BVS/ABR Workshop
on dose related to multimodality imaging.
February 18th 2011 13h
Auditorium Kinsbergen – University Hospital Antwerp

Hybrid Imaging: CT dose related problems and some solutions

Peter Smeets, MD
UZGent
radiologie & medische beeldvorming
Universitair Ziekenhuis Gent

PET/CT

- **positron emission tomographic** (PET) scanner **+** **computed tomographic** (CT) scanner
- *coregistered* images
  - ***anatomic*** and ***functional*** information
  - in a ***single* study**

PET/CT

- clinical applications of PET/CT
  - mainly **oncology**
    - diagnosis and management
  - **other** indications:
    - neurology, cardiology
    - investigation of fever of unknown origin
    - inflammatory disease
    - …
- more people, live longer: more cancer
- much improved therapeutic results:
  ⇒ more people live longer with cancer
- ⇒ **increasing** demand for PET/CT
- ⇒ **more** combined PET/CT scanners installed in hospitals and clinics worldwide

Figure XII. Annual per caput effective dose (mSv) for the United States population in 1980 [M37]

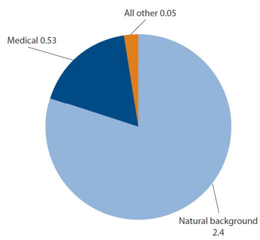
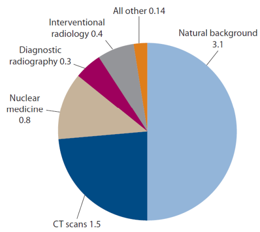


Figure XIII. Annual per caput effective dose (mSv) for the United States population in 2006 [N26]



PET/CT

- effective dose: *combination* of dose from **PET *and* CT**

  ⇒ PET/CT examinations result in **increased patient radiation exposure**
- **cancer risk** induced from radiation

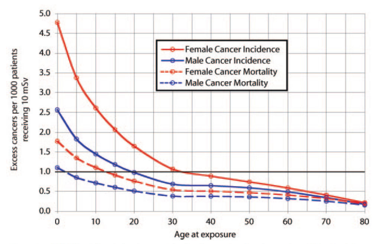


Figure 1: BEIR VII radiation-induced cancer risk estimation as a function of age and sex. Data extracted from tables 12D-1 and 12D-2 of BEIR VII (19). For a standardized U.S. population, BEIR VII predicts one excess cancer per 1000 patients receiving a 10-mSv exposure (thick horizontal line), approximately half of which are expected to be fatal. Interpolation between BEIR VII data points (○) was performed with exponential interpolation up to age 30 years, linear interpolation above age 30 years. A LAR of zero was used for age at exposure greater than 80 years.

Sodickson et al. ***Radiology:*** Volume 251: Number 1—April 2009

Whole-Body PET/CT Scanning: Estimation of Radiation Dose and Cancer Risk

CT Dose for Male and Female Patients with Protocols A, B, and C

Organ	Tissue Weighting Factor*	Protocol A Female Patients	Protocol A Male Patients	Protocol B Female Patients	Protocol B Male Patients	Protocol C Female Patients	Protocol C Male Patients
Gonad	0.08	8.8	8.4	19.0	20.4	27.0	27.4
Colon	0.12	7.8	8.4	22.1	18.6	31.0	29.3
Stomach	0.12	7.4	7.6	19.4	19.2	26.0	26.2
Lung	0.12	6.7	6.8	17.3	16.6	25.2	24.8
Bone marrow	0.12	6.0	6.0	17.4	17.5	21.1	21.2
Breast	0.12	5.7	7.3	13.9	19.0	19.1	25.3
Thyroid	0.04	10.6	10.1	27.3	27.1	37.5	36.4
Liver	0.04	8.5	8.0	20.9	19.8	29.9	28.3
Esophagus	0.04	7.6	7.5	19.8	18.7	28.3	27.2
Bladder	0.04	6.4	6.2	15.3	14.3	21.9	20.8
Skin	0.01	7.0	6.9	17.7	18.0	25.3	25.3
Bone surface	0.01	6.0	6.0	14.1	17.4	19.1	21.2
Brain	0.01	7.7	8.4	20.3	20.0	29.0	29.9
Kidney	0.013	8.0	7.9	20.2	19.5	28.1	27.4
Spleen	0.013	6.9	7.6	19.4	19.6	25.5	26.7
Adrenal gland	0.013	8.0	7.1	19.3	18.1	30.8	28.2
Uterus or prostate	0.013	7.3	7.4	19.3	17.4	27.1	25.9
Pancreas	0.013	7.2	7.1	19.0	17.7	27.1	25.8
Small intestines	0.013	7.3	6.5	17.2	14.8	25.6	22.2
Large intestines	0.013	7.5	6.8	17.4	15.5	25.4	22.9
Thymus	0.013	7.5	7.2	17.3	18.5	24.0	24.2
Muscle	0.013	6.4	6.7	15.6	14.3	21.2	20.8
Heart	0.013	7.0	7.9	18.4	20.2	25.3	28.1
Lens	. . .	8.1	8.3	18.4	18.6	27.2	27.3
Effective dose†	. . .	7.22	7.42	18.56	18.57	25.68	25.95

Note.—Unless otherwise specified, data are in millisieverts.
* As recommended in ICRP publication 103 (10), in which no weighting factor is defined for the lens of the eye.
† Sum of organ doses weighted by tissue weighting factor.

Parameters of the Three CT Protocols

CT Protocol	Tube Potential (kV)	Rotation Time (sec)	Section Thickness (mm)	Pitch	Tube Current (mA)	Noise Level*
A	120	0.5	0.625	0.984	100–300	20
B	120	0.5	0.625	0.984	250	. . .
C	140	0.5	0.625	0.984	150–350	3.5

* With use of AutomA.

PET Dose

Organ	Dose Coefficient (μSv/MBq)*	Organ Dose (mSv)	Tissue Weighting Factor†
Gonads	13.5	5.0	0.08
Lung	10	3.7	0.12
Stomach	11	4.1	0.12
Colon	13	4.8	0.12
Bone marrow	11	4.1	0.12
Esophagus	11	4.1	0.04
Thyroid	10	3.7	0.04
Liver	11	4.1	0.04
Bladder	160	59.2	0.04
Breast	6.8	2.5	0.12
Bone surface	11	4.1	0.01
Skin	8	3.0	0.01
Brain	11	4.1	0.01
Thymus	11	4.1	0.013
Spleen	11	4.1	0.013
Adrenal gland	11	4.1	0.013
Pancreas	11	4.1	0.013
Kidney	11	4.1	0.013
Large intestines	11	4.1	0.013
Small intestines	11	4.1	0.013
Uterus	21	7.8	0.013
Muscle	11	4.1	0.013
Heart	11	4.1	0.013

Note.—The overall effective dose (the sum of organ doses weighted by the tissue weighting factor) was 6.23 mSv.
* As recommended in ICRP publication 80 (9).
† As recommended in ICRP publication 103 (10).

FDG activity of 370 MBq

Bingsheng Huang ea, *2009 Radiology, 251, 166-174*
using a 64-detector CT system (Discovery PET/CT; GE Healthcare)

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Bone marrow	0.12	6.0	6.0	17.4	17.5	21.1	21.2
Breast	0.12	5.7	7.3	13.9	19.0	19.1	25.3
Thyroid	0.04	10.6	10.1	27.3	27.1	37.5	36.4
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Uterus or prostate	0.013	7.3	7.4	19.3	17.4	27.1	25.9
Pancreas	0.013	7.2	7.1	19.0	17.7	27.1	25.8
Small intestines	0.013	7.3	6.5	17.2	14.8	25.6	22.2
Large intestines	0.013	7.5	6.8	17.4	15.5	25.4	22.9
Thymus	0.013	7.5	7.2	17.3	18.5	24.0	24.2
Muscle	0.013	6.4	6.7	15.6	14.3	21.2	20.8
Heart	0.013	7.0	7.9	18.4	20.2	25.3	28.1
Lens	. . .	8.1	8.3	18.4	18.6	27.2	27.3
Effective dose†	. . .	7.22	7.42	18.56	18.57	25.68	25.95

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PET Dose

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Gonads	13.5	5.0	0.08
Lung	10	3.7	0.12
Stomach	11	4.1	0.12
Colon	13	4.8	0.12
Bone marrow	11	4.1	0.12
Esophagus	11	4.1	0.04
Thyroid	10	3.7	0.04
Liver	11	4.1	0.04
Bladder	160	59.2	0.04
Breast	6.8	2.5	0.12
Bone surface	11	4.1	0.01
Skin	8	3.0	0.01
Brain	11	4.1	0.01
Thymus	11	4.1	0.013
Spleen	11	4.1	0.013
Adrenal gland	11	4.1	0.013
Pancreas	11	4.1	0.013
Kidney	11	4.1	0.013
Large intestines	11	4.1	0.013
Small intestines	11	4.1	0.013
Uterus	21	7.8	0.013
Muscle	11	4.1	0.013
Heart	11	4.1	0.013

Note.—The overall effective dose (the sum of organ doses weighted by the tissue weighting factor) was 6.23 mSv.
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using a 64-detector CT system (Discovery PET/CT; GE Healthcare)

PET/CT

- total effective doses of combined PET/CT:
  - calculated by summing the effective doses of **CT and PET**
    - **13 - 31** mSv for *female* patients
    - **13 - 32** mSv for *male* patients
- **CT component contributed 54% – 81% of the total combined dose**

Bingsheng Huang ea, *2009 Radiology, 251, 166-174*
using a 64-detector CT system (Discovery PET/CT; GE Healthcare)

PET/CT

- total effective dose from *each* PET/CT study

= 5 to 13 times worldwide average effective dose from background radiation over 1 year

(estimated to be about 2.4 mSv)

Medical Physics and Informatics • Clinical Perspective

AJR FOCUS ON:

How Effective Is Effective Dose as a Predictor of Radiation Risk?

Cynthia H. McCollough[1]
Jodie A. Christner
James M. Kofler

OBJECTIVE. This article discusses the relatively recent adoption of effective dose in medicine that allows comparison between different imaging techniques, and describes the principles, pitfalls, and potential value of effective dose. The medical community must use this information wisely, realizing that effective dose represents a generic *estimate* of risk from a given procedure for a generic model of the human body.

CONCLUSION. Effective dose is not the risk for any one individual. Due to the inherent uncertainties and oversimplifications involved, effective dose should not be used for epidemiologic studies or for estimating population risks.

[1]All authors: Department of Radiology, Mayo Clinic, 200 First St., SW, Rochester, MN 55905. Address correspondence to C. H. McCollough (mccollough.cynthia@mayo.edu).

AJR 2010; 194:890–896

0361–803X/10/1944–890

“risk”

- negligible, < 0.1 mSv
- minimal, 0.1–1 mSv
- very low, 1–10 mSv
- low, 10–100 mSv

- Martin CJ. Effective dose: how should it be applied to medical exposures? *Br J Radiol* 2007; 80:639–647

– *whether cancer is a risk of **low-dose** radiation is still **unproven**, as there have not been any epidemiologic studies to date to support this*

– *there are no experimental data to support the linear no-threshold extrapolation for low-dose risk estimation*

United Nations

Report of the United Nations Scientific Committee on the Effects of Atomic Radiation

Fifty-sixth session (10-18 July 2008)

Chernobyl accident

- "The 1986 accident at the Chernobyl nuclear power plant in the former Soviet Union was the **most severe** such accident in the history of civilian nuclear power."
- "The accident caused the **largest uncontrolled radio active release** into the environment ever recorded for any civilian operation; large quantities of radioactive substances were released into the atmosphere for about 10 days. The radioactive cloud created by the accident dispersed over the **entire northern hemisphere**."
- "Two radionuclides, the short-lived **iodine-131** (with a half-life of 8 days) and the long-lived **caesium-137** (with a half-life of 30 years), were particularly significant because of the radiation dose they delivered to the public."
- "However, the doses delivered were quite different for the two radionuclides: the **thyroid doses from iodine-131 ranged up to several grays** within a few weeks after the accident, while the whole-body doses from caesium-137 ranged up to a few hundred millisieverts over the following few years."

Chernobyl accident

- "The contamination of fresh milk with iodine-131 and the lack of prompt countermeasures led to **high thyroid doses**, particularly among children, in the former Soviet Union."
- "Aside from the emergency workers, several hundred thousand people were involved in recovery operations but, apart from indications of an increase in incidence of leukaemia and of cataracts among those who received higher doses, **there is to date no consistent evidence of health effects that can be attributed to radiation exposure."**
- "A substantial increase in thyroid cancer incidence among persons exposed to the accident-related radiation as children or adolescents in 1986 (attributed to drinking milk contaminated with iodine-131) has been observed in Belarus, Ukraine and four of the more affected regions of the Russian Federation. Up to 2005 "only" 15 cases had proved fatal."
- "Among the general public, **to date there has been no consistent evidence of any other health effect that can be attributed to radiation exposure**."

Chernobyl accident

- "Aside from the emergency workers, several hundred thousand people were involved in recovery operations but, apart from indications of an increase in incidence of leukaemia and of cataracts among those who received higher doses, **there is to date no consistent evidence of health effects that can be attributed to radiation exposure."**
- "Among the general public, **to date there has been no consistent evidence of any other health effect that can be attributed to radiation exposure**."

PET/CT

- PET/CT **scanning protocols should be optimized** for reducing **dose** and its associated **cancer risk**
  - risk-benefit ratios should be carefully weighed prior to every study
  - especially important
    - when clinical utility is less well established or is based on anecdotal evidence
    - when PET/CT is used in **younger patients**

PET/CT

- cancer risks from radiation may be of **less** impact in patients known to **have cancer**
- ***however:***
  - information is still of interest and relevant to patient education
  - patients with cancer often undergo multiple PET/CT examinations for response assessment and treatment monitoring
  - survival rates are markedly improved

Estimated Number and Collective Effective Doses from Radiologic and Nuclear Medicine Procedures in the United States for 2006

Type of Procedure	No. of Procedures in Millions	Percentage of Total No. of Procedures	Collective Effective Dose (person-sievert)	Percentage of Collective Dose from Procedures	Per-Capita Dose (mSv)
Diagnostic radiographic and fluoroscopic studies*	293	74	100 000	11	0.33
Interventional procedures	17	4	128 000	14	0.43
CT scanning	67	17	440 000	49	1.47
Nuclear medicine studies	18	5	231 000	26	0.77
Total	395	100	899 000	100	3.01

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Nuclear medicine studies	18	5	231 000	26	0.77
Total	395	100	899 000	100	3.01

Estimated Collective Effective Dose from Various Sources in the United States for Selected Years

Source	Dose for 1980–1982*	Dose for 2006†
All	678	1660
Natural background‡	552	720
Medical procedures	124	899
Radiologic procedures§	92	668
Radiographic and fluoroscopic procedures	88.3	100
CT scanning	3.7	440
Interventional procedures	4.2	128
Dental radiographic examinations	NA	2.5
Nuclear medicine studies	32	231
Occupational exposures	2.0	1.4
Nuclear power	0.136	0.1
Consumer products and miscellaneous origins	. . .	39

Note.—The collective effective dose was based on a dose of 1000 person-sievert. NA = not available.
* Data are from reference 8 and are for a population of 230 million.
† Data are from reference 14 and are for a population of 300 million.
‡ Using UNSCEAR value for natural background, from reference 15.
§ Includes CT and interventional procedures.

Estimated Numbers of Radiologic and Nuclear Medicine Procedures for Selected Years in the United States

Type of Procedure	1950*	1964†	1970‡	1980–1982§	2006‖
Radiologic procedures#	. . .	. . .	. . .	180	377
Radiographic and fluoroscopic studies	25	109	136	177	293
CT scanning	. . .	. . .	. . .	3.3 (2–3.5)**	67
Interventional procedures	. . .	. . .	. . .	. . .	17
Dental radiographic examinations	. . .	54	67	101††	500‡‡
Nuclear medicine studies	. . .	. . .	. . .	7	18

Note.—Data are numbers of procedures in millions except as otherwise indicated.

Mettler et al. ***Radiology:*** Volume 253: Number 2—November 2009
SPECIAL REPORT: U.S. and Worldwide Radiology and Nuclear Medicine

Effective Doses for Adults from Various Nuclear Medicine Examinations

Examination*	Effective Dose (mSv)	Administered Activity (MBq)†	Effective Dose (mSv/MBq)‡
Brain (^{99m}Tc-HMPAO–exametazime)	6.9	740	0.0093
Brain (^{99m}Tc-ECD–Neurolite)	5.7	740	0.0077
Brain (^{18}F-FDG)	14.1	740	0.019
Thyroid scan (sodium iodine 123)	1.9	25	0.075 (15% uptake)
Thyroid scan (^{99m}Tc-pertechnetate)	4.8	370	0.013
Parathyroid scan (^{99m}Tc-sestamibi)	6.7	740	0.009
Cardiac stress-rest test (thallium 201 chloride)	40.7	185	0.22
Cardiac rest-stress test (^{99m}Tc-sestamibi 1-day protocol)	9.4	1100	0.0085 (0.0079 stress, 0.0090 rest)
Cardiac rest-stress test (^{99m}Tc-sestamibi 2-day protocol)	12.8	1500	0.0085 (0.0079 stress, 0.0090 rest)
Cardiac rest-stress test (Tc-tetrofosmin)	11.4	1500	0.0076
Cardiac ventriculography (^{99m}Tc-labeled red blood cells)	7.8	1110	0.007
Cardiac (^{18}F-FDG)	14.1	740	0.019
Lung perfusion (^{99m}Tc-MAA)	2.0	185	0.011
Lung ventilation (xenon 133)	0.5	740	0.00074
Lung ventilation (^{99m}Tc-DTPA)	0.2	1300 (40 actually inhaled)	0.0049
Liver-spleen (^{99m}Tc–sulfur colloid)	2.1	222	0.0094
Biliary tract (^{99m}Tc-disofenin)	3.1	185	0.017
Gastrointestinal bleeding (^{99m}Tc-labeled red blood cells)	7.8	1110	0.007
Gastrointestinal emptying (^{99m}Tc-labeled solids)	0.4	14.8	0.024
Renal (^{99m}Tc-DTPA)	1.8	370	0.0049
Renal (^{99m}Tc-MAG3)	2.6	370	0.007
Renal (^{99m}Tc-DMSA)	3.3	370	0.0088
Renal (^{99m}Tc-glucoheptonate)	2.0	370	0.0054
Bone (^{99m}Tc-MDP)	6.3	1110	0.0057
Gallium 67 citrate	15	150	0.100
Pentreotide (^{111}In)	12	222	0.054
White blood cells (^{99m}Tc)	8.1	740	0.011
White blood cells (^{111}In)	6.7	18.5	0.360
Tumor (^{18}F-FDG)	14.1	740	0.019

* DMSA = dimercaptosuccinic acid, DTPA = diethylenetriaminepentaacetic acid, ECD = ethyl cysteinate dimer, ^{18}F = fluorine 18, FDG = fluorodeoxyglucose, HMPAO = hexamethylpropyleneamine oxime, ^{111}In = indium 111, MAA = macroaggregated albumin, MAG3 = mercaptoacetyltriglycine, MDP = methylene diphosphonate, ^{99m}Tc = technetium 99m.
† Recommended ranges vary, although most laboratories tend to use the upper end of suggested ranges.
‡ From reference 74.

SPECIAL REPORT: Effective Doses in Radiology and Nuclear Medicine Mettler et al. ***Radiology:*** Volume 248: Number 1—July 2008

TABLE 1
^{18}F-FDG Radiation Dosimetry for Adults and Children

Patient	Intravenously administered activity, MBq/kg (mCi/kg)	Organ receiving the largest radiation dose, mGy/MBq (rads/mCi)	Effective dose, mSv/MBq (rems/mCi)
Adult	370–740 (10–20)	Bladder, 0.16* (0.59)	0.019 (0.070)
Child (5 y old)	5.18–7.4 (0.14–0.20)	Bladder, 0.32† (1.2)	0.050 (0.18)

*Voiding interval, 3.5 h. Changes in bladder wall dose are approximately linear with changes in voiding interval; therefore, for a voiding interval of 2.0 h, dose to bladder wall would change by a factor of 2/3.5.
†Voiding interval, 2.0 h.
Data are from International Commission on Radiological Protection. *Radiation Dose to Patients from Radiopharmaceuticals*. St. Louis, MO: Elsevier; 2000:49. ICRP publication 80.

740 * 0.019 = 14.06 mSv

Delbeke et al. JOURNAL OF NUCLEAR MEDICINE • Vol. 47 • No. 5 • May 2006

Adult Effective Doses for Various CT Procedures

Examination	Average Effective Dose (mSv)	Values Reported in Literature (mSv)
Head	$\boxed{2}$	0.9–4.0
Neck	$\boxed{3}$	. . .
Chest	$\boxed{7}$	4.0–18.0
Chest for pulmonary embolism	15	13–40
Abdomen	$\boxed{8}$	3.5–25
Pelvis	$\boxed{6}$	3.3–10
Three-phase liver study	15	. . .
Spine	6	1.5–10
Coronary angiography	16	5.0–32
Calcium scoring	3	1.0–12
Virtual colonoscopy	10	4.0–13.2

SPECIAL REPORT: Effective Doses in Radiology and Nuclear Medicine Mettler et al. ***Radiology:*** Volume 248: Number 1—July 2008


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Oxford Journals › Medicine › Annals of Oncology › Volume 17, Issue 1 › Pp. 117-122.

Is CT scan still necessary for staging in Hodgkin and non-Hodgkin lymphoma patients in the PET/CT era?

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Combined PET and low-dose, noncontrast CT scanning obviates the need for additional diagnostic contrast-enhanced CT scans in patients undergoing staging or restaging for lymphoma

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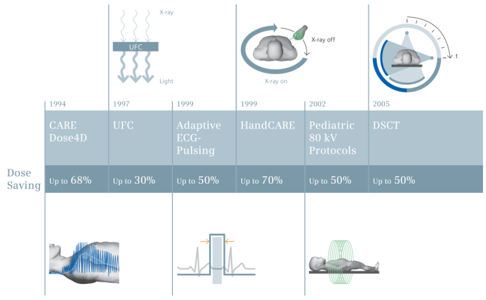
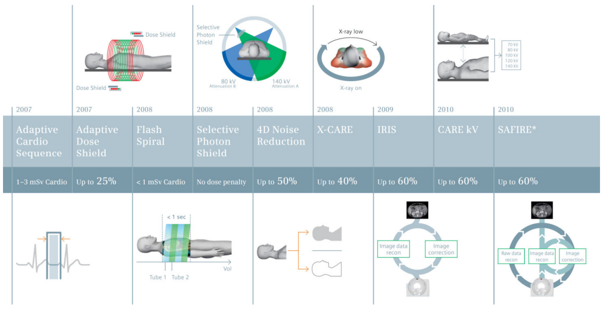




Iterative Reconstruction

- approach was the one first used by Hounsfield !
- large variety of algorithms:
  - each starts with an *assumed image*,
  - *computes* projections from the image,
  - *compares* the original projection data and
  - *updates* the image based upon the difference between the *calculated* and the *actual* projections

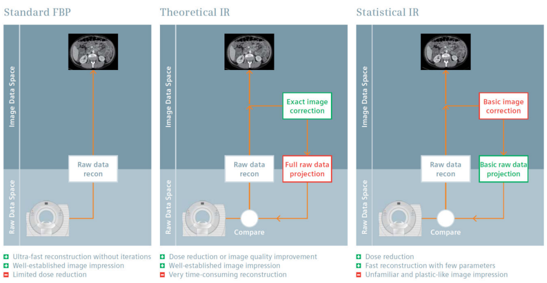
Iterative Reconstruction

- image generation process
- includes a "correction loop“
  - sectional images calculated in stages by gradual approximation to actual density distribution
    - system makes **assumption** about density distribution of tissue slices to be examined and calculates *output image*
    - synthetic projection data are generated from this *output image*
    - compared to actual, "real" raw measuring data
    - if they don't match, system will calculate a corresponding *correction* image to correct the output image
  - in a next **step**, the system will again synthesize the projection data and compare them to the measured raw data
  - **iteration** continues until a specified abort criterion is met
  - after this process, corrected image shows improved spatial image resolution in high-contrast regions, while image noise in low-contrast areas is reduced

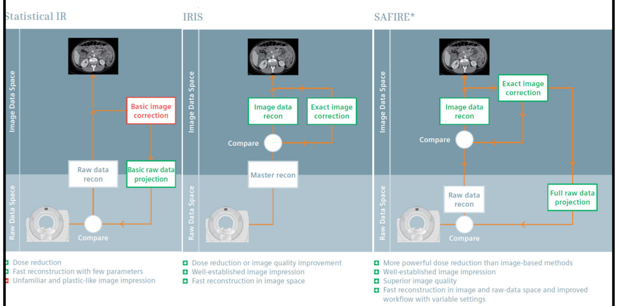
Iterative Reconstruction

- ***GE***
  - Adaptive Statistical Iterative Reconstruction (**ASIR**)
  - Model-Based Iterative Reconstruction (**MBIR**)
- ***Siemens***
  - Iterative Reconstruction in Image Space (**IRIS**)
  - Sinogram-AFfirmed Iterative Reconstruction (**Safire)**
- ***Philips***
  - iDose
- ***Toshiba***
  - AIDR

Iterative Reconstruction



Iterative Reconstruction



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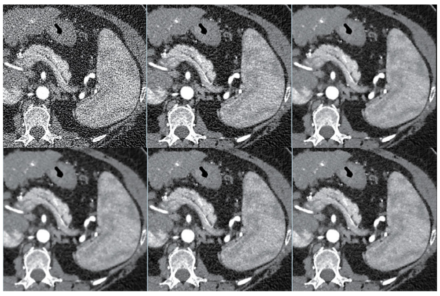
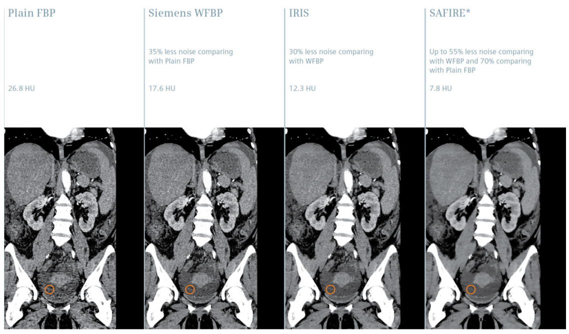
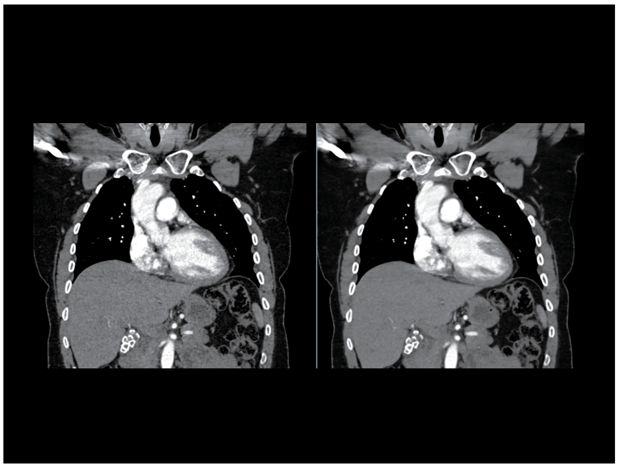
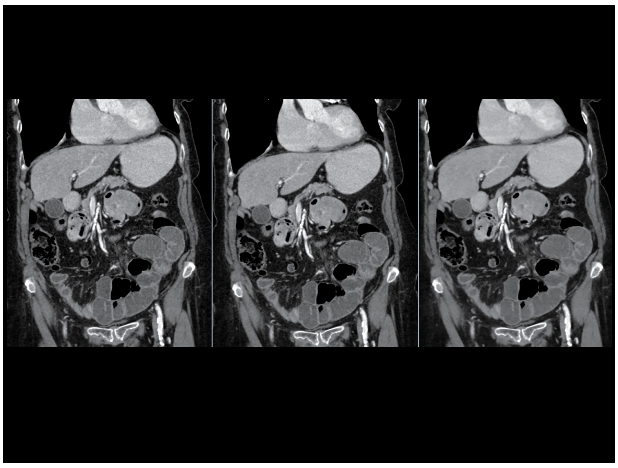
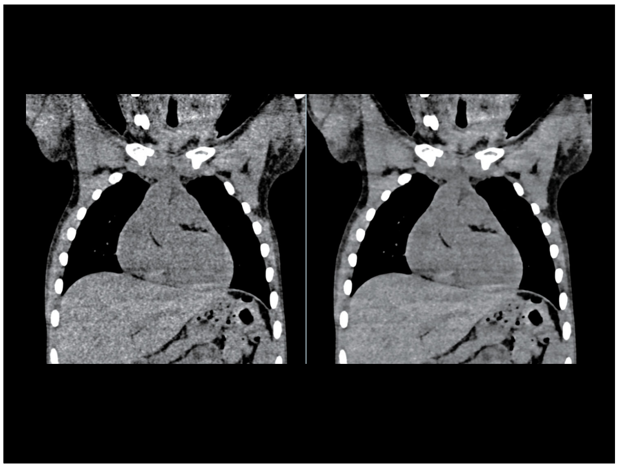


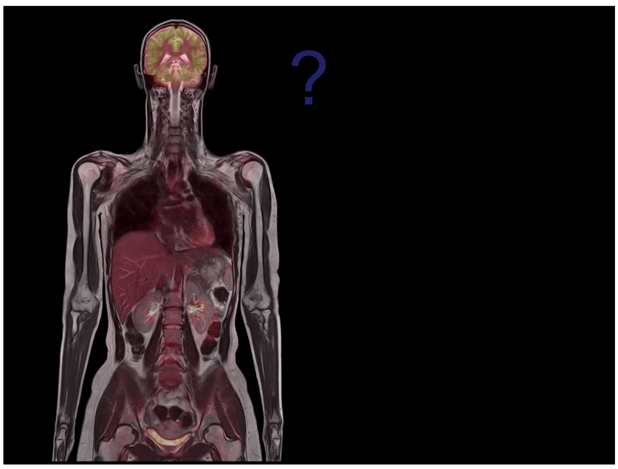
Iterative Reconstruction

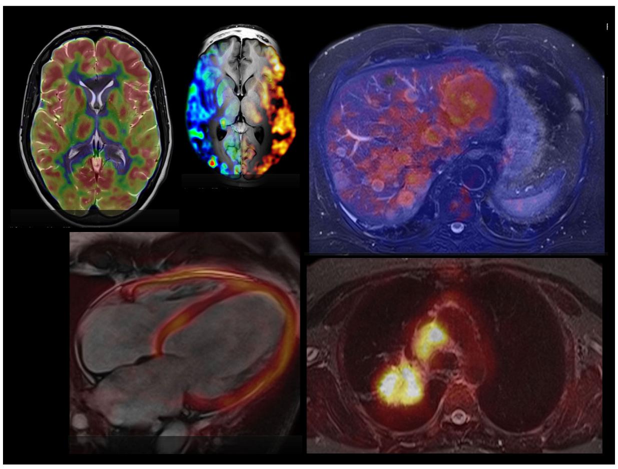


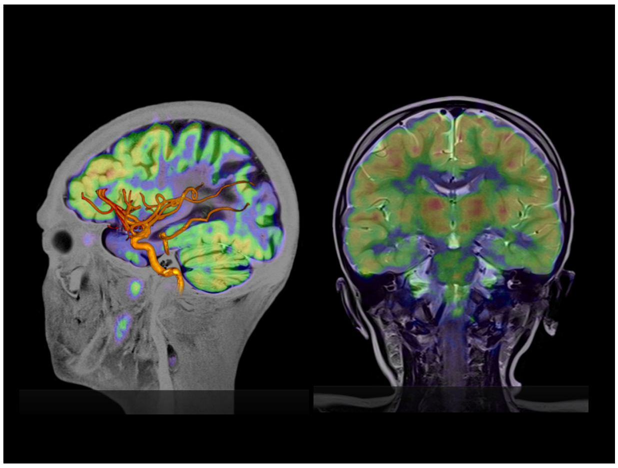


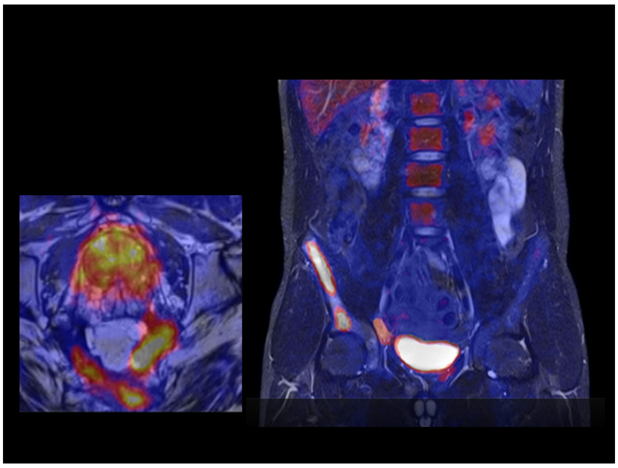


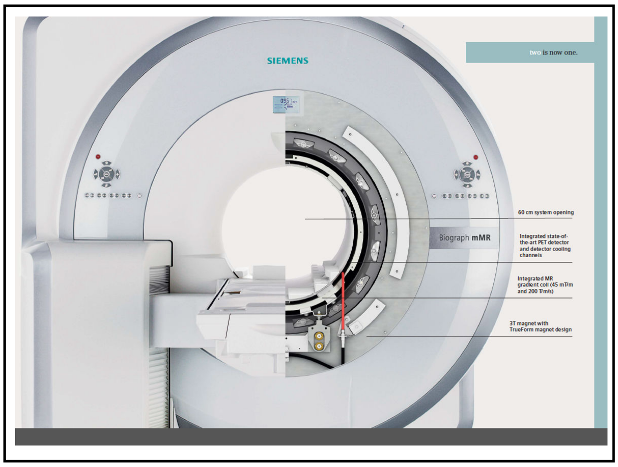


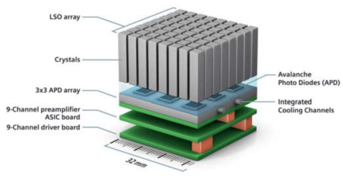









SIEMENS
two is now one.
60 cm system opening
Biograph mMR
Integrated state-of-the-art PET detector and detector cooling channels
Integrated MR gradient coil (45 mT/m and 200 T/m/s)
3T magnet with TrueForm magnet design


LSO array
Crystals
3x3 APD array
9-Channel preamplifier ASIC board
9-Channel driver board
Avalanche Photo Diodes (APD)
Integrated Cooling Channels
32 mm