Use of the deviation index (DI) for quality control in digital radiography

A. Kyle Jones, Ph.D.
MD Anderson Cancer Center, Houston, TX

Jaydev Dave, Ph.D.
Jefferson Hospital, Philadelphia, PA

Disclosures

- None

Contributors to AAPM TG 232

- **Co-chairs**: A. Kyle Jones and Jaydev Dave
- **Members**: Ryan Fisher (CCF), Katie Hulme (CCF), Lynn Rill (UF), David Zamora (UW), Andrew Woodward (UNC), Samuel Brady(St. Jude's), Bobby MacDougall (Children's Hospital Boston), Lee Goldman (Hartford Hospital), Susan Lang (Henry Ford), Donald Peck (Henry Ford), Bruce Apgar (Agfa), Jeff Shepard (MDACC), Bob Uzenoff (Fujifilm), Chuck Willis (MDACC)
- Eric Gingold (**RFSC chair, now IPC chair**)
- Behrang Amini and Patrick O'keefe (**radiologists**)

The infamous Table 2

Table 2. Exposure Indicator DI Control Limits for Clinical Images

DI	Range Action
> +3.0	Excessive patient radiation exposure Repeat only if relevant anatomy is clipped or "burned out" Require immediate management follow-up.
+1 to +3.0	Overexposure: Repeat only if relevant anatomy is clipped or "burned out"
−0.5 to +0.5	Target range
Less than −1.0	Underexposed: Consult radiologist for repeat
Less than −3.0	Repeat

Good intentions

Once $K_{TGT}(b,v)$ levels are set, it is useful to identify several types of "control limits" on DI: a target range, a "management trigger" range, or a "repeat" range (see Table 2). The reason for this is that unlike filmed images, in which inadequate or excessive image optical density is a determinant of when a repeated film is needed, the reason for repeating a digital image is primarily noise related. What would be an underexposed film image may be of adequate diagnostic value in digital form. Similarly, it is never appropriate to repeat overexposed digital images unless analog-to-digital converter saturation has occurred, which may cause relevant parts of the image to be "burned out" or "clipped" (that is, all pixels in the affected region are forced to the maximum digital value and thus containing no information) or contrast to be affected in excessively exposed regions of the image. Since this judgment depends upon the diagnostic task, it is appropriate to seek consultation with a radiologist for certain ranges of DI-indicated under- and overexposure prior to repeating.

But perhaps flawed logic

A properly functioning AEC system will produce optical densities of ±0.15 OD under varying combinations of kV_p and phantom thickness (adjusting mA to result in exposure times greater than 10 ms).[16] For a screen/film combination, optical density in the straight-line portion of the H&D curve is related to detector exposure (or K_{ESD}) as follows:

$$\Delta OD = \gamma \log_{10}\left(\frac{K_{ESD_1}}{K_{ESD_2}}\right). \quad (3)$$

Combining equations (2) and (3), the range of deviation indices corresponding to a given OD range would be:

$$\Delta DI = \left(\frac{10}{\gamma}\right) \times \Delta OD. \quad (4)$$

For a screen/film combination with a gamma of 2.85 (a fairly common gamma in clinical use), the acceptable DI range would be:

$$\Delta DI = \left(\frac{10}{2.85}\right) \times 0.3 = 1.05 = \pm 0.5. \quad (4a)$$

The task group recommends the action levels shown in Table 2.

But perhaps flawed logic

A properly functioning AEC system will produce optical densities of ±0.15 OD under varying combinations of kV_p and phantom thickness (adjusting mA to result in exposure times greater than 10 ms).[14] For a screen/film combination, optical density in the straight-line portion of the H&D curve is related to detector exposure (or K_{SND}) as follows:

$$\Delta OD = \gamma \log_{10}\left(\frac{K_{SND_2}}{K_{SND_1}}\right) \quad (3)$$

Combining equations (2) and (3), the range of deviation indices corresponding to a given OD range would be:

$$\Delta DI = \left(\frac{10}{\gamma}\right) \times \Delta OD. \quad (4)$$

For a screen/film combination with a gamma of 2.85 (a fairly common gamma in clinical use), the acceptable DI range would be:

$$\Delta DI = \left(\frac{10}{2.85}\right) \times 0.3 = 1.05 \approx \pm 0.5. \quad (4a)$$

The task group recommends the action levels shown in Table 2.

Review and replace

- **Charge**: To investigate the current state of practice for CR/DR Exposure and Deviation Indices based on AAPM TG 116 and IEC-62494, for the purpose of establishing achievable goals (reference levels) and action levels in digital radiography.

Methods

- Solicited data for 9 body parts and views for adult and pediatric digital radiography from 10 sites
  - Abdomen: AP/KUB, Upright, Decubitus
  - Chest: PA, AP, Lateral, Decubitus
  - Pelvis: AP
  - Extremity: without multiple views on same image
  - Institutional Review Board/Quality Improvement Assessment Board approvals
- DI calculated from EI_T and EI
- Minimal pre-processing of data
- $-9.9 \leq DI \leq +9.9$
- 505,930 exposures analyzed

Table 1. Mandatory and optional data criteria.

Mandatory data criteria	Optional data criteria
1. Anonymized and NO PHI* is included 2. Must be collected from systems with known relationship between EI and receptor dose 3. EI calibration of vendor used, or well-defined alternative used 4. Known equipment problems disclosed and linked to suspect data 5. EI known for each data point 6. Any processing of data disclosed 7. Body part and view listed for each data point	1. Radiographic room where image was acquired 2. Beam quality for each radiographic room 3. Method of exposure control (AEC/manual) known for each data point 4. Status of image (accepted/rejected) and reason for rejection if known

*PHI = protected healthcare information

Methods

- Analysis was performed in aggregate and stratified by
  - Patient type
    - Adult vs. pediatric
  - Exposure control method
    - Manual vs. AEC
  - Image receptor technology
    - Scanned pixel vs. fixed pixel
  - Practice setting
    - Academic Hospital vs. Community Hospital

Breakdown of views analyzed by this task group.

Body Part	Adult/pediatric	View	Number of views	% of total views
Abdomen	Adult	KUB	34803	6.9%
		Upright	5858	1.2%
		Decubitus	9182	1.8%
	Pediatric	KUB/Babygram	2648	0.5%
		Upright	307	0.1%
		Decubitus	208	<0.1%
Chest	Adult	AP	91756	18.1%
		PA	59906	11.8%
		Lateral	65511	12.9%
		Decubitus	258	0.1%
	Pediatric	AP	8609	1.7%
		PA	3410	0.7%
		Lateral	5195	1.0%
		Decubitus	15	<0.1%
Pelvis	Adult	AP	14300	2.8%
	Pediatric	AP	1285	0.3%
Extremity	Adult	Included views	181674	35.9%
	Pediatric	Included views	21005	4.2%

What we learned about the state of practice

We know where we're going but we don't know where we are…

EI_T varied widely among participating sites

Table 5. EI_T (IEC) values used at sites submitting data for analysis by this task group.

Body part	Adult/pediatric	Technology	Number of participating sites	Range of EI_T
Abdomen	Adult	Scanned pixel (CR)	7	400 - 945
		Fixed pixel (DR)	4	149 - 890
	Pediatric	Scanned pixel (CR)	7	400 - 888
		Fixed pixel (DR)	4	445 - 700
Chest	Adult	Scanned pixel (CR)	7	340 - 888
		Fixed pixel (DR)	4	102 - 685
	Pediatric	Scanned pixel (CR)	7	345 - 571
		Fixed pixel (DR)	4	158 - 700
Pelvis	Adult	Scanned pixel (CR)	7	400 - 945
		Fixed pixel (DR)	4	250 - 802
	Pediatric	Scanned pixel (CR)	7	400 - 1110
		Fixed pixel (DR)	4	445 - 500
Extremity	Adult	Scanned pixel (CR)	7	400 - 1776
		Fixed pixel (DR)	4	104 - 1730
	Pediatric	Scanned pixel (CR)	7	400 - 1629
		Fixed pixel (DR)	4	250 - 1258

*Note the EI_T values were provided by the participating sites and these values may or may not match values recommended by equipment manufacturers. At each participating site, there were no differences in the EI_T values for different views of the same body part for the same imaging technology from the same manufacturer.

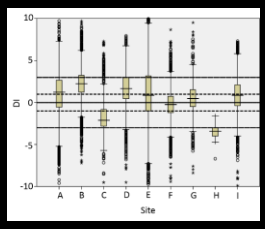
Many DI fell outside TG-116 significant action limits

Table 8. Percentage of cases falling within the categories listed in Table 2 of the report of AAPM TG-116 for adult patients (the category with the maximum number of instances for each view is listed in **bold**).

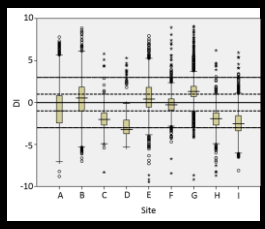
Body part	Abdomen			Chest				Pelvis	Extremity
View	KUB	Upright	Decubitus	AP	PA	Lateral	Decubitus	AP	Included views
n	34803	5858	9182	91756	59906	65511	258	14300	381674
≤-3	5.3%	11.1%	11.5%	5.6%	10.6%	4.0%	20.9%	4.9%	10.1%
-3 to -2	14.4%	17.1%	**22.1%**	14.0%	**26.8%**	22.7%	**29.4%**	15.9%	**20.1%**
-2 to -0.5	6.0%	7.0%	7.5%	8.2%	8.7%	9.9%	4.7%	7.0%	7.0%
-0.5 to 0.5	15.1%	15.3%	15.1%	18.9%	17.1%	18.1%	10.1%	19.8%	13.9%
0.5 to 1	7.6%	8.4%	7.1%	9.8%	8.4%	7.9%	6.6%	11.3%	6.4%
1 to 3	**31.6%**	**26.2%**	19.1%	**28.0%**	21.0%	**25.7%**	21.7%	**32.1%**	17.7%
>3	19.9%	17.0%	17.4%	13.5%	5.4%	11.8%	10.5%	13.0%	11.8%

Table 9. Percentage of cases falling within the categories listed in Table 2 of the report of AAPM TG-116 for pediatric patients (the category with the maximum number of instances for each view is listed in **bold**).

Body part	Abdomen			Chest				Pelvis	Extremity
View	KUB	Upright	Decubitus	AP	PA	Lateral	Decubitus	AP	Included views
n	2948	307	308	8869	3453	5195	15	1285	21005
≤-3	13.7%	32.6%	15.4%	10.7%	6.5%	4.0%	6.7%	10.4%	12.0%
-3 to -2	**23.3%**	**30.6%**	**32.2%**	**25.6%**	21.7%	11.7%	20.0%	20.5%	17.7%
-2 to -0.5	6.3%	2.3%	6.7%	9.6%	7.2%	7.4%	6.7%	10.2%	9.6%
-0.5 to 0.5	15.9%	9.8%	14.4%	22.6%	21.7%	19.1%	20.0%	**22.4%**	13.4%
0.5 to 1	7.9%	2.6%	6.7%	6.7%	10.9%	11.1%	6.7%	8.2%	7.1%
1 to 3	20.5%	15.3%	20.2%	16.3%	**26.1%**	**31.8%**	**33.3%**	19.2%	**26.3%**
>3	12.3%	7.8%	4.3%	8.5%	5.9%	14.7%	6.7%	9.1%	12.8%

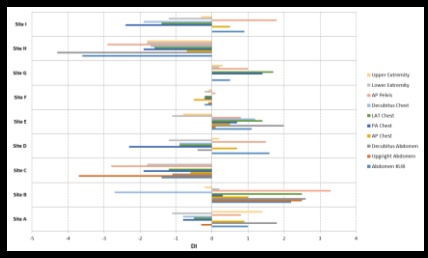


Adult AP abdomen



Adult PA Chest

Mean DI was often not equal to 0.0



No single site was the best at everything

Table A.3.5. Descriptive statistics by site for DI values for all adult PA chest views.

Site		A	B	C	D	E	F	G	H	I
n		20424	8972	1680	136	12061	4517	5366	2700	4050
Mean		-0.8	0.3	-1.9	-2.3	0.7	-0.2	1.4	-1.9	-2.4
95% Confidence Interval for Mean	Lower Bound	-0.8	0.3	-2.0	-2.7	0.6	-0.2	1.4	-2.0	-2.5
	Upper Bound	-0.8	0.4	-1.9	-1.9	0.7	-0.2	1.4	-1.9	-2.4
5% Trimmed Mean		-0.8	0.4	-2.0	-2.5	0.6	-0.2	1.4	-1.9	-2.5
Median		-1.0	0.5	-2.0	-3.2	0.4	-0.3	1.3	-1.9	-2.5
Variance		4.8	4.2	1.4	6.5	2.8	1.0	1.5	1.5	2.1
Std. Deviation		2.2	2.0	1.2	2.5	1.7	1.0	1.2	1.2	1.4

Table A.1.4. Descriptive statistics by site for DI values for adult KUB abdominal views.

Site		A	B	C	D	E	F	G	H	I
n		7352	5883	1066	3381	8389	3746	2189	21	2776
Mean		1.0	2.2	-1.4	1.6	1.1	-0.2	0.5	-3.6	0.9
95% Confidence Interval for Mean	Lower Bound	0.9	-1.6	1.6	1.0	-0.3	0.4	-4.1	0.8	.8
	Upper Bound	1.0	-1.3	1.7	1.2	-0.2	0.5	-3.1	0.9	.9
5% Trimmed Mean		1.0	2.2	-1.6	1.7	1.1	-0.2	0.5	-3.5	0.9
Median		1.3	2.3	-2.1	1.7	0.9	-0.2	0.5	-3.4	0.9
Variance		5.5	3.5	5.9	4.2	9.4	3.4	3.0	1.1	5.0
Std. Deviation		2.3	1.9	2.4	2.0	3.1	1.8	1.7	1.1	2.2

Use of AEC resulted in a narrower DI distribution

Table A.1.9. Descriptive statistics by exposure control method and technology for DI values for adult abdominal views.

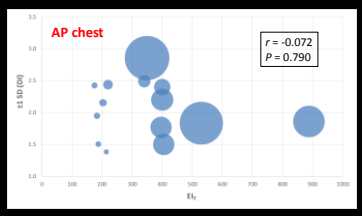
View		Category 1						Category 2			Category 3
Exposure control		Manual		AEC		Unknown		AEC	Unknown		Unknown
Technology		CR	DR	CR	DR	CR	DR	CR	CR	DR	CR
n		4012	2351	9564	768	13240	1487	1511	3177	931	2528
Mean		1.8	1.4	0.5	-2.4	1.3	-0.2	-0.3	1.1	-0.1	2.0
95% Confidence Interval for Mean	Lower Bound	1.7	1.3	0.4	-2.5	1.3	-0.2	-0.5	1.0	-0.2	1.8
	Upper Bound	1.9	1.5	0.5	-2.3	1.3	-0.1	-0.2	1.2	0.0	2.1
5% Trimmed Mean		1.8	1.4	0.5	-2.4	1.3	-0.2	-0.3	1.2	-0.1	2.1
Median		1.9	1.4	0.5	-2.5	1.5	-0.2	0.0	1.2	0.0	2.3
Variance		9.6	5.6	4.8	1.5	6.1	1.8	7.2	7.7	1.6	11.6
Std. Deviation		3.1	2.4	2.2	1.2	2.5	1.3	2.7	2.8	1.3	3.4
Minimum		-9.5	-9.6	-9.4	-9.5	-9.9	-6.5	-9.9	-9.5	-3.9	-9.8
Maximum		10.0	9.7	9.5	4.2	9.9	8.7	9.8	9.2	7.5	9.9
Range		19.5	19.3	18.9	13.7	19.8	15.2	19.7	18.7	11.3	19.7
Interquartile Range		4.2	3.1	3.0	1.3	3.0	1.4	3.7	3.8	1.6	4.5
Skewness		-0.2	-0.2	-0.4	-0.2	-0.3	-0.1	-0.4	-0.3	-0.1	-0.5
Kurtosis		-0.2	0.9	0.7	6.8	0.9	4.6	0.0	0.0	1.5	0.0

Use of AEC resulted in a narrower DI distribution

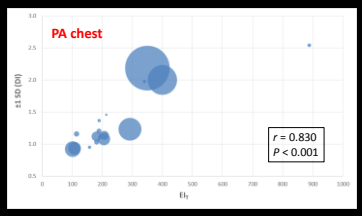
Table A.1.10. Descriptive statistics by exposure control method and technology for DI values for adult chest views.

View		Category 1						Category 2			Category 3		
Exposure control		Manual	Manual	AEC	Unknown	AEC	AEC	Unknown	Unknown	AEC	AEC	Unknown	Unknown
Technology		CR	DR	CR	CR	CR	DR	CR	DR	CR	DR	CR	DR
n		37502	19863	1908	27823	25542	4362	25183	4391	26479	4981	29197	4561
Mean		0.2	0.5	0.8	0.7	-0.4	-1.9	0.0	-0.2	0.0	-1.4	1.2	-0.2
95% Confidence Interval for Mean	Lower Bound	0.2	0.5	0.7	0.7	-0.4	-2.0	0.0	-0.2	0.0	-1.4	1.2	-0.2
	Upper Bound	0.2	0.5	0.8	0.8	-0.3	-1.9	0.1	-0.1	0.0	-1.3	1.2	-0.2
5% Trimmed Mean		0.2	0.5	0.8	0.8	-0.3	-1.9	0.1	-0.2	0.0	-1.3	1.2	-0.3
Median		0.1	0.6	0.8	0.8	-0.2	-1.9	0.1	-0.2	-0.2	-1.3	1.3	-0.3
Variance		5.3	3.1	2.4	6.2	4.9	1.4	4.4	0.9	3.5	1.1	5.0	1.5
Std. Deviation		2.3	1.8	1.6	2.5	2.2	1.2	2.1	0.9	1.9	1.0	2.2	1.2
Minimum		-9.8	-9.5	-9.5	-9.9	-9.2	-8.7	-9.5	-2.0	-9.9	-9.8	-9.9	-2.5
Maximum		8.3	9.6	7.1	10.0	9.1	7.0	8.9	8.9	9.9	2.8	10.0	9.9
Range		18.1	19.1	16.5	19.9	18.3	15.7	18.3	11.0	19.8	12.6	19.9	12.3
Interquartile Range		2.9	2.3	1.8	3.0	3.4	1.5	2.9	1.3	2.5	1.2	3.0	1.5
Skewness		0.0	-0.2	-0.6	-0.2	0.0	0.1	-0.1	1.4	0.2	-0.7	-0.3	1.5
Kurtosis		0.3	1.0	3.2	1.1	-0.4	3.3	-0.2	7.4	0.5	3.5	0.4	6.5

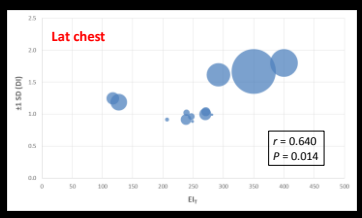
DI distribution was not reliably correlated with EI_T



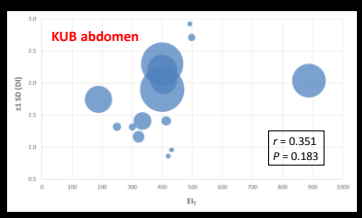
DI distribution was not reliably correlated with EI_T



DI distribution was not reliably correlated with EI_T



DI distribution was not reliably correlated with EI_T



How can we use this information for quality control?

Well isn't that neat! What do you use it for?

1. Review your DI data.

- Mean DI should equal 0.0
  - EI_T configured properly
  - Equipment calibrated properly
  - Equipment used properly (process)
- Compare your DI distribution to the data in TG-232
  - Most importantly, the standard deviation of the DI

Best and worst case SD(DI) – all sites – adult

Table 12. Standard deviation of the DI for adult radiography.

Body part	View	Site with the smallest standard deviation of the DI*		Site with the largest standard deviation of the DI*	
		Number of exams	Standard deviation of DI	Number of exams	Standard deviation of DI
Abdomen	KUB	3746	1.8	8389	3.1
	Upright	931	1.3	1002	2.9
	Decubitus	6401	2.3	1200	3.6
Chest	AP	12491	2.0	43915	2.3
	PA	12061	1.7	20424	2.2
	Lateral	20810	1.7	16260	1.9
	Decubitus	--	--	--	--
Pelvis	AP	2236	1.6	1480	2.8
Extremity	Lower Extremity	17175	2.7	83209	3.3
	Upper Extremity	4877	1.8	21389	2.7

*Number of examinations from site was at least 10% of the total number of examinations from all sites
--: Insufficient sample size (data provided in Appendix A for reference).

Best and worst case SD(DI) – all sites – peds

Table 13. Standard deviation of the DI for pediatric radiography.

Body part	View	Site with the smallest standard deviation of the DI*		Site with the largest standard deviation of the DI*	
		Number of exams	Standard deviation of DI	Number of exams	Standard deviation of DI
Abdomen	KUB/Babygram	437	1.5	1499	2.7
	Upright	--	--	--	--
	Decubitus	--	--	--	--
Chest	AP	928	1.8	888	2.2
	PA	957	1.5	1960	2.2
	Lateral	1422	1.7	2922	2.5
	Decubitus	--	--	--	--
Pelvis	AP	177	1.3	630	2.5
Extremity	Lower Extremity	1452	2.2	10759	3.0
	Upper Extremity	1036	1.7	6012	2.5

*Number of examinations from site was at least 10% of the total number of examinations from all sites
--: Insufficient sample size (data provided in Appendix A for reference).

2. Review your EI_T values.

- Mean DI should equal 0.0
- Remember, the EI is an ***indicator***
- Stick around for the next talk

3. Adjust your DI limits.

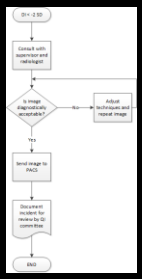
- DI limits should consider
  - Body part and view
  - Practice setting, including characteristics of radiologists
  - Image receptor technology
  - Image processing algorithm
  - VOI identification method
- A tiered review process should be triggered when DI limits are exceeded

Tiered review process

Table 14. Recommended action limits and associated actions for the deviation index (DI).

DI	Possible action
DI outside ±1 standard deviation	Log for possible review, tally number of occurrences for periodic review.
DI greater than +2 standard deviations	See fault tree in Figure 5.
DI less than -2 standard deviations	See fault tree in Figure 6.

*Note these limits may need to be adjusted based on EI_T.



4. Repeat

Needs to make the DI more useful

- Utilities for configuring global EI_T values for broad categories
- The ability to set DI limits at any level of granularity, from a single universal set of limits to limits by individual body parts and views
- Both of the above may be accomplished by allowing upload of EI_T values and DI limits in a specified file format
- Utilities for easily filtering and downloading EI_T values, EI data, and DI data, preferably over the network
- An optional overlay of the identified VOI on the FOR PROCESSING image data

In the end

- It's time that we used the data that are available to us
- To drive quality control and quality improvement
- The FDA should mandate that the IEC EI and DI be reported by all digital radiography systems in the US
- State regulatory agencies should mandate that sites have a QA program for their radiography operation and log and review the DI and EI_T