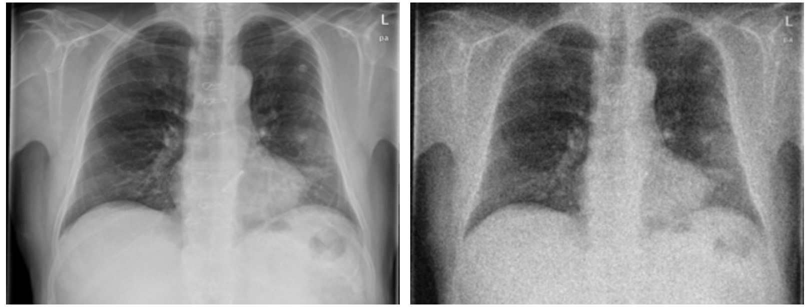

FIGURE 29

Chest X-ray. Same image. Left: high SNR. Right: Low SNR.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 信噪比 (SNR)

- 图像的信噪比 (Signal-to-Noise Ratio，SNR) 是信号与噪声之间的比值。
- 信号是平均像素值，反映探测器将 X 线转换为电信号的数量。
- 噪声是像素值在平均像素值附近的随机变化水平，通过均匀区域中像素值的标准偏差进行量化。
- X 线的 SNR 随探测器剂量、像素剂量和探测器探测效率的增加而增加。
- 可使用降低图像频率带宽的图像处理增加 SNR。
- X 线图像的 SNR 是以下因素的折中
  - 患者剂量（mAs 和解剖厚度）。
  - 空间分辨率（像素大小和图像处理）。

图 29

胸部 X 线检查。 相同的图像。左：高 SNR。右侧：低 SNR。

/ Spatial Resolution

- / The spatial resolution of an image **quantifies the sharpness of the signal in the image** (Fig. 30).
- / The spatial resolution of an X-ray decreases when increasing:
  - / the pixel size
  - / the magnification
  - / the focal spot size
  - / the irradiation time (motion blur)
- / The spatial resolution can be increased using image processing that increases the frequency bandwidth of the image.
- / The spatial resolution of an X-ray is a compromise with
  - / SNR (pixel size and image processing).

>|< **COMPARE**

A greater source-to-detector distance decreases the geometric blur but increases the exposure time and motion blur.

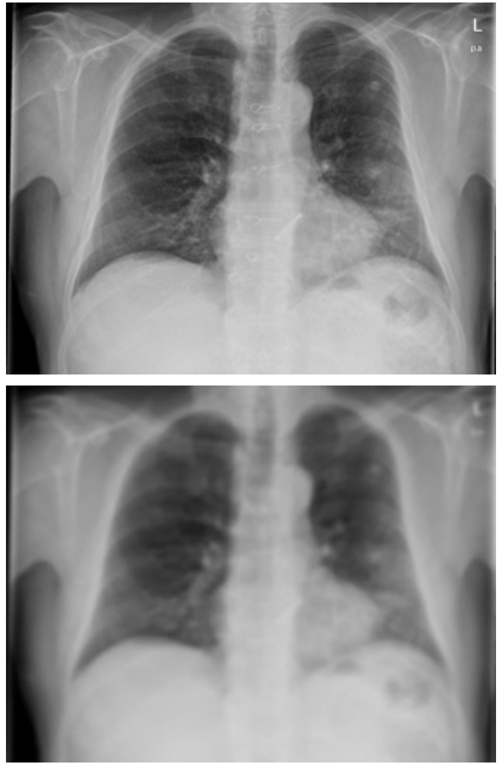

FIGURE 30

Chest X-ray. Top: high resolution. Bottom: Low resolution.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 空间分辨率

- / 图像的空间分辨率**量化图像中信号的锐度**（图 30）。
- / X 线的空间分辨率随以下因素增加而降低：
  - / 像素大小
  - / 放大倍率
  - / 焦斑尺寸
  - / 辐照时间（运动模糊）
- / 可使用增大图像频率带宽的图像处理来增加空间分辨率。
- / X 线的空间分辨率是以下因素的折中
  - / SNR（像素大小和图像处理）。

>|< **比较**

增大焦点 — 探测器距离虽可降低几何模糊，却需延长曝光时间，反而易引入运动模糊。

图 30

胸部 X 线检查。上：高分辨率。下：低分辨率。

/ Take-Home Messages

/ X-rays are high-frequency electromagnetic waves produced in an X-ray tube.

/ Conventional X-ray imaging modalities provide projections of the attenuating properties of tissues traversed by X-rays.

/ The voltage and the current time product set roughly the energy and the quantity of X-rays.

/ There are 3 outcomes of the passage of X-rays through matter: transmission, absorption and scatter.

/ Rejection of X-rays scattered in the patient is done by an anti-scatter grid or an air gap between the patient and the detector.

/ Radiological image formation results from the projection of the differential transmission of the X-rays transmitted through the different anatomic tissues.

/ Magnification and blur occur in X-ray imaging because the X-ray beam is divergent and spreads out from a focal spot of finite size.

/ Radiological digital detectors convert X-rays to electric signals.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 核心要点

/ X 线是在 X 线管中产生的高频电磁波。

/ 传统 X 线成像技术仅提供组织对X射线衰减特性的投影。

/ 电压和电流时间乘积大致设定了 X 线的能量和数量。

/ X 线穿过物质有 3 种结果：透射、吸收和散射。

/ 借助防散射滤线栅或患者-探测器间空气间隙，可抑制体内散射 X 线。

/ 放射影像是 X 线穿过不同解剖组织后差异透射的投影映射。

/ 由于 X 线自有限尺寸的焦斑呈发散状传播，成像必然伴随放大与模糊。

/ 放射学数字探测器将 X 线转换为电信号。

/ The air kerma is the dose to a point in the air in the X-ray beam and does not take into account scattering or beam size.

/ The entrance skin dose is the dose to a thin layer of skin at the entrant plane of the patient.

/ The dose area product is the product of the air kerma and the exposed area and gives an estimation of the radiation dose delivered to a patient during a radiological examination.

/ Three parameters define image quality: contrast, signal-to-noise ratio and spatial resolution.

>•< FURTHER KNOWLEDGE

/ The automatic exposure control (AEC) device controls the radiation dose reaching the detector by regulating the length of exposure.

/ The exposure index gives the user feedback about the detector dose of a radiography.

X-Ray Imaging

CHAPTER OUTLINE:

X线成像

章节大纲：

/ 空气比释动能是 X 线射束在空气中某个点的剂量，不考虑散射或射束尺寸。

/ 入射皮肤剂量是患者入射平面处皮肤薄层的剂量。

/ 剂量面积乘积是空气比释动能和暴露面积的乘积，可估计放射学检查期间患者的辐射剂量。

/ 三个参数决定图像质量：对比度、信噪比和空间分辨率。

>•< 进阶知识

/ 自动曝光控制 (automatic exposure control，AEC) 设备通过调节曝光长度来控制到达探测器的辐射剂量。

/ 曝光指数为用户提供放射摄影探测器剂量的反馈。

/ References

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/ Test Your Knowledge

/ X-Ray Imaging

/ X 线成像

CHAPTER OUTLINE:

章节大纲：

/ 知识测试

/ Test Your Knowledge

<?> QUESTION

1 What is the effective spot size?

- ☐ The area on the anode struck by electrons.
- ☐ The projection of the focal spot size on the image plane.
- ☐ The size of the electrons beam on the anode.
- ☐ The size of the filament selected in the cathode.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

1 有效焦斑尺寸是什么？

- ☐ 阳极上被电子撞击的面积。
- ☐ 焦斑大小在图像平面上的投影。
- ☐ 阳极上电子束的大小。
- ☐ 阴极中选择的灯丝尺寸。

/ Test Your Knowledge

<?> ANSWER

1 What is the effective spot size?

- □ The area on the anode struck by electrons.
- ■ The projection of the focal spot size on the image plane.
- □ The size of the electrons beam on the anode.
- □ The size of the filament selected in the cathode.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 回答

1 有效焦斑尺寸是什么？

- □ 阳极上被电子撞击的面积。
- ■ 焦斑大小在图像平面上的投影。
- □ 阳极上电子束的大小。
- □ 阴极中选择的灯丝尺寸。

/ Test Your Knowledge

<?> QUESTION

2 What is the role of the additional filtration of a X-ray tube?

- ☐ Cut off low-energy X-rays.
- ☐ Improve the radiological contrast.
- ☐ Shape a spatially homogenous X-ray beam.
- ☐ Stop the X-rays scattered in the X-ray tube window.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

2 X 线管的附加过滤有什么作用?

- ☐ 截断低能量 X 线。
- ☐ 提高放射对比度。
- ☐ 塑造空间均匀的 X 线射束。
- ☐ 停止 X 线管窗中散射的 X 线。

/ Test Your Knowledge

<?> ANSWER

2 What is the role of the additional filtration of a X-ray tube?

- ■ Cut off low-energy X-rays.
- ☐ Improve the radiological contrast.
- ☐ Shape a spatially homogenous X-ray beam.
- ☐ Stop the X-rays scattered in the X-ray tube window.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 回答

2 X 线管的附加过滤有什么作用？

- ■ 截断低能量 X 线。
- ☐ 提高放射对比度。
- ☐ 塑造空间均匀的 X 线射束。
- ☐ 停止 X 线管窗中散射的 X 线。

/ Test Your Knowledge

<?> QUESTION

3 What are characteristic X-rays?

- ☐ X-rays whose energy is characterised by the additional aluminium filter.
- ☐ X-rays whose energy is characterised by the anode material.
- ☐ X-rays whose energy is increased by multiple interactions in the anode.
- ☐ X-rays whose energy is increased by the additional aluminium filter.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

3 什么是特征 X 线?

- ☐ 能量由额外的铝过滤器表征的 X 线。
- ☐ 能量由阳极材料表征的 X 线。
- ☐ 能量因阳极的多重相互作用而增加的 X 线。
- ☐ 通过额外的铝过滤器增加能量的 X 线。

/ Test Your Knowledge

<?> ANSWER

3 What are characteristic X-rays?

- ☐ X-rays whose energy is characterized by the additional aluminium filter.
- ■ X-rays whose energy is characterised by the anode material.
- ☐ X-rays whose energy is increased by multiple interactions in the anode.
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/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 回答

3 什么是特征 X 线?

- ☐ 能量由额外的铝过滤器表征的 X 线。
- ■ 能量由阳极材料表征的 X 线。
- ☐ 能量因阳极的多重相互作用而增加的 X 线。
- ☐ 通过额外的铝过滤器增加能量的 X 线。

/ Test Your Knowledge

<?> QUESTION

4 Which is true about the probability of photoelectric effect?

- ☐ It increases with the electronic density of the material.
- ☐ It increases with the material density.
- ☐ It increases with the tube voltage.
- ☐ It increases with the X-ray energy.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

4 关于光电效应的概率，哪个是真的?

- ☐ 它随材料电子密度的增加而增加。
- ☐ 它随材料密度的增加而增加。
- ☐ 它随管电压的增加而增加。
- ☐ 它随 X 线能量的增加而增加。

/ Test Your Knowledge

<?> ANSWER

4 Which is true about the probability of photoelectric effect?

- ■ It increases with the electronic density of the material.
- ☐ It increases with the material density.
- ☐ It increases with the tube voltage.
- ☐ It increases with the X-ray energy.

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 回答

4 关于光电效应的概率，哪个是真的?

- ■ 它随材料电子密度的增加而增加。
- ☐ 它随材料密度的增加而增加。
- ☐ 它随管电压的增加而增加。
- ☐ 它随 X 线能量的增加而增加。

/ Test Your Knowledge

<?> QUESTION

5 What could be done to reduce the geometric blur of an X-ray?

- ☐ Choose a higher AEC setting.
- ☐ Decrease the exposure time.
- ☐ Increase the tube-to-detector distance.
- ☐ Use an anti-scatter grid.

CHAPTER OUTLINE:

章节大纲：

/ 知识测试

<?> 问题

5 如何减少 X 线的几何模糊？

- ☐ 选择更高的AEC 设置。
- ☐ 减少曝光时间。
- ☐ 增加管到探测器的距离。
- ☐ 使用防散射滤线栅。

/ Test Your Knowledge

<?> ANSWER

5 What could be done to reduce the geometric blur of an X-ray?

- ☐ Choose a higher AEC setting.
- ☐ Decrease the exposure time.
- ■ Increase the tube-to-detector distance.
- ☐ Use an anti-scatter grid.

/ X-Ray Imaging

/ X 线成像

/ 知识测试

<?> 回答

5 如何减少 X 线的几何模糊?

- ☐ 选择更高的 AEC 设置。
- ☐ 减少曝光时间。
- ■ 增加管到探测器的距离。
- ☐ 使用防散射滤线栅。

/ Test Your Knowledge

<?> QUESTION

6 A DAP is 1,000 $mGy.cm^2$ at 1 m from the X-ray tube. What will be at 2 m?

- ☐ 250 $mGy.cm^2$
- ☐ 500 $mGy.cm^2$
- ☐ 1,000 $mGy.cm^2$
- ☐ 4,000 $mGy.cm^2$

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

6 在距离 X 线管 1 m 处，DAP 为 1,000 $mGy.cm^2$。2 m 处是多少?

- ☐ 250 $mGy.cm^2$
- ☐ 500 $mGy.cm^2$
- ☐ 1,000 $mGy.cm^2$
- ☐ 4,000 $mGy.cm^2$

/ Test Your Knowledge

<?> ANSWER

6 A DAP is 1,000 mGy.cm² at 1 m from the X-ray tube. What will be at 2 m?

- ☐ 250 mGy.cm²
- ☐ 500 mGy.cm²
- ■ 1,000 mGy.cm²
- ☐ 4,000 mGy.cm²

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 回答

6 在距离 X 线管 1 m 处，DAP 为 1,000 mGy.cm²。2 m 处是多少?

- ☐ 250 mGy.cm²
- ☐ 500 mGy.cm²
- ■ 1,000 mGy.cm²
- ☐ 4,000 mGy.cm²

/ Test Your Knowledge

<?> QUESTION

7 How does the AEC control the dose?

- ☐ By focusing the energy of electrons in the X-ray tube.
- ☐ By modifying the intensity of X-rays during the irradiation time.
- ☐ By regulating the length of exposure.
- ☐ By setting a target tube current (mA).

/ X-Ray Imaging

CHAPTER OUTLINE:

/ X 线成像

章节大纲：

/ 知识测试

<?> 问题

7 AEC 如何控制剂量？

- ☐ 通过聚焦 X 线管中的电子能量。
- ☐ 通过在辐射时间内调整 X 线的强度。
- ☐ 通过调节曝光时间的长短。
- ☐ 通过设置目标管电流 (mA)。

/ Test Your Knowledge

<?> ANSWER

7 How does the AEC control the dose?

- ☐ By focusing the energy of electrons in the X-ray tube.
- ☐ By modifying the intensity of X-rays during the irradiation time.
- ■ By regulating the length of exposure.
- ☐ By setting a target tube current (mA).

/ X-Ray Imaging

/ X 线成像

/ 知识测试

<?> 回答

7 AEC 如何控制剂量？

- ☐ 通过聚焦 X 线管中的电子能量。
- ☐ 通过在辐射时间内调整 X 线的强度。
- ■ 通过调节曝光时间的长短。
- ☐ 通过设置目标管电流 (mA)。

/ Test Your Knowledge

<?> QUESTION

8 How could we increase the SNR of an X-ray?

- ☐ By choosing the large focus instead of the small focus.
- ☐ By decreasing the tube voltage.
- ☐ By increasing the AEC setting to +1.
- ☐ By reducing the pixel size.

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8 如何提高 X 线的 SNR?

- ☐ 通过选择大焦点而不是小焦点。
- ☐ 通过降低管电压。
- ☐ 通过将 AEC 设置增加到 +1。
- ☐ 通过降低像素大小。

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<?> ANSWER

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<?> QUESTION

9 Why is ESD larger than air kerma at the patient surface?

- ☐ Because ESD includes backscatter dose.
- ☐ Because ESD is not expressed in the same unit.
- ☐ Because ESD is not measured at the same distance from the X-ray source.
- ☐ Because ESD takes into account the radiosensitivity of the skin.

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9 为什么在患者表面 ESD 比空气比释动能大？

- ☐ 因为 ESD 包括背向散射剂量。
- ☐ 因为 ESD 不以同一单位表示。
- ☐ 因为未在与 X 线源相同的距离处测量 ESD。
- ☐ 因为 ESD 考虑皮肤的辐射敏感性。

/ Test Your Knowledge

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<?> QUESTION

10 What is the detector dose which corresponds to an EI = 250?

- ☐ 2.5 µGy
- ☐ 25 µGy
- ☐ 250 µGy
- ☐ 250 mGy

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