Adjusting kV to Improve Image Quality or Reduce Radiation Dose

120 kV
CTDIvol =
24.5 mGy

80 kV
CTDIvol =
5.2 mGy

J. G. Fletcher, MD
Professor of Radiology
CT Clinical Innovation Center, Department of Radiology
Mayo Clinic, Rochester MN

DISCLOSURES

Research Support:

Siemens Healthcare

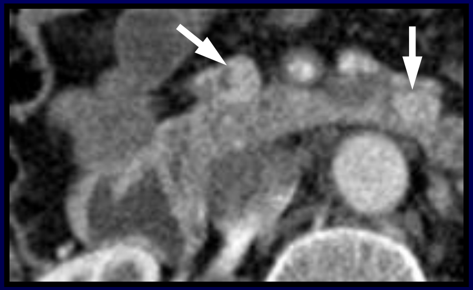
Off Label Usage

None

Background

- Majority of abdominal CT scans: 120 kV
- It is possible to reduce to 80-90 kV*
- Benefits of low-kV CT:
  - Radiation dose reduction**
  - Increased contrast provides increased conspicuity to enhancing lesions and structures ***

80 kV

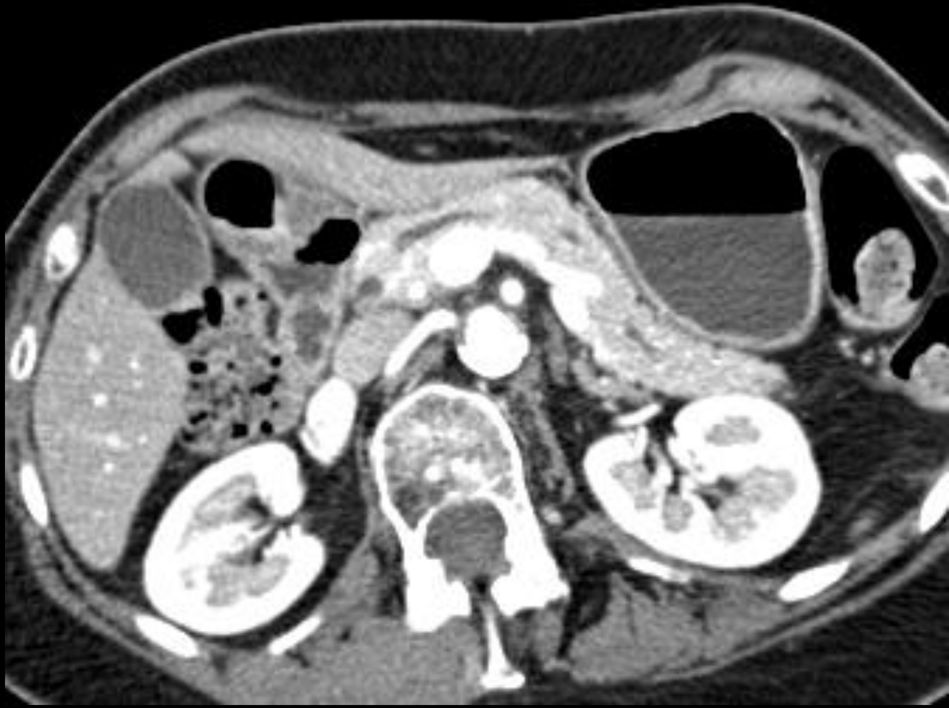


120 kV

*Funama, et al., Radiology 2005
*Nakayama, et al., Radiology 2005
**Ende, et al., Invest Radiol 1999
**Huda, et al., Med Phys 2004
***Nakayama, et al. AJR 2006
*** Macari, et al. AJR 2010

120 kV

80 kV



Lower-kV Benefits –

Increased Iodine Contrast

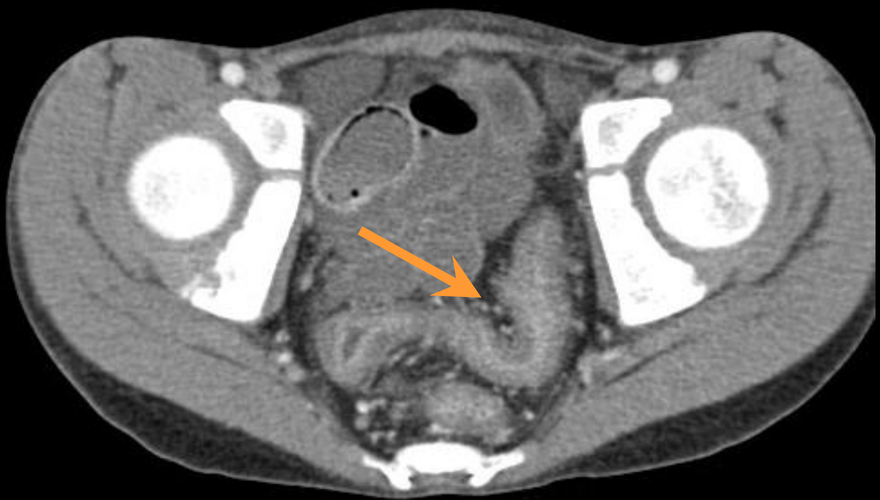
140 kV

80 kV

Lower-kV Benefits – Increased Iodine Contrast

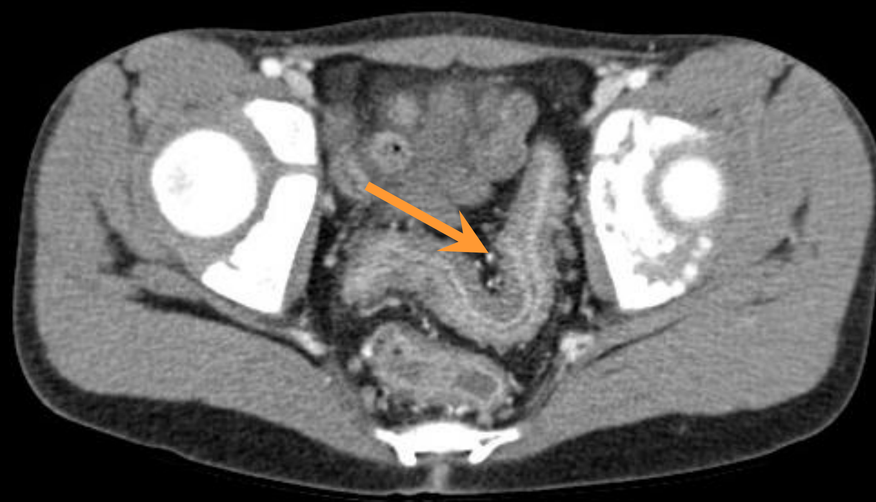
Yu et al. Radiographics 2011; 31(3):835-48.

120 kV



$CTDI_{vol}$=5.18 mGy

80 kV



$CTDI_{vol}$=3.98 mGy

Lower-kV Benefits – Reduced Radiation Dose

140 kV

80 kV

Lower-kV Risks –
Increased Noise or Artifacts

The appropriateness of using lower-kV is highly dependent on patient size and diagnostic task

Overview

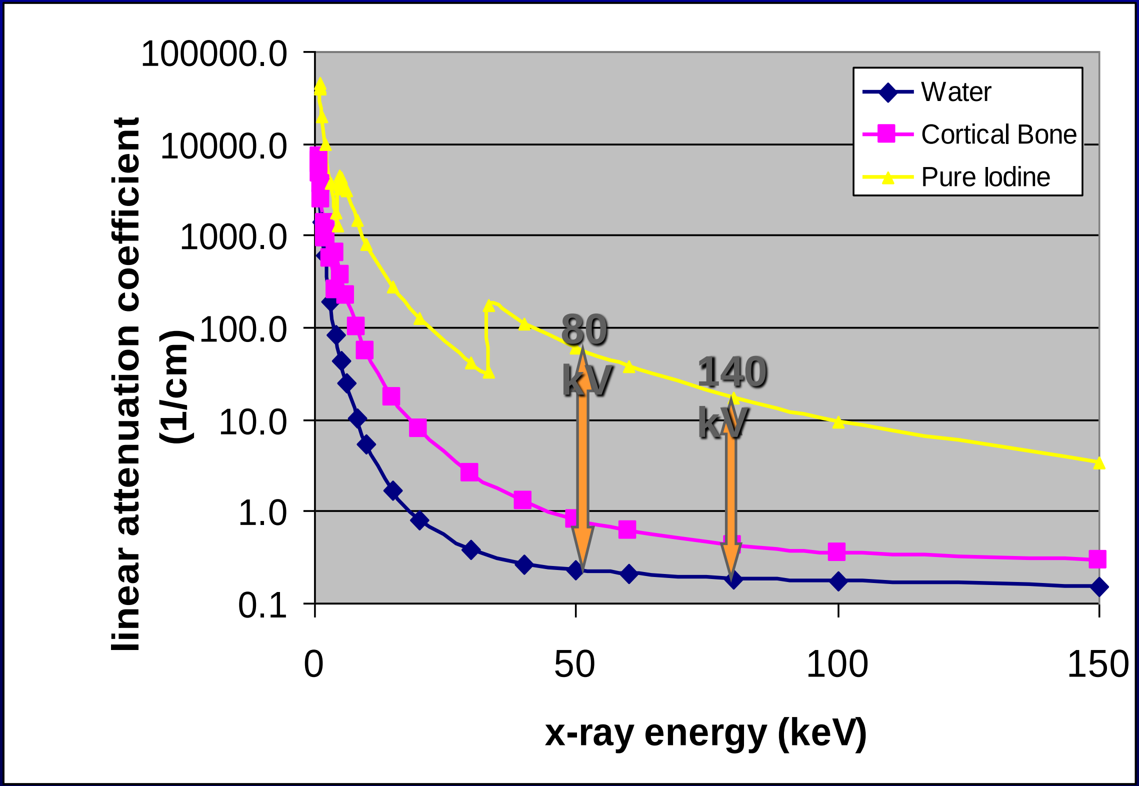
- How does kV affect iodine enhancement and noise?
- How does patient size affect this relationship?
- Who is going to benefit from low kV imaging?
- How can I safely pick lower kV imaging without sacrificing diagnostic image quality?
- How can I integrate lower kV imaging into my practice?
- How do lower kV images look different?
- Future of lower kV imaging

How does kV affect ***iodine*** *enhancement?*

- Iodine att'n at 80 kV twice that of 140 kV
- Relative to iodine att'n at 120 kV
  - 70% higher at 80 kV
  - 25% higher at 100 kV

Yu et al. Radiographics 2011; 31(3):835-48.

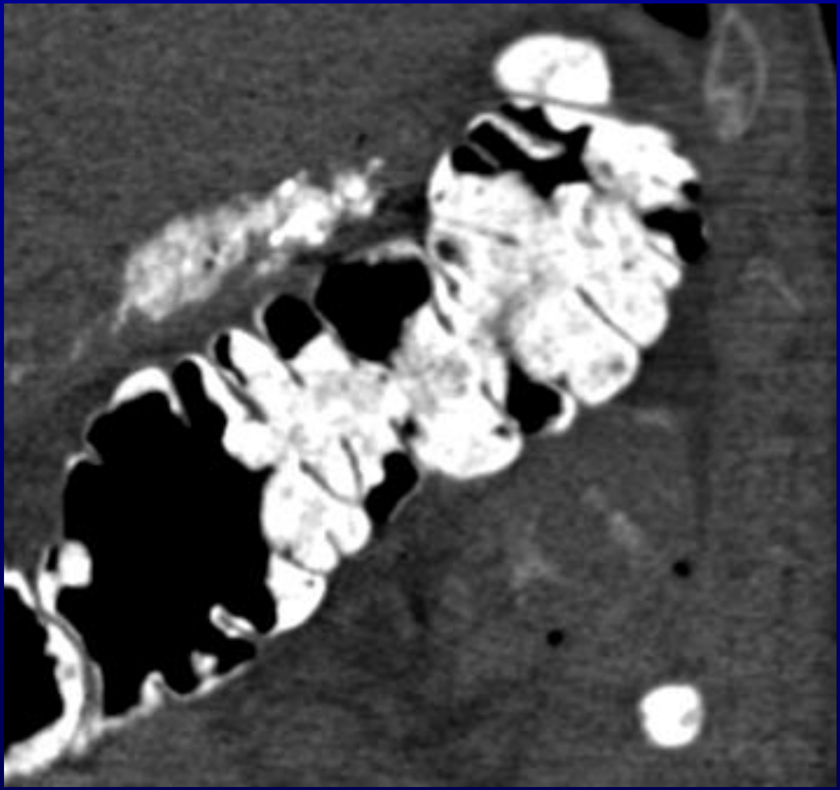
*How does kV affect **water** enhancement?*



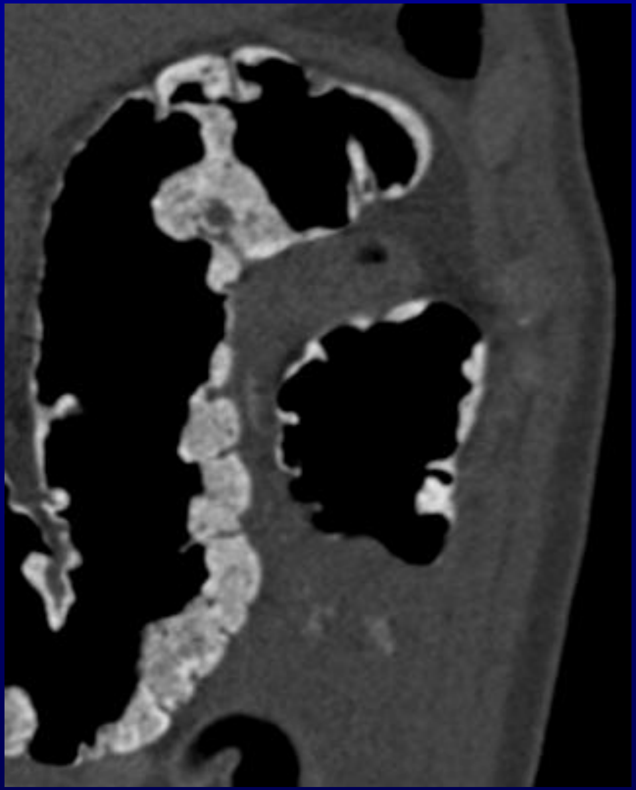
- Relative contrast changes only hold for high atomic number substances
  - Iodine, barium
  - *NOT* water, soft tissue, calcium

Yu et al. Radiographics 2011; 31(3):835-48.

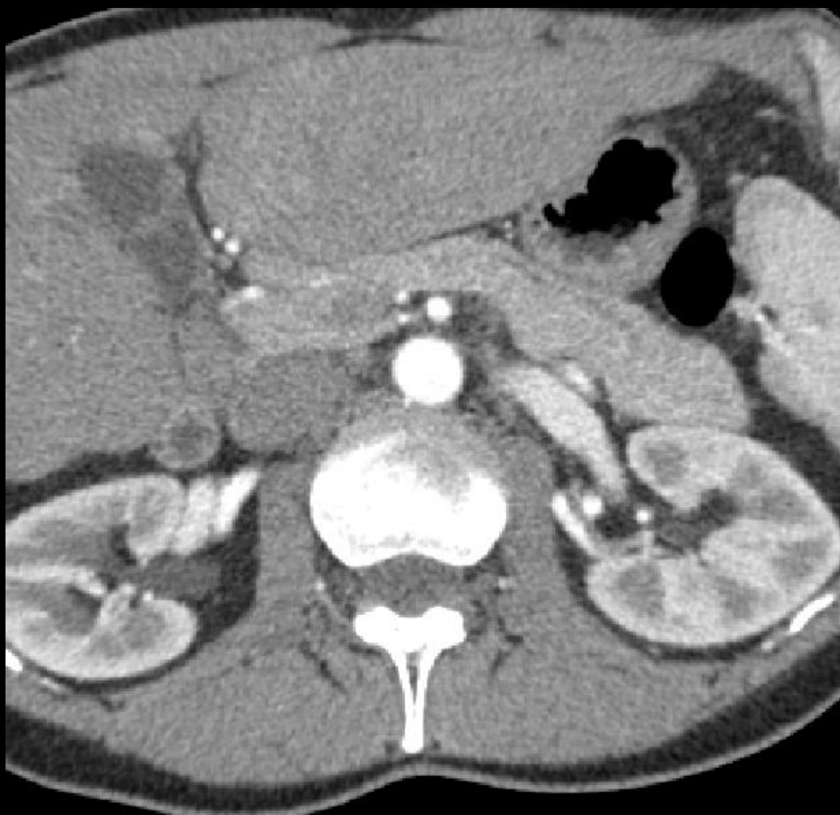
How does kV affect iodine enhancement?



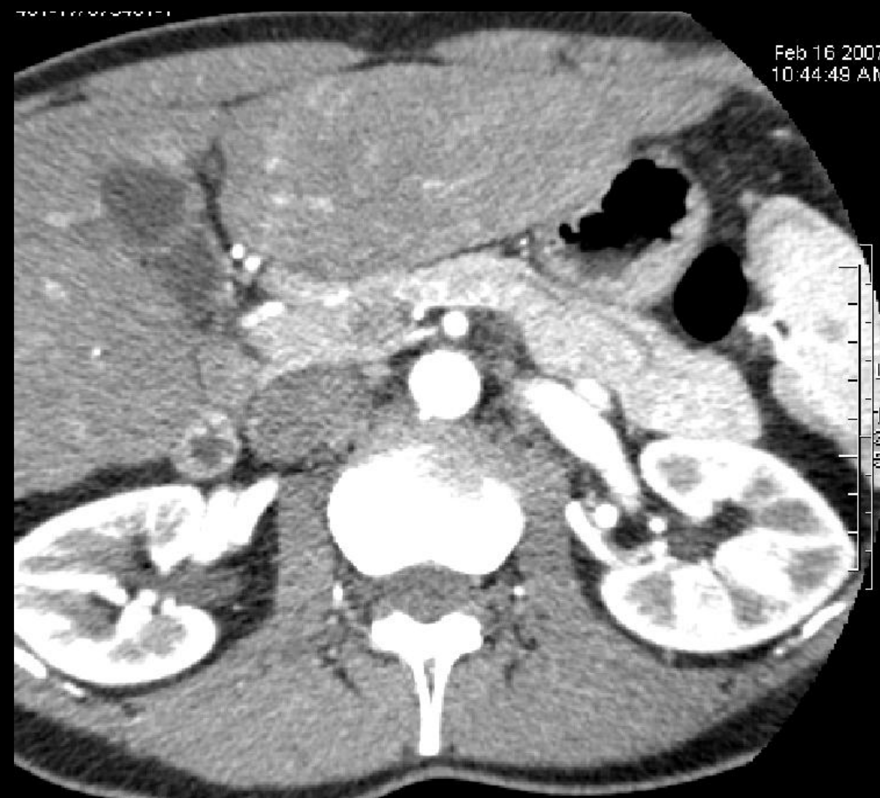
80 kV
1193 HU



120 kV
695 HU

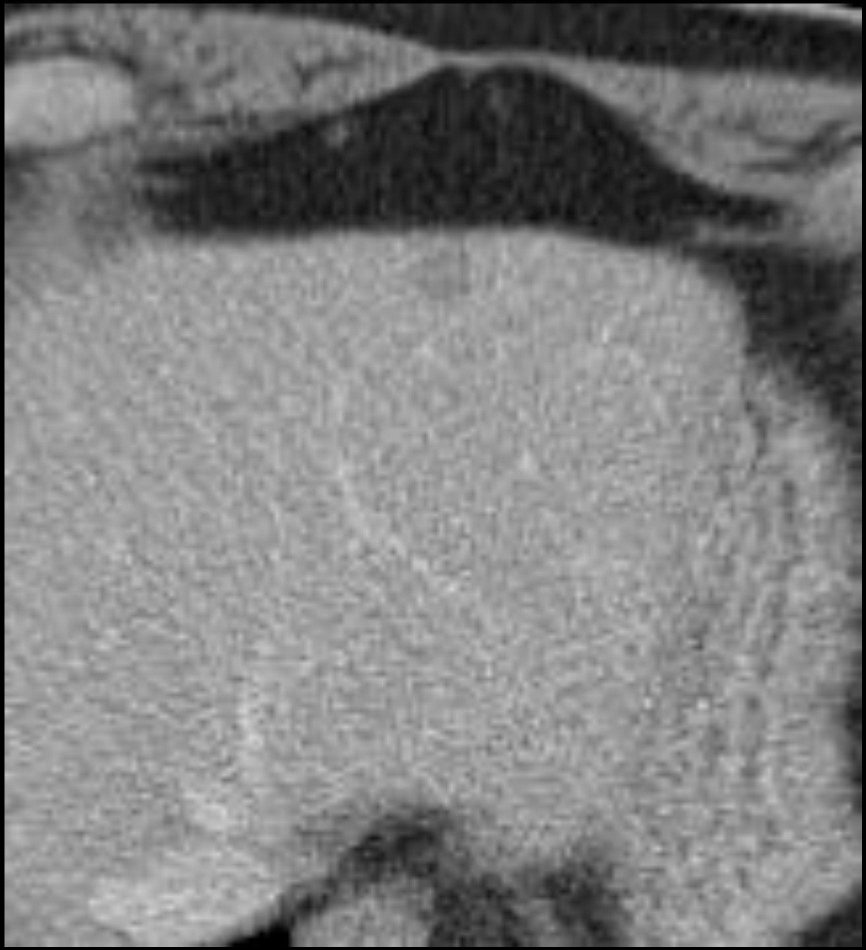


140 kV

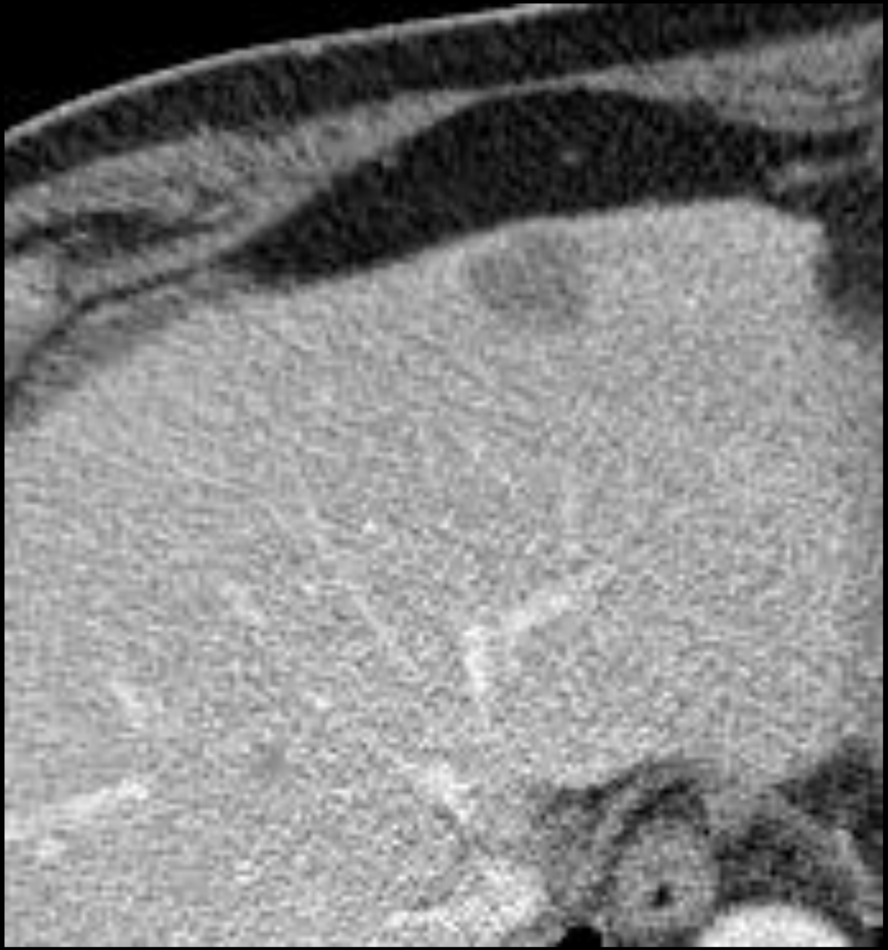


80 kV

Relative Contrast Differences due to Iodine Also Increase at Low kV



120 kV



100 kV

Relative Contrast Differences due to Iodine Also Increase at Low kV

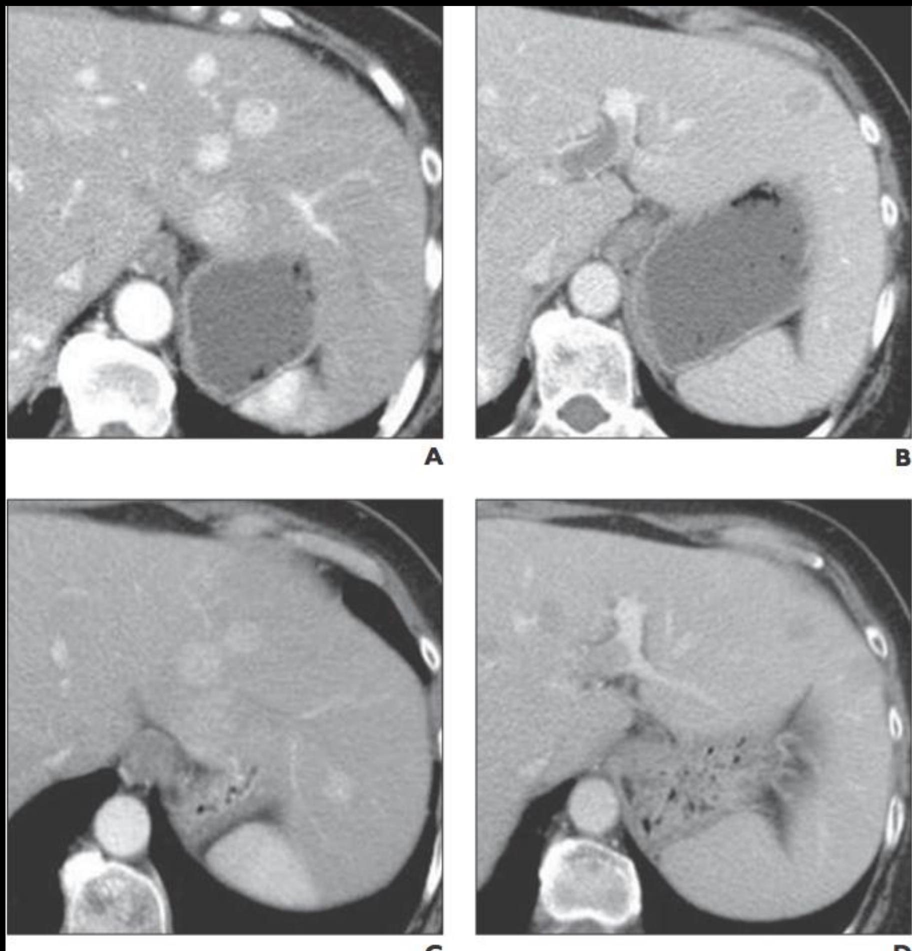
140 kV

80 kV

Improved Disease Conspicuity

Macari M et al. AJR 2010

Relative Contrast Differences due to Iodine Also Increase at Low kV



80 kV

120 kV

Improved Disease Conspicuity

Yanaga et al. AJR 2011

Original Research

Hepatocellular Carcinoma in Patients Weighing 70 kg or Less: Initial Trial of Compact-Bolus Dynamic CT With Low-Dose Contrast Material at 80 kVp

Yumi Yanaga[1]
Kazuo Awai[2]
Takeshi Nakaura[1]
Daisuke Utsunomiya[1]
Yoshinori Funama[1]
Shuji Date[2]
Yasuyuki Yamashita[1]

Yanaga Y, Awai K, Nakaura T, et al.

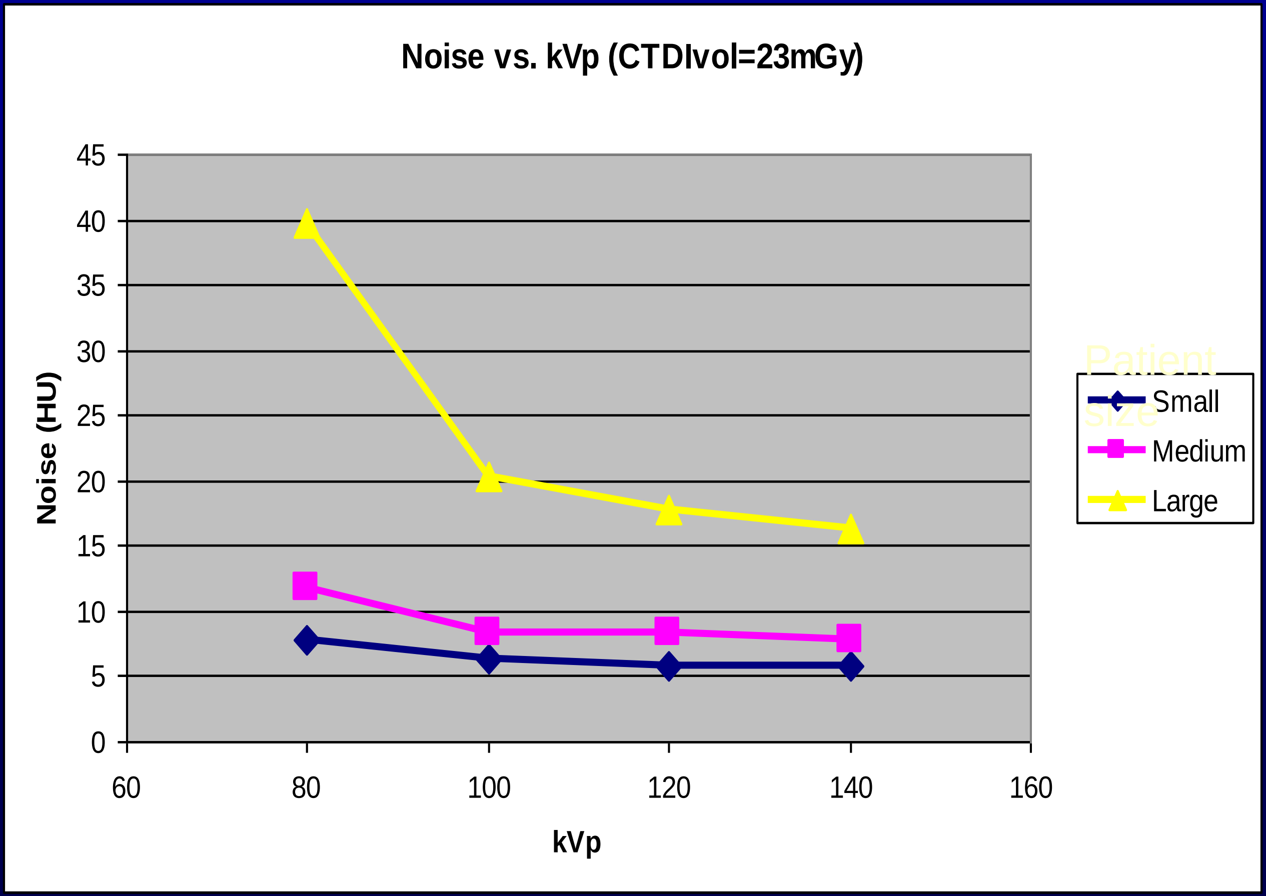
OBJECTIVE. The purpose of this study was to compare the diagnostic capability of hepatic dynamic CT with low-dose contrast material (420 mg I/kg body weight) at 80 kVp with that of the same modality performed with standard-dose contrast material at 120 kVp.

SUBJECTS AND METHODS. We randomly assigned 111 patients (50 women, 61 men; mean age, 69.1 years) with known or suspected hepatocellular carcinoma and a body weight of 70 kg or less to one of two protocols. In the 80-kVp protocol, the contrast material (444 mg I/kg body weight) was delivered over 15 seconds at a tube voltage of 80 kVp. In the 120-kVp protocol, a contrast dose of 600 mg I/kg was delivered over 30 seconds at 120 kVp. Of the 111 patients, 38 had hypervascular hepatocellular carcinoma. Using the Mann-Whitney U test, we compared the two protocols for the contrast-to-noise ratio of the tumors (difference between tumor attenuation and liver attenuation divided by noise in the liver) and the figure of merit (square of contrast-to-noise ratio divided by effective dose) of the tumors during the arterial phase of imaging. Effective doses also were compared.

RESULTS. The contrast-to-noise ratio of the tumors was significantly higher with the 80-kVp than with the 120-kVp protocol (median, 5.3 vs 4.2; $p = 0.04$). The figure of merit also was significantly higher with the 80-kVp than with the 120-kVp protocol (10.2 vs 5.3, $p = 0.02$). The effective dose was significantly lower with the 80-kVp than with the 120-kVp protocol (2.97 vs 3.41 mSv, $p < 0.01$).

CONCLUSION. With 80-kVp acquisition, the contrast-to-noise ratio and figure of merit of tumors during the arterial phase improved despite the lower contrast dose and radiation exposure.

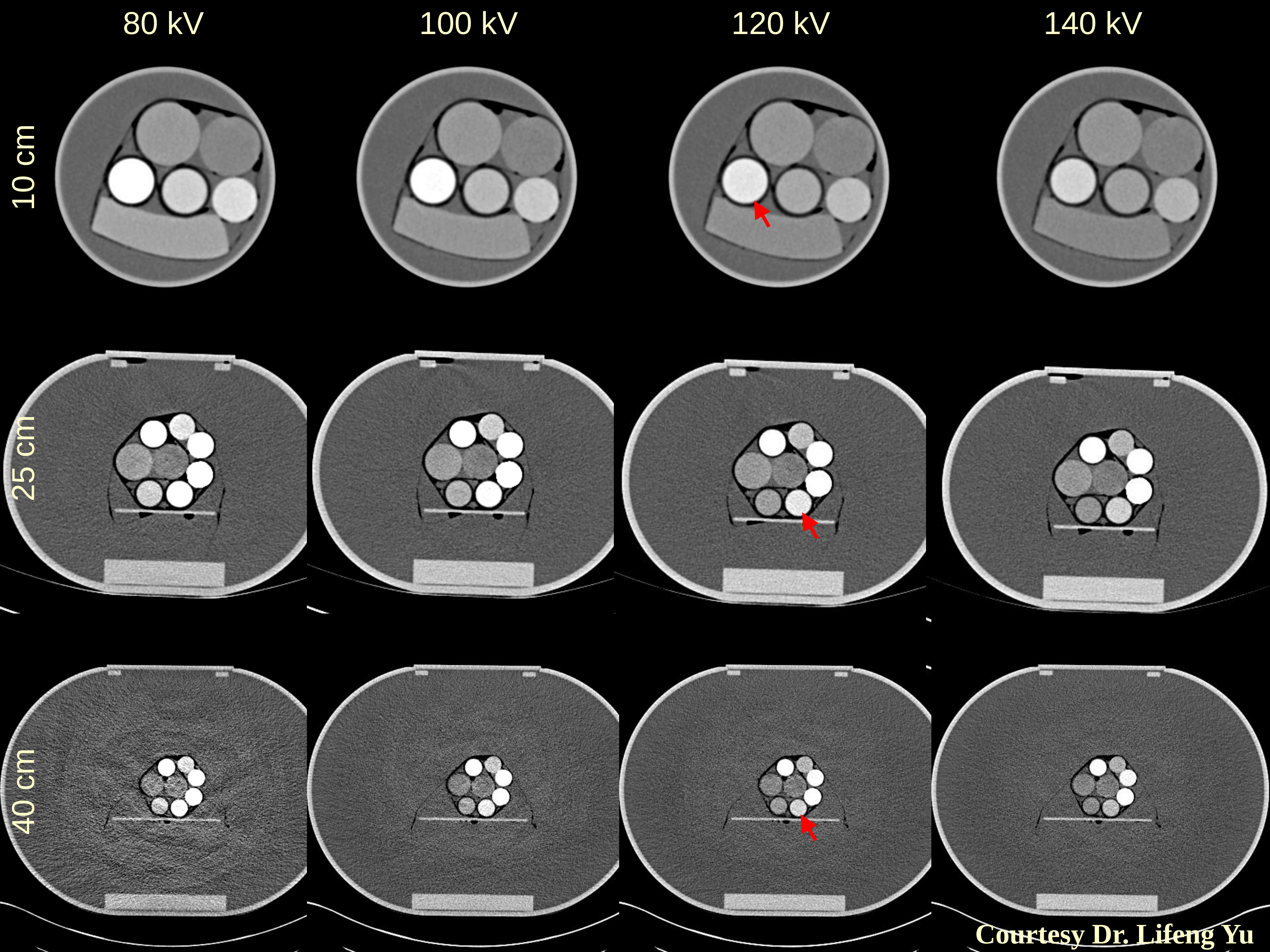
How does kV affect iodine noise?



For large patients, lower kV imaging can result in excessive beam hardening and other artifacts

Yu et al. Radiographics 2011; 31(3):835-48.

80 kV imaging with excessive artifacts limiting diagnostic quality



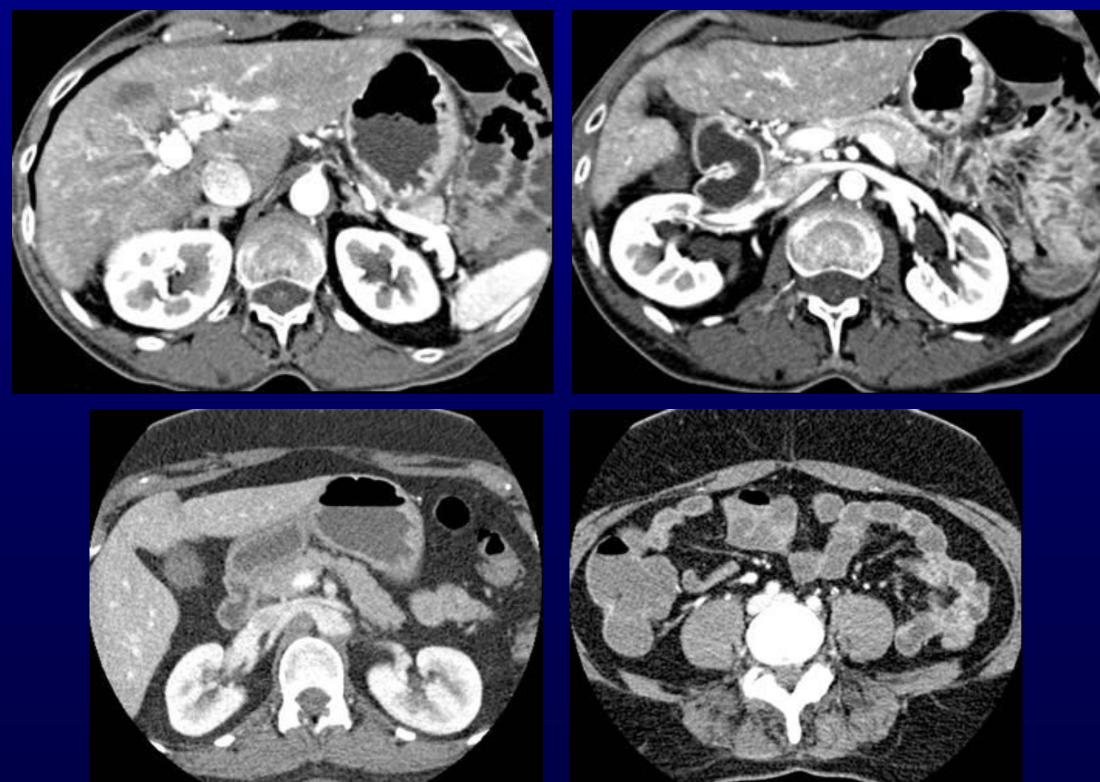
Courtesy Dr. Lifeng Yu

Low kV Imaging: Maintaining Image Quality

- Issue is noise (patient size)
  - Organ of interest
  - Measurements of size

Guimaraes et al. Radiology 2010; 2010 Dec;257(3):732-42

- 116 pts undergoing 80 kV CT
- 2 – 3 mm thick images
- IQ, artifact, confidence
- Multiple pt size measures



Association of Patient Size with Unacceptability

	Odds Ratio	p-value
14 x 1.2 mm		
Liver	**2.5**	**0.005**
Pancreas	**1.9**	**0.014**
Kidneys	**1.2**	**0.42**
Ileum	**1.4**	**0.11**
64 x 0.6 mm		
Liver	**1.8**	**0.005**
Pancreas	**2.0**	**0.014**
Kidneys	**4.8**	**0.42**
Ileum	**1.7**	**0.11**

Association of Patient Size with Unacceptability

cm	14 x 1.2 mm	64 x 0.6 mm
	≥ 90% Sensitivity	≥ 90% Sensitivity
Liver	**36**	**33**
Pancreas	**35**	**34**
Kidney	**36***	**37**
Ileum	**35***	**35**

Dimension cut-offs (cm) that would achieve **≥90%** sensitivity and **≥80%** sensitivity for prediction of an unacceptable exam

*** Likely underestimated due to small # of unacceptable cases (n=2 or 3)**

Association of Patient Size with Unacceptability

- Lateral width the best predictor of acceptable image quality

  < 36 cm => 80 kV imaging acceptable

  < 41 cm => 100 kV imaging acceptable

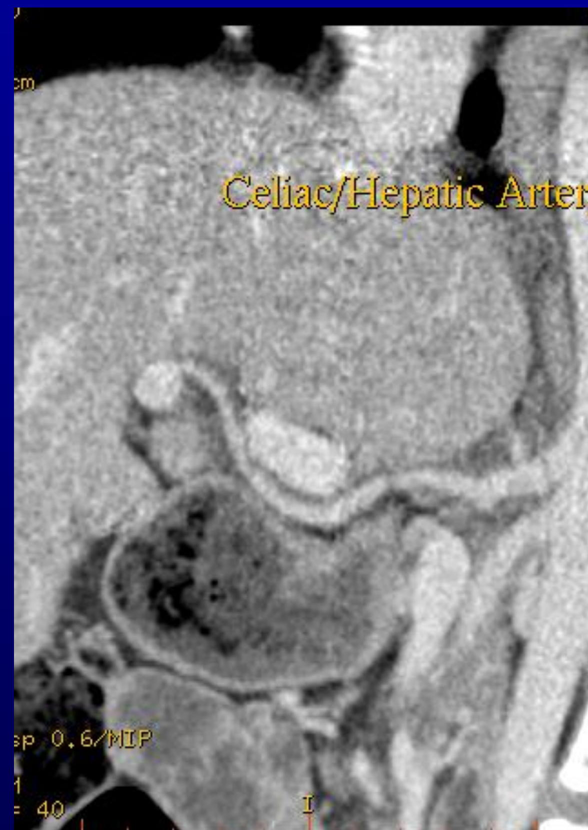
- Larger patients may not be able to undergo low kV imaging
- Patient size selection only insures good quality
  - Dose reduction is considered separately (later)

Who is going to benefit from lower kV imaging?

Who is going to benefit from lower kV imaging?

- Limited IV access or suboptimal timing
- Limited contrast dose
- Subtle attenuation differences
- Young patients
- Small and medium-sized adult patients

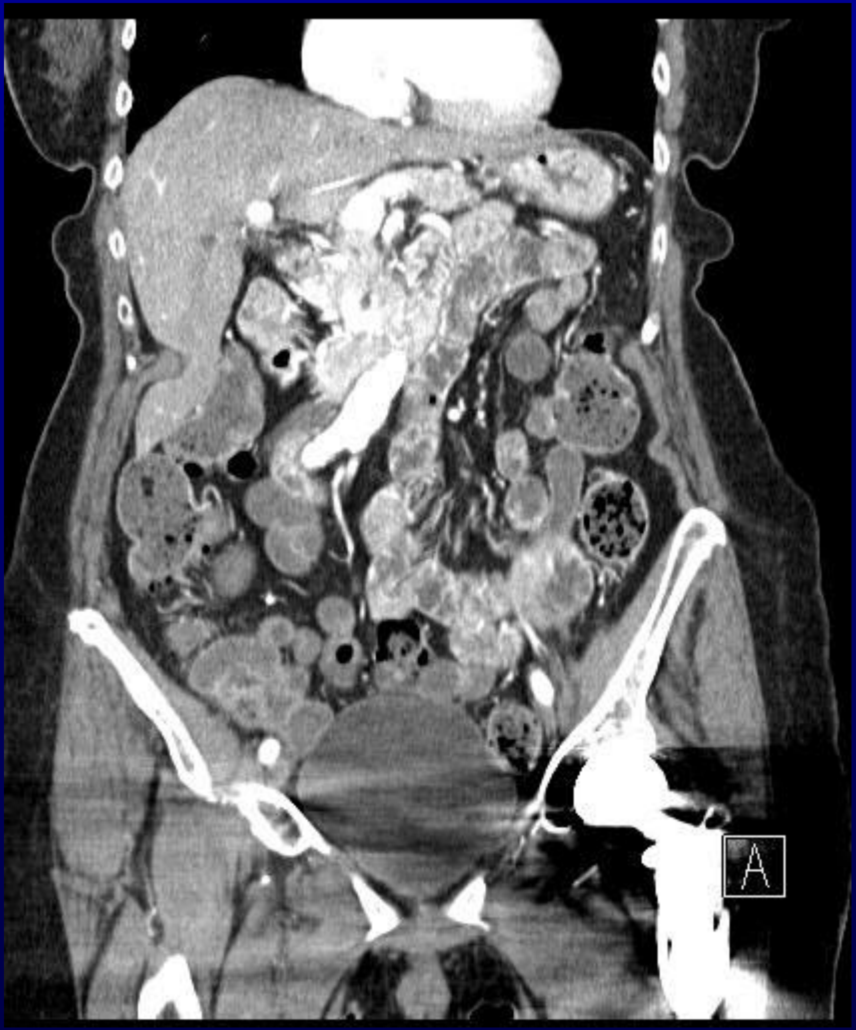
Limited IV access or Suboptimal Timing



80 kV

< 1 cc/s injection over 3 minutes

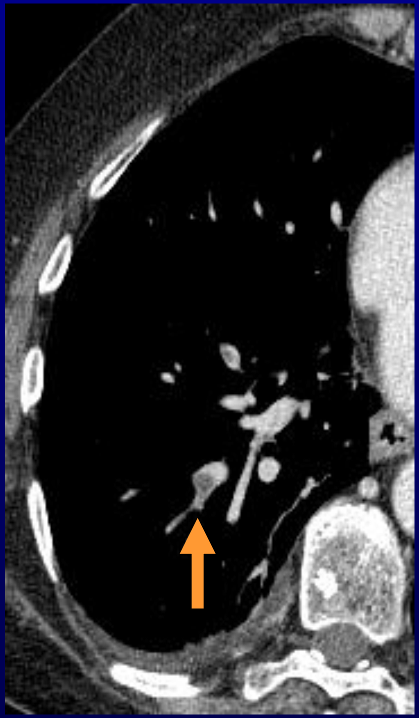
Limited IV access or Suboptimal Timing



2 cc/s with pedal access
Imaged at 85 sec

Limited IV access or Suboptimal Timing

Restaging unresectable Islet Cell tumor



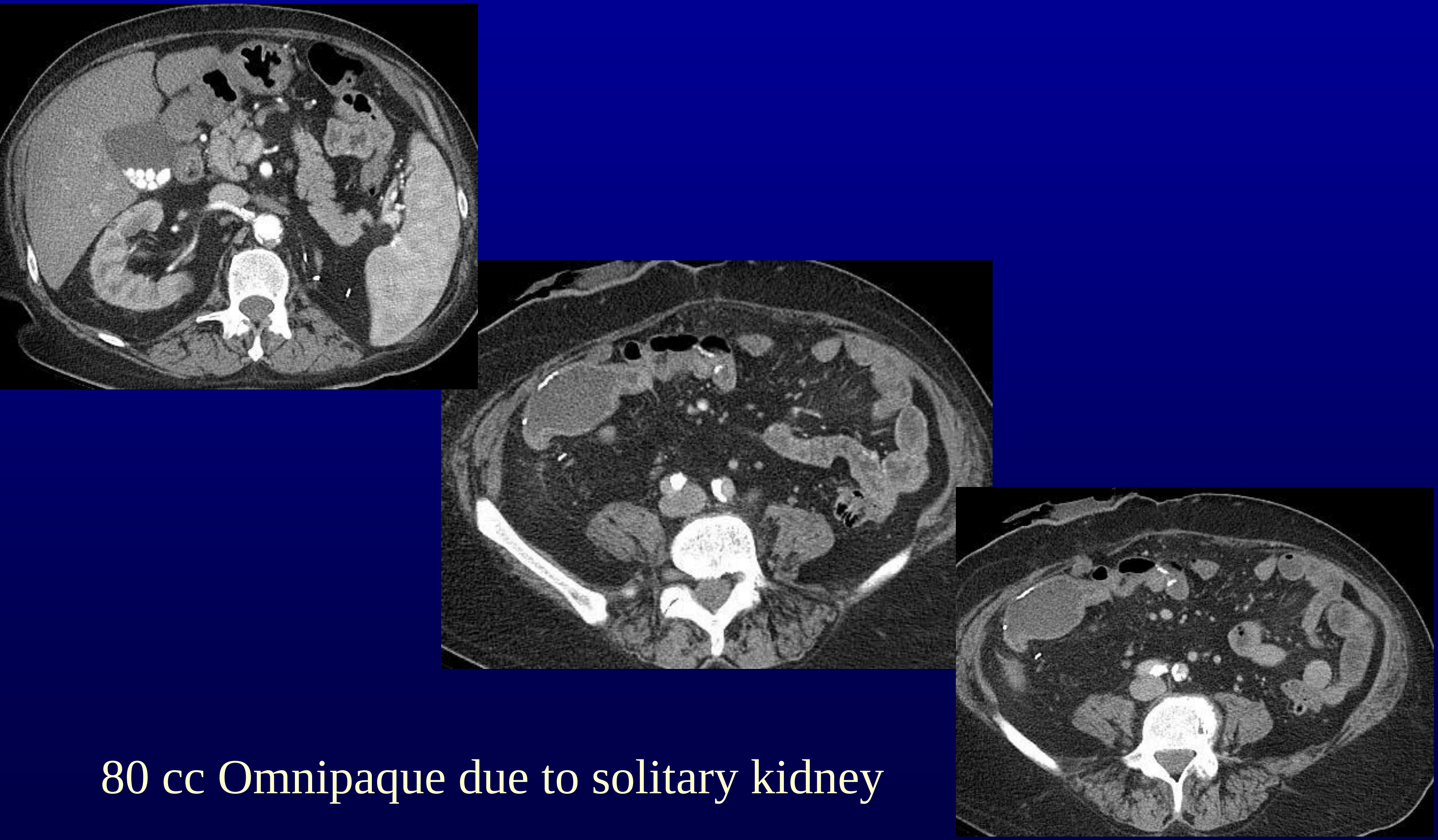
Chest CT at 80 seconds (to avoid compromise of abdominal timing)

100 kV Chest

Who is going to benefit from lower kV imaging?

- Limited IV access or suboptimal timing
- Limited contrast dose
- Subtle attenuation differences
- Young patients
- Small and medium-sized adult patients

Limited Contrast Dose

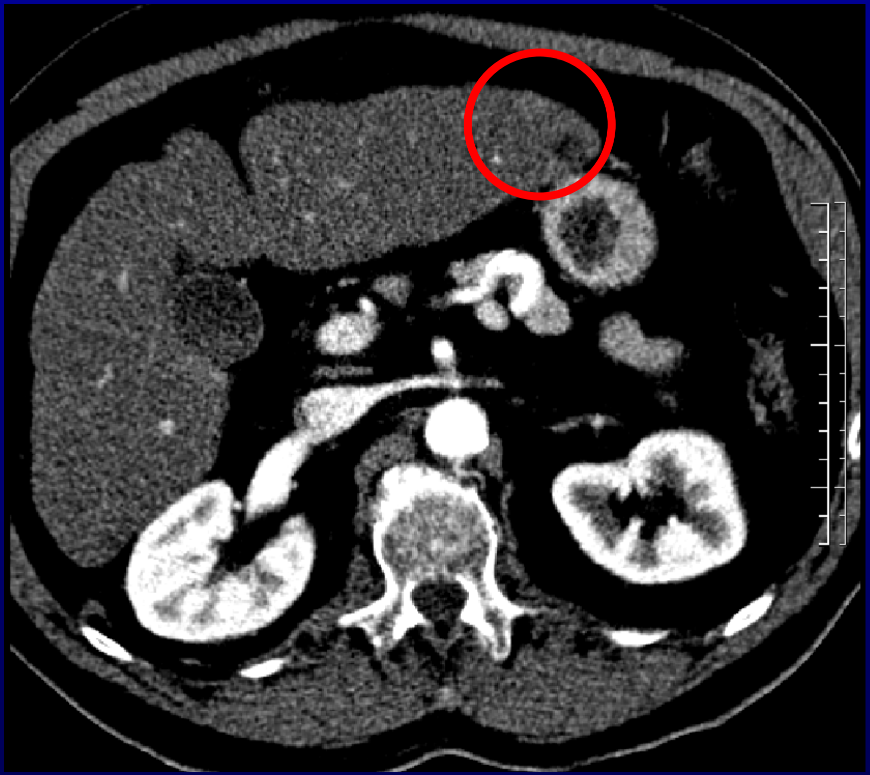


80 cc Omnipaque due to solitary kidney

Who is going to benefit from lower kV imaging?

- Limited IV access
- Limited contrast dose
- Subtle attenuation differences
- Young patients
- Small and medium-sized adult patients

Subtle Attenuation Differences



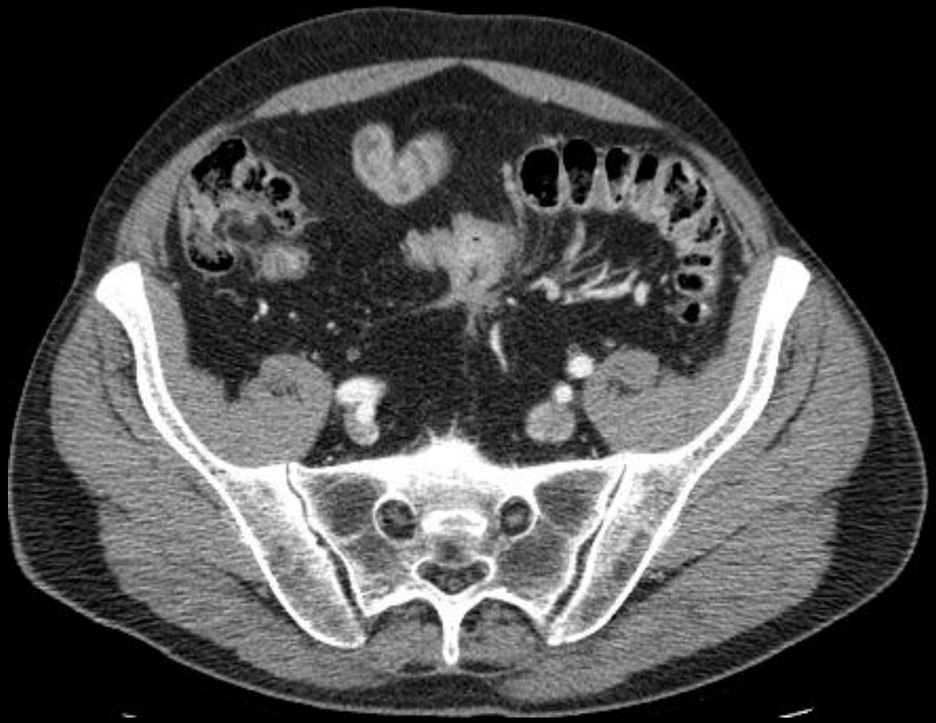
80 kV
45 HU diff$_{\text{lesion-liver}}$

120 kV
21 HU diff$_{\text{lesion-liver}}$

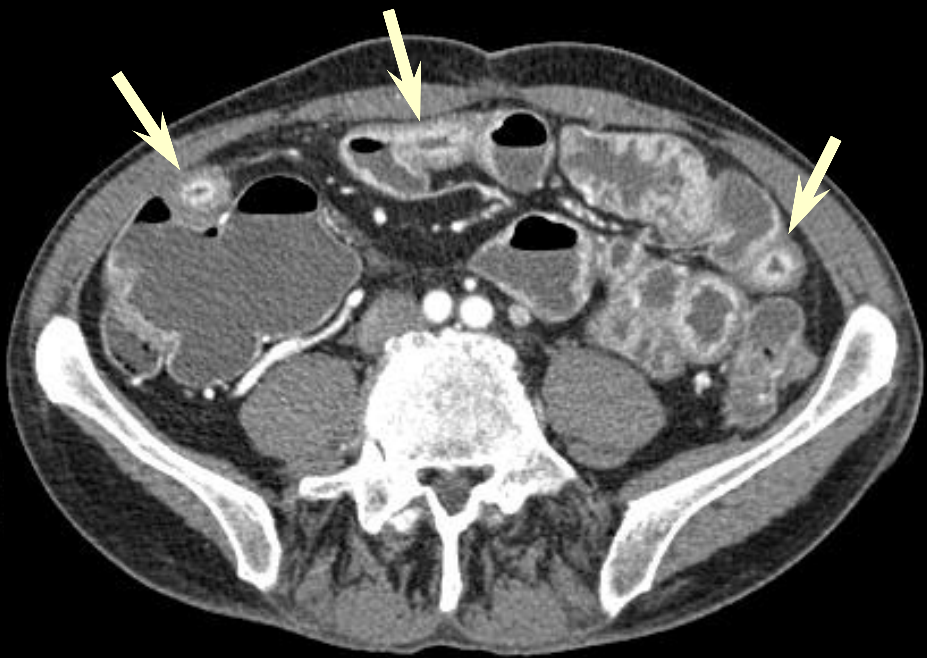
Who is going to benefit from lower kV imaging?

- Limited IV access
- Limited contrast dose
- Subtle attenuation differences
- Young patients
- Small and medium-sized adult patients

Low kV to Lower Radiation Dose



120 kV
17.3 mGy



100 kV
7.71 mGy

Who is going to benefit from lower kV imaging?

- Limited IV access
- Limited contrast dose

Maintain Radiation Dose ($CTDI_{vol}$)

- Subtle attenuation differences

- Young patients
- Small and medium-sized adult patients

↓ Radiation Dose ($CTDI_{vol}$)

Who is going to benefit from lower kV imaging?

- Limited IV access
- Limited contrast dose

Maintain Radiation Dose ($CTDI_{vol}$) → Dose-match Look-up table (or = CTDIvol)

- Subtle attenuation differences
- Young patients
- Small and medium-sized adult patients

↓ Radiation Dose ($CTDI_{vol}$) → Later

Low kV Imaging While Maintaining Dose

- Limited IV access
- Limited contrast dose
- Subtle attenuation differences

- Size < 36 cm => 80 kV
- Size ≤ 41 cm => 100 kV

- Plug protocol from 120 kV scan and record $CTDI_{vol}$
  - Change tube energy
  - Adjust mAs upwards until $CTDI_{vol@120\ kV}$ is achieved
  - Make sure you are operating within tube limits
- Use a look-up table with your technique charts

mAs Conversion for Siemens Scanners*			
mAs at 80 kVp	mAs at 100 kVp	mAs at 120 kVp	mAs at 140 kVp
190	90	50	30
230	100	60	40
270	120	70	50
300	140	80	50
340	150	90	60
380	170	100	70
420	190	110	70
460	200	120	80
490	220	130	80
530	240	140	90
570	260	150	100
610	270	160	100
650	290	170	110
680	310	180	120
720	320	190	120
760	340	200	130
800	360	210	140
840	370	220	140
870	390	230	150
910	410	240	160
950	430	250	160
990	440	260	170
1030	460	270	180
1060	480	280	180
1100	490	290	190
1140	510	300	200
1180	530	310	200
1220	540	320	210
1250	560	330	210
1290	580	340	220
1330	600	350	230
1370	610	360	230
1410	630	370	240
1440	650	380	250
1480	660	390	250
1520	680	400	260

*Not all mAs settings may be possible

mAs Conversion for Siemens Scanners*			
mAs at 80 kVp	mAs at 100 kVp	mAs at 120 kVp	mAs at 140 kVp
1560	700	410	270
1600	710	420	270
1630	730	430	280
1670	750	440	290
1710	770	450	290
1750	780	460	300
1790	800	470	310
1820	820	480	310
1860	830	490	320
1900	850	500	330
1940	870	510	330
1980	880	520	340
2010	900	530	340
2050	920	540	350
2090	940	550	360
2130	950	560	360
2170	970	570	370
2200	990	580	380
2240	1000	590	380
2280	1020	600	390
2320	1040	610	400
2360	1050	620	400
2390	1070	630	410
2430	1090	640	420
2470	1110	650	420
2510	1120	660	430
2550	1140	670	440
2580	1160	680	440
2620	1170	690	450
2660	1190	700	460
2700	1210	710	460
2740	1220	720	470
2770	1240	730	470
2810	1260	740	480
2850	1280	750	490
2890	1290	760	490

*Not all mAs settings may be possible

mA Conversion for GE-64 Scanners*			
mA at 80 kVp	mA at 100 kVp	mA at 120 kVp	mA at 140 kVp
160	80	50	40
190	100	60	40
230	110	70	50
260	130	80	60
290	150	90	60
320	160	100	70
350	180	110	80
390	190	120	90
420	210	130	90
450	230	140	100
480	240	150	110
520	260	160	110
550	270	170	120
580	290	180	130
610	310	190	140
650	320	200	140
680	340	210	150
710	350	220	160
740	370	230	160
770	390	240	170
810	400	250	180
840	420	260	190
870	440	270	190
900	450	280	200
940	470	290	210
970	480	300	210
1000	500	310	220
1030	520	320	230
1060	530	330	240
1100	550	340	240
1130	560	350	250
1160	580	360	260
1190	600	370	260
1230	610	380	270
1260	630	390	280
1290	650	400	290

*Not all mA settings may be possible

mA Conversion for GE-64 Scanners*			
mA at 80 kVp	mA at 100 kVp	mA at 120 kVp	mA at 140 kVp
1320	660	410	290
1350	680	420	300
1390	690	430	310
1420	710	440	310
1450	730	450	320
1480	740	460	330
1520	760	470	340
1550	770	480	340
1580	790	490	350
1610	810	500	360
1650	820	510	360
1680	840	520	370
1710	850	530	380
1740	870	540	390
1770	890	550	390
1810	900	560	400
1840	920	570	410
1870	940	580	410
1900	950	590	420
1940	970	600	430
1970	980	610	440
2000	1000	620	440
2030	1020	630	450
2060	1030	640	460
2100	1050	650	460
2130	1060	660	470
2160	1080	670	480
2190	1100	680	490
2230	1110	690	490
2260	1130	700	500
2290	1150	710	510
2320	1160	720	510
2350	1180	730	520
2390	1190	740	530
2420	1210	750	540
2450	1230	760	540

*Not all mA setting may be possible

Low kV Imaging While Reducing Dose

- More complicated
- Need to consider both patient size and diagnostic task into kV selection process
  - Greater the iodine contrast differences, the greater ability to reduce dose for smaller pts
- kV selection *combined with* lowering of dose-matched mAs
- Creates a new technique chart for each diagnostic task

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

General Strategy for kV selection

- Two items to consider
  - Iodine CNR (iCNR)
  - Acceptable noise level ($\alpha * \sigma_{120kv}$)

$$\mathbf{iCNR_{low\ kV} \geq iCNR_{120kV}}$$

and

$$\boldsymbol{\sigma_{lowkv} \leq \alpha * \sigma_{120kV},}$$

α = a noise constraint unique to a diagnostic task

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

↑ Contrast by 70%

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

↑ Contrast by 70%

↑ Noise by 70%

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

$$\frac{\Uparrow \text{Contrast by 70\%}}{\Uparrow \text{Noise by 70\%}} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

$$\frac{\uparrow \text{ Contrast by 70\%}}{\uparrow \text{ Noise by 70\%}} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

Improved contrast permits the noise level to increase

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

$$\frac{\uparrow \text{Contrast by 70\%}}{\uparrow \text{Noise by 70\%}} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

Increased noise permits the dose reduction

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

$$\frac{\uparrow \text{Contrast by 70\%}}{\uparrow \text{Noise by 60\%}} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

As patients get larger (or task requires less noise), the acceptable increase noise (σ) becomes smaller

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

$$\frac{\uparrow \text{Contrast by } 70\%}{\uparrow \text{Noise by } 50\%} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

As patients get larger (or task requires less noise), the acceptable increase noise (σ) becomes smaller

L. Yu, H. Li, J. Fletcher, C. McCollough, Medical Physics, 37(1), 2010.

Here's the idea

Consider 80 kV imaging

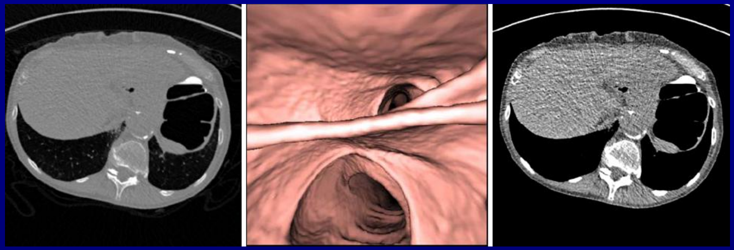
$$\frac{\uparrow \text{Contrast by 70\%}}{\uparrow \text{Noise by 40\%}} \geq \frac{\text{Contrast}_{120}}{\text{Noise}_{120}}$$

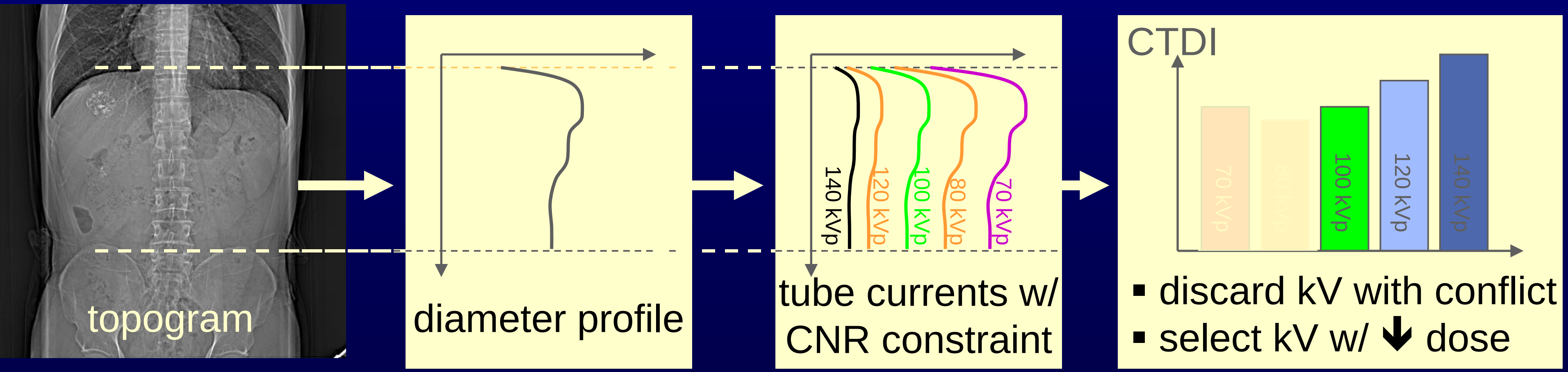
As patients get larger (or task requires less noise), the acceptable increase noise (σ) becomes smaller

Dose reduction will be limited

Low kV- Commercial Methods

- Considerations
  - Patient attenuation (~size)
  - Task (iCNR, α)
  - Scanner limitations



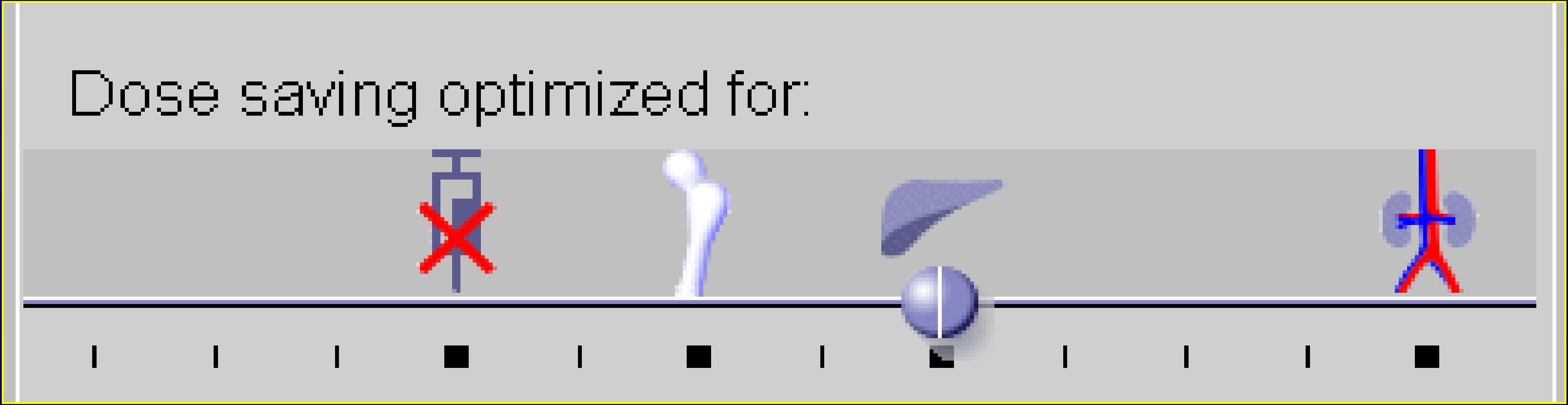


Courtesy Dr. Katie Grant, Siemens Healthcare

Low kV- Commercial Methods

- Patient attenuation (~size)
- Task (CNR, α)
- Scanner limitations

Strength Setting



0
Non-contrast

6 – 7
Routine

8
CTE

11
CTA

Low kV- Commercial Methods

120 kV
240 QRM

120 kV
11.2 mGy
5 mm slice

100 kV
410 Qual Ref mAs ⇓
Care kV Strength = 6

100 kV
8.9 mGy
5 mm slice

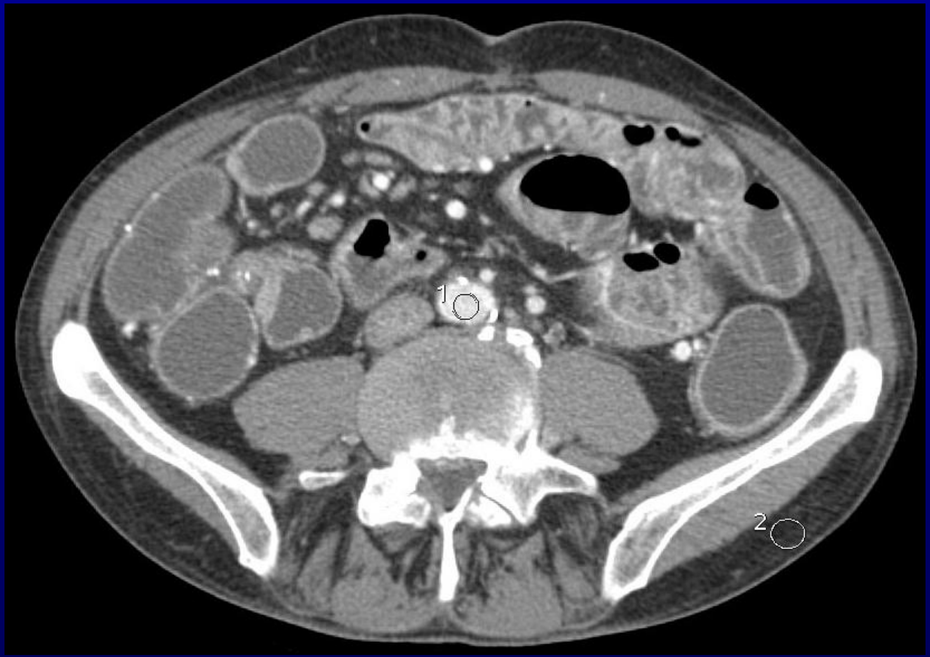
100 kV
310 QRM

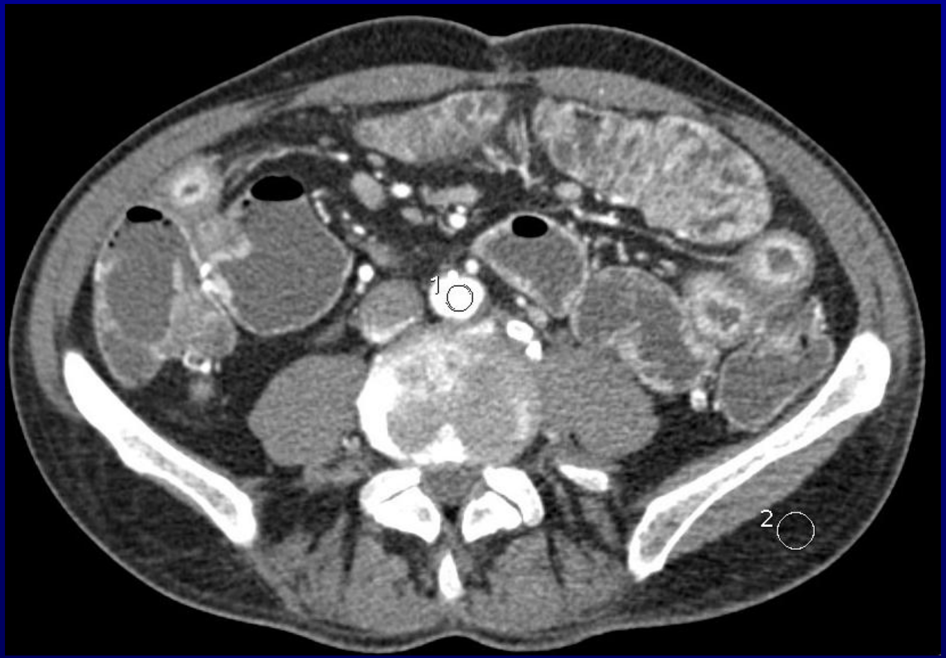
20% Dose Savings

No Decrease in Conspicuity

Strength = 6

Low kV- Commercial Methods





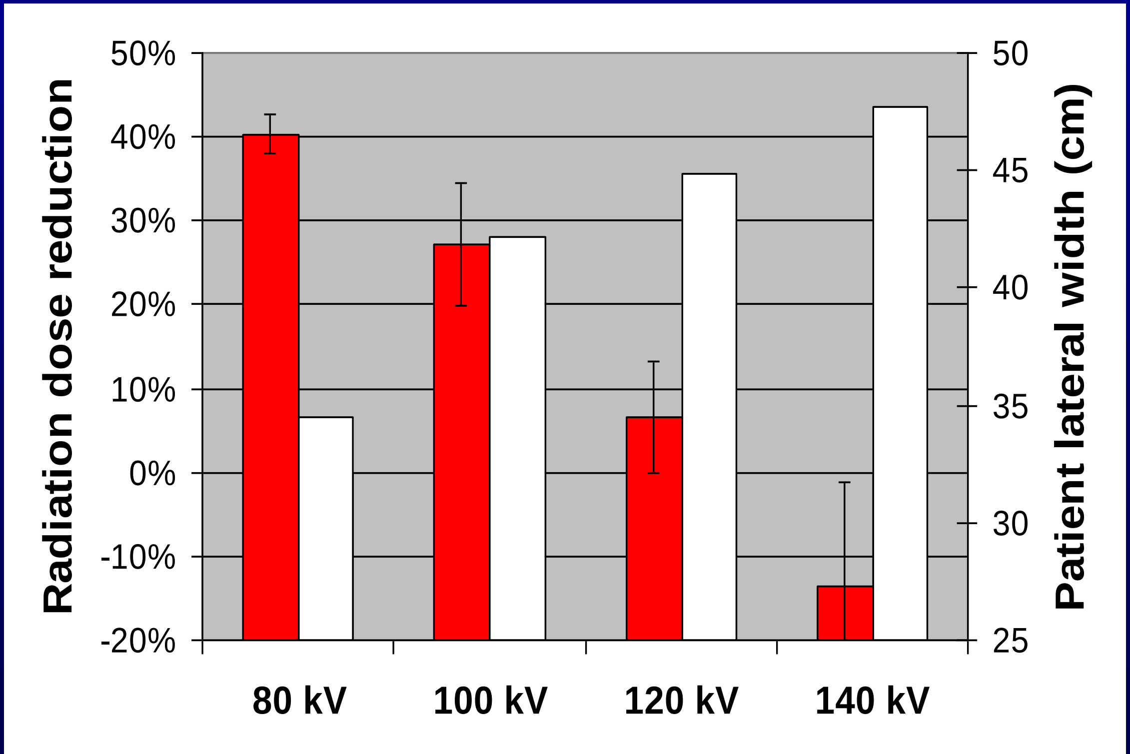
120 kV
17.3 mGy

100 kV
7.71 mGy

Iodine contrast-to-noise Ratio Equivalent

Low kV- Commercial Methods

Routine Abdominal CT



Care kV Strength = 6

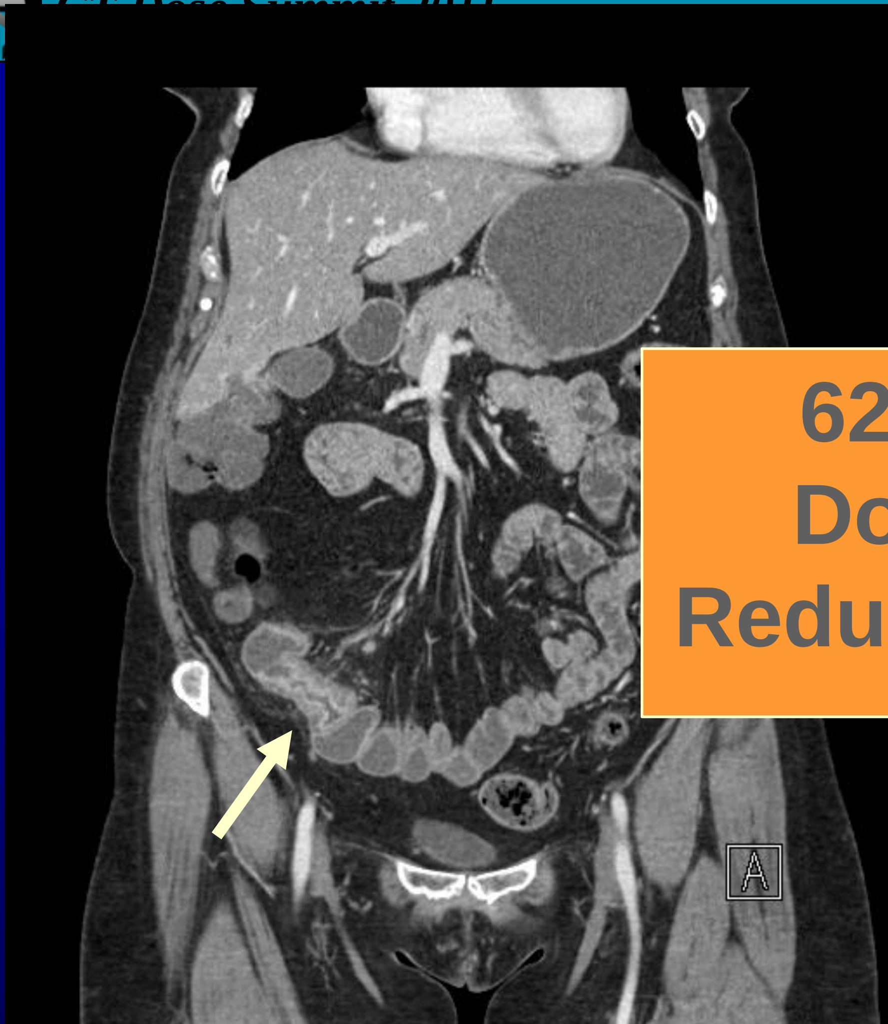
- Overall 20% dose reduction, but depends on patient size
- iCNR and image quality (EQC) identical in subset with comparisons @ 120 kV despite dose savings

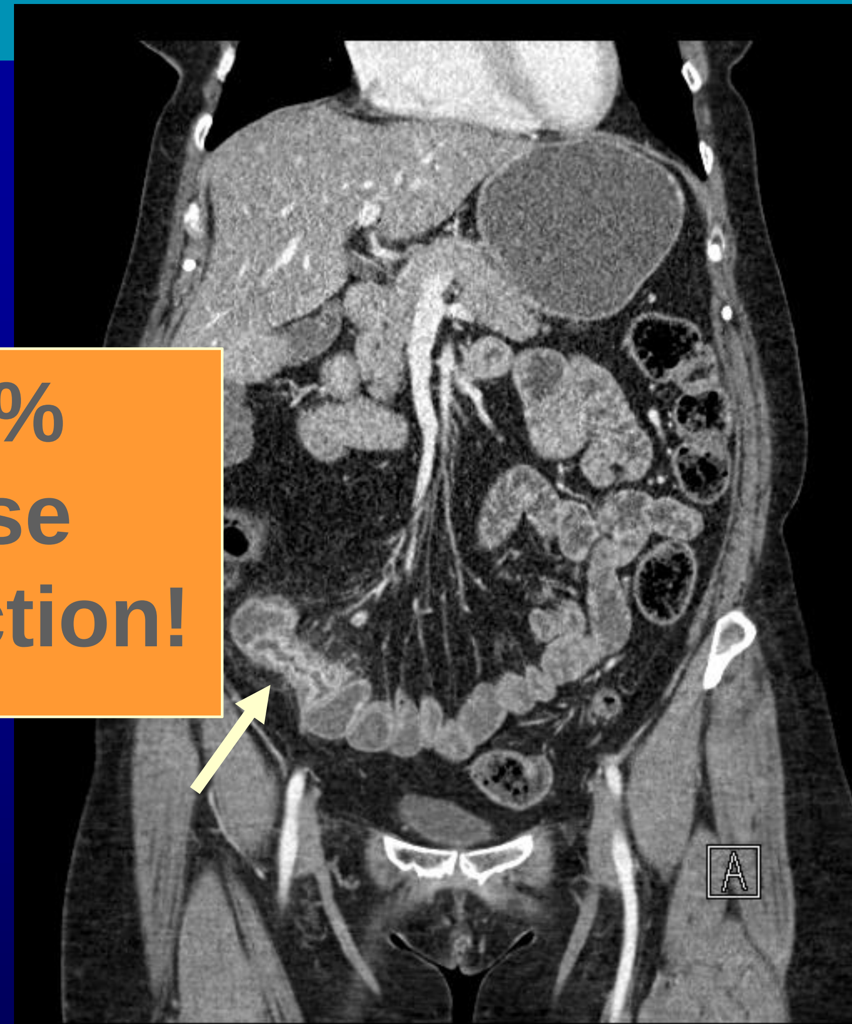
Yu et al. Mayo CT practice data. Submitted to RSNA 2011

The Grand Scheme

kV Selection to Reduce Radiation Dose

- Part of an overall strategy, so don't forget to eliminate…
  - unjustified exams
  - superfluous acquisitions (e.g., unenhanced, delayed)
- Should facilitate (not hinder) accomplishment of diagnostic task
- Performed *with* mAs reduction
- Synergistic with noise reduction





62 %
Dose
Reduction!

120 kV
(CTDIvol 18.89 mGy)

100 kV
(CTDIvol 7.13 mGy)
Routine Reconstruction

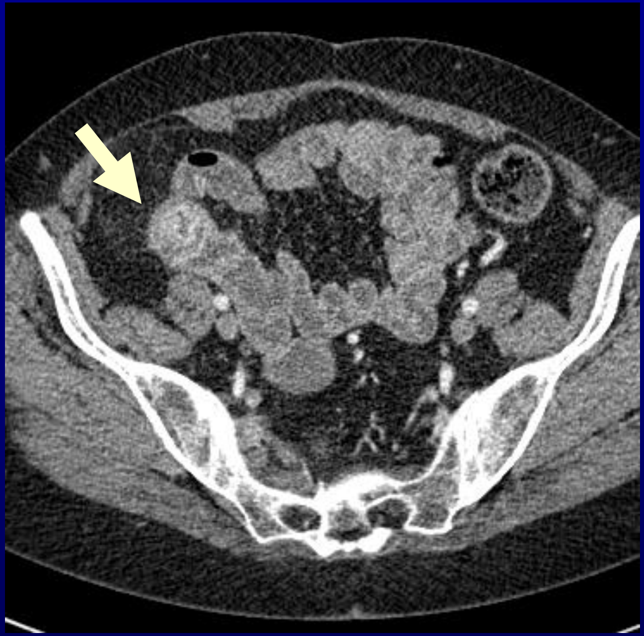
More dramatic dose reductions can be achieved if we permit noise levels to increase further

Low kV & Noise Reduction

120 kV

18.89 mGy

Routine dose and noise

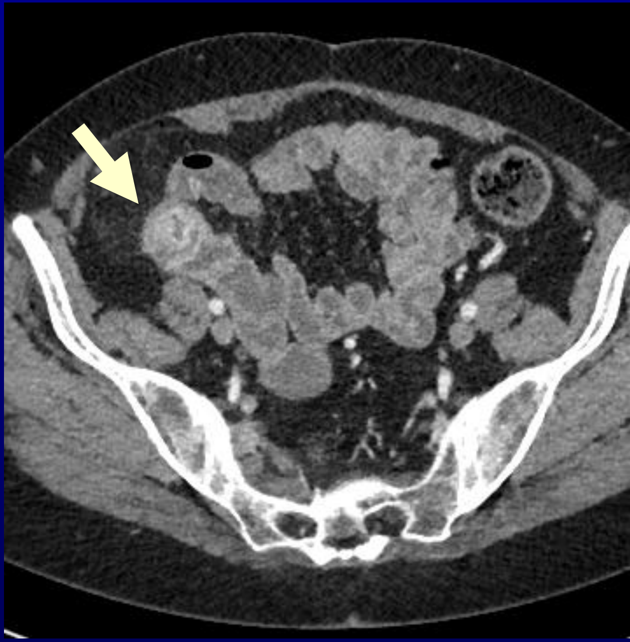


kV Selection + lower QRM

100 kV

Excessive noise

7.13 mGy



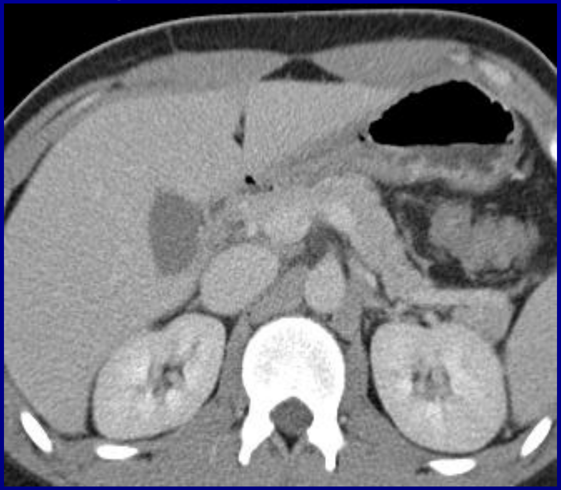
Noise Reduction

7.13 mGy

Lower dose and similar noise

24 yo man, abdominal pain

Care kV Strength = 8 for CT enterography

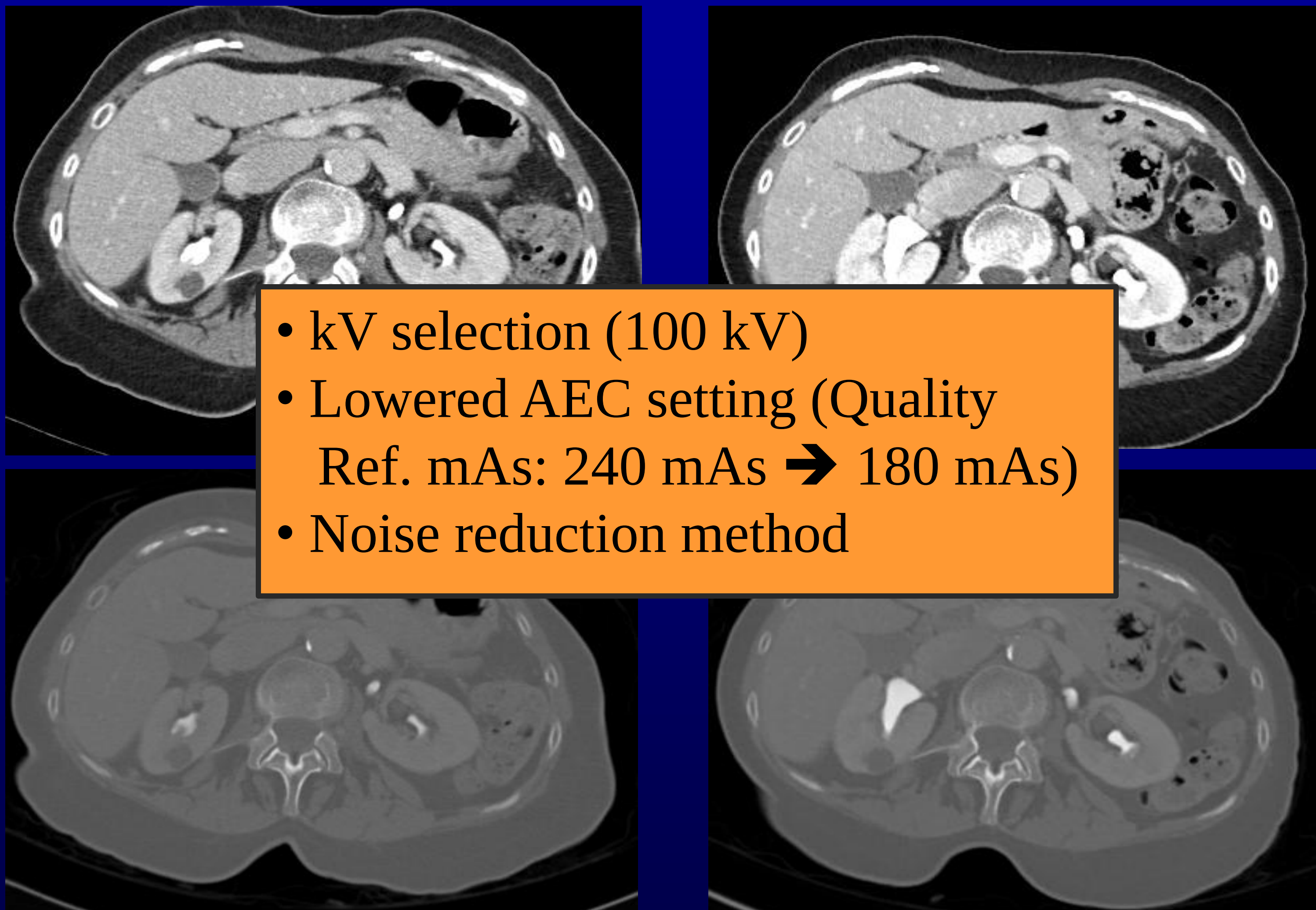


ER
5 mm slice
120 kV, 240 QRM
17.5 mGy CTDIvol

kV selection + dose ↓
3 mm slice
Base 120 kV, 160 QRM
100 kV, 207 QRM
6.2 mGy CTDIvol

kV selection + dose ↓
3 mm slice
SAFIRE, Strengh 3
100 kV, 207 QRM
6.2 mGy CTDIvol

Low kV & Noise Reduction

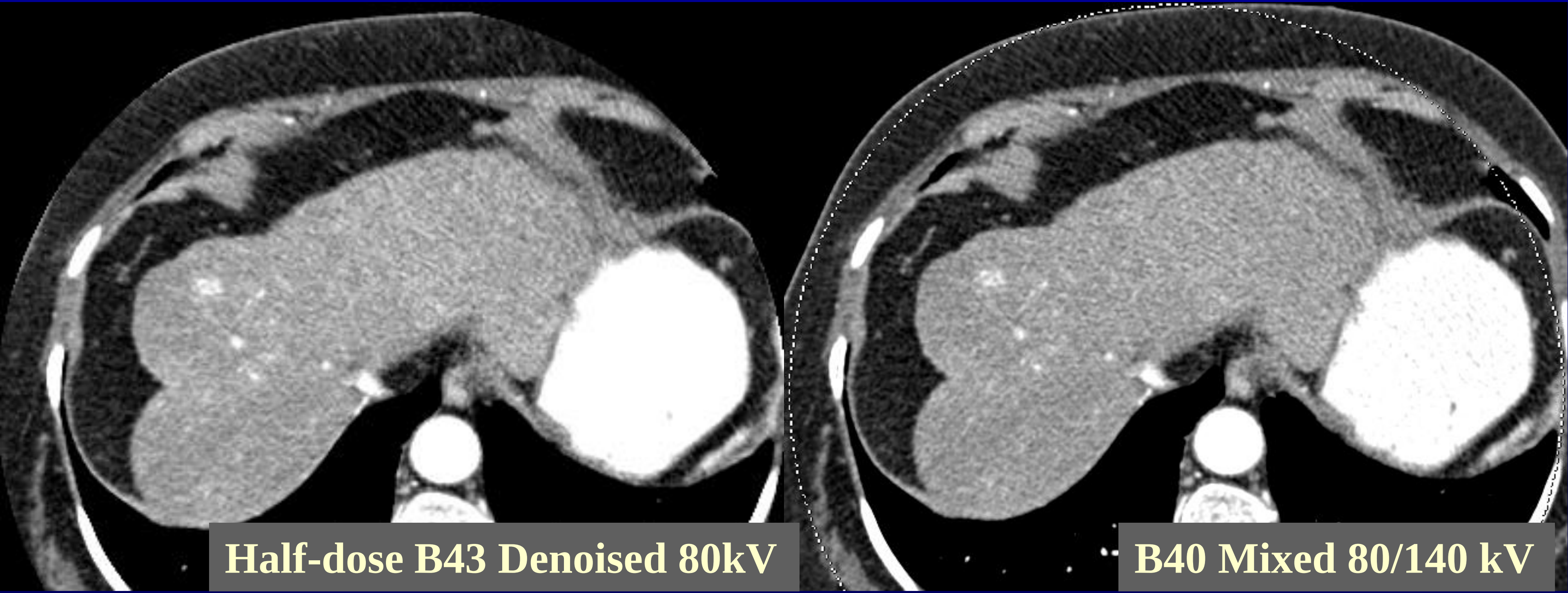


- kV selection (100 kV)
- Lowered AEC setting (Quality Ref. mAs: 240 mAs ➔ 180 mAs)
- Noise reduction method

CTDIvol = 14.0 mGy

CTDIvol = 6.8 mGy

Low kV & Noise Reduction

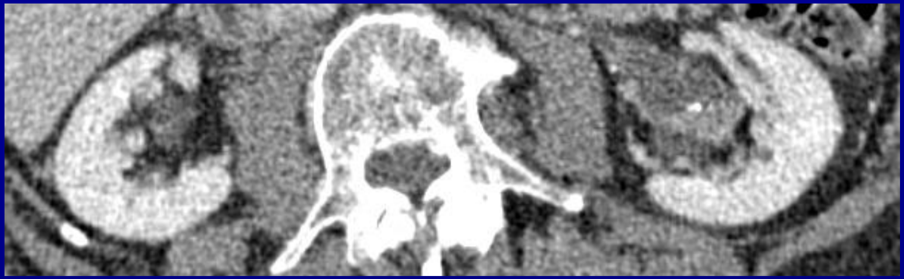


Half-dose Low kV + Noise Reduction

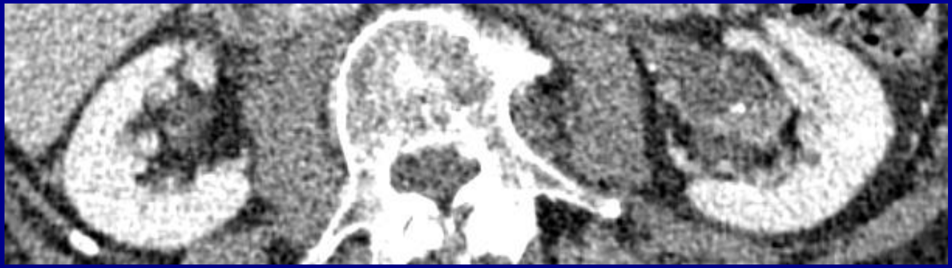
3/3 readers rated conspicuity same/greater for ½ dose low kV with noise reduction

Ehman et al. AJR 2011 (in press)

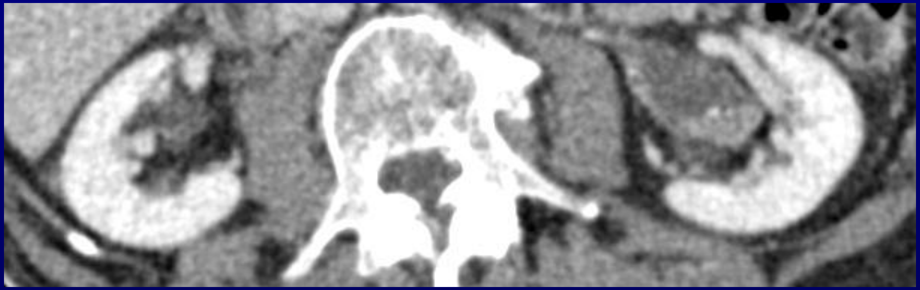
Low kV & Noise Reduction



Full dose Mixed 80/140 kV



Half dose 80 kV



80 kV + PS

Half-dose Low kV + Noise Reduction

4/4 readers rated conspicuity same/greater for ½ dose low kV with noise reduction

Paulsen et al. ARC 2010

How do low kV images look different?

- More contrast, more noise
- Require modified window-level settings, based on radiologist preference

120 kV
17.3 $CTDI_{vol}$

100 kV
11.9 $CTDI_{vol}$

How do low kV images look different?

Routine Window/Level

Window/Level adapted for patient

100 kV, 8.9 mGy
2 mm slice
(12.2 mGy Rx'd @ 120 kV; 27% dose savings)

Future of Low kV Imaging

- 100 kV can be practically implemented already in most patients
  - Task-specific technique charts will include kV and mAs selection to perform most dose-efficient exam
  - 140 kV imaging may be most dose-efficient for large pts
- Manufacturers integrating automatic kV selection tools into CT systems
  - Based on iCNR, but also take automatic exposure control and tube current limits into account
- Provide a new level of individualization for CT imaging (task + patient-specific)

Conclusions

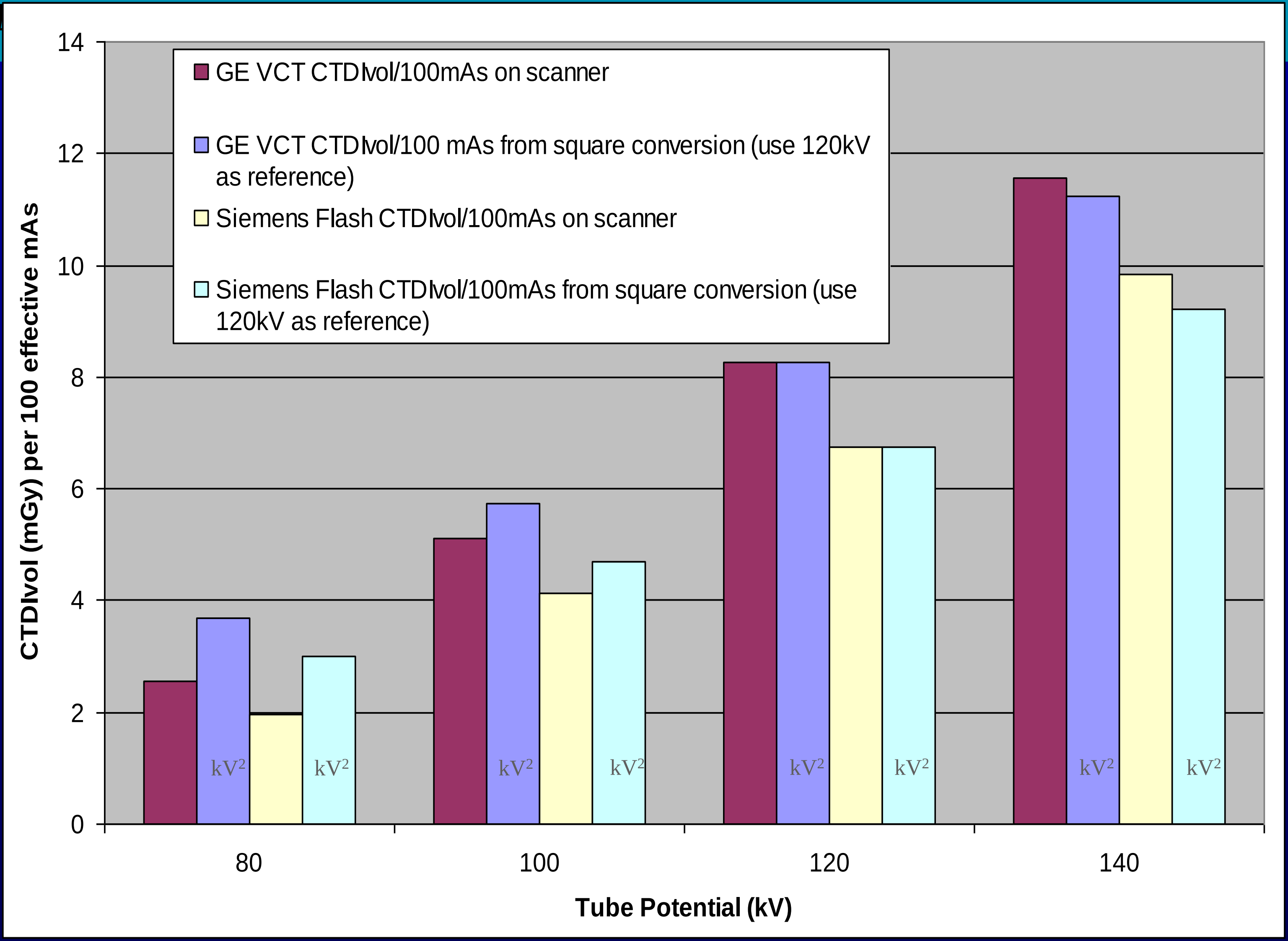
- Tube energy (kV) selection can benefit your patients
  - Limited IV access/suboptimal timing, renal insufficiency, iodine-sensitive pathology
  - Dose reduction
- kV selection is dependent upon patient size (attenuation) and diagnostic task (noise is limiting factor)
- Several pathways to begin kV modulation in your practice
  - Dose-matched exams
  - Technique charts & automated kV selection tools
- Seamless integration with noise reduction for greatest dose savings

Thank you

Mayo CT Clinic Innovation Center and Dept. of Radiology

http://mayoresearch.mayo.edu/CTCIC

CT I



The widely used relation "Radiation output CTDIvol is proportional to kVp^2 for the same mAs" is not accurate.

As shown above, the actual CTDIvol at 80 kVp is about ~50% lower on both GE and Siemens scanners for the lower kV's