Pediatr Radiol
DOI 10.1007/s00247-010-1951-9

MINISYMPOSIUM

Quality assurance: using the exposure index and the deviation index to monitor radiation exposure for portable chest radiographs in neonates

Mervyn D. Cohen · Matt L. Cooper · Kelly Piersall · Bruce K. Apgar

Received: 4 June 2010 / Revised: 19 November 2010 / Accepted: 27 November 2010

Abstract
Background Many methods are used to track patient exposure during acquisition of plain film radiographs. A uniform international standard would aid this process.
Objective To evaluate and describe a new, simple quality-assurance method for monitoring patient exposure. This method uses the "exposure index" and the "deviation index," recently developed by the International Electrotechnical Commission (IEC) and American Association of Physicists in Medicine (AAPM). The deviation index measures variation from an ideal target exposure index value. Our objective was to determine whether the exposure index and the deviation index can be used to monitor and control exposure drift over time.
Materials and methods Our Agfa workstation automatically keeps a record of the exposure index for every patient. The exposure index and deviation index were calculated on 1,884 consecutive neonatal chest images. Exposure of a neonatal chest phantom was performed as a control.
Results Acquisition of the exposure index and calculation of the deviation index was easily achieved. The weekly mean exposure index of the phantom and the patients was stable and showed <10% change during the study, indicating no exposure drift during the study period.
Conclusion The exposure index is an excellent tool to monitor the consistency of patient exposures. It does not indicate the exposure value used, but is an index to track compliance with a pre-determined target exposure.

Keywords Exposure index · Deviation index · Radiation safety · Neonate

Introduction

Plain film radiographs should be obtained using a radiation exposure level that is as low as reasonably achievable [1]. There are many difficulties in minimizing radiation exposure for portable chest radiographs in premature infants. There are many reasons the radiographic exposure might be much higher than needed.

The majority of portable pediatric chest radiographs are performed on digital computed radiography systems (CR). The benefits of the CR systems include faster acquisition and image processing than old screen-film systems, plus a wide dynamic range, computer-aided adjustment of contrast and brightness, and electronic cropping. Unfortunately, the amount of radiation exposure is more difficult to assess with digital imaging than with a screen-film system [2–5]. With screen-film systems the density on the film is closely related to the exposure to the patient. Assessing patient exposure on plain films is a straightforward process, i.e., overexposed images are too dark and underexposed images are too light. On digital images underexposure is relatively easy to detect, as images contain a large amount of noise and appear very grainy. There is no appreciable noise in overexposed images. Because of the wide dynamic range of

M. D. Cohen · M. L. Cooper · K. Piersall
Department of Radiology, Riley Children's Hospital,
Indiana University School of Medicine,
Indianapolis, IN, USA

M. D. Cohen (✉)
Department of Radiology, Riley Hospital for Children,
702 Barnhill Drive, Rm. 1053,
Indianapolis, IN 46202, USA
e-mail: mecohen@iupui.edu

B. K. Apgar
Agfa HealthCare Corporation,
Greenville, SC, United States

Published online: 30 December 2010

digital systems, post-processing of an overexposed image will result in no appreciable difference detectable to the human eye between an image that was obtained with the proper amount of radiation and a study that was obtained with excessive radiation. They all have the same grayscale. Unintended excessive exposure and subsequent unnecessary patient radiation is termed "dose creep" or "dose drift." Radiation dose can increase markedly without any detectable change in the final image [3–5]. Upward drifting of radiation exposure can be a significant problem in the newborn nursery [2]; it can occur without the radiologist being aware of the problem. Thus some type of monitoring other than the appearance of the clinical image is required to assure that excessive exposure does not occur.

An imaging department has many methods to track radiation exposure in the newborn nursery. These methods track dose to the detector. Almost all of these methods are time-consuming to implement, cumbersome, and often not very accurate. Accurately measuring exposure with CR imaging is a problem that medical equipment manufacturers have attempted to address. Each manufacturer developed its own exposure index to reflect exposure (Table 1). Each index had its own name and value range [6]. These indices can be viewed on individual images but are difficult to collect and analyze for large numbers of patients.

In 2008 the International Electrotechnical Commission (IEC) and in 2009 the American Association of Physicists in Medicine (AAPM) separately developed the exposure index (EI) to set an international standard to indirectly measure the radiation exposure to a digital detector [7, 8]. The EI is designed to generate a linear relationship between the index value and detector exposure. A target exposure index value is set for each examination type. This target exposure index is different for each body part (chest, abdomen, foot, etc.), and can vary by examination room (dependent on factors such as filtration, sensitivity of detector plate, etc.). Thus the actual value of the exposure index cannot be used by technologists or radiologists to track patient dose. To overcome this problem the concept of a deviation index was developed. Once an acceptable detector exposure has been decided and a target exposure index set, one can easily calculate a deviation index. The deviation index calculates the difference between a desired target exposure index and the actual exposure. The units used to describe the degree of deviation are clearly defined (Table 2) [8]. Using the table it can easily be seen that for any digital CR radiograph, a deviation index of +3 indicates that the technologist used an exposure double that of the target for that body part. The deviation index can be displayed automatically in PACs for every radiograph and can also be collected for large numbers of patients over time, for analysis.

The formula for calculating the deviation index is:

$$\text{Deviation index} = 10 \times (\text{Log}_{10}(\text{exposure index}/\text{target exposure index})$$

The purpose of this study was to apply and evaluate the newly developed exposure index in clinical practice. We did this by evaluating exposure index in chest radiographs in our newborn nursery. In particular we wished to find out whether exposure index could be easily determined in large numbers of patients and to understand difficulties in data collection and analysis. We wished to determine the mean and range of the measured exposure index. Using a phantom as a control we wished to determine the stability of the index over time. We also wished to explore application of the deviation index—a method of expressing deviation from a predetermined target exposure index. Finally, we wished to understand the strengths and limitations of using the exposure index in routine clinical practice and to make recommendations for its use.

Materials and methods

The exposures were all made using a GE AMX 4 portable X-ray unit (GE Healthcare, Milwaukee, WI, USA). Total

Table 1 Four manufacturers' ways of measuring image receptor exposure. This is contrasted with the new IEC exposure index

Exposure in microgray	Fuji S number	Canon REX	Agfa Healthcare LGM	Carestream EI	Exposure index
2.5	710	30	1.96	1,451	250
5	355	60	2.26	1,751	500
10	177	120	2.56	2,051	1,000
20	89	240	2.86	2,351	2,000

Table 2 Deviation index. This table shows how the deviation index varies for fixed percentage changes in the exposure index

Microgray	Exposure index	Target exposure index	Deviation index	Exposure factor	Percentage change
13	1,300	500	4	2.60	160%
10	1,000	500	3	2.00	100%
8	800	500	2	1.60	60%
6.3	630	500	1	1.26	26%
5	500	500	0	1.00	0%
4	400	500	−1	0.80	−20%
3	300	500	−2	0.60	−40%
2.5	250	500	−3	0.50	−50%
2	200	500	−4	0.40	−60%

filtration on this unit is 3.4 mm of aluminum. We continued utilization of our existing exposure instructions for our technologist. These require a standard exposure of 64 kVp and 0.8 mAs for the majority of infants. For very small babies (less than about 750 g), this is reduced to 62 kVp and 0.8 mAs. For large babies (more than about 2,500 g), exposure is increased to 66 kVp and 0.8 mAs. Babies' weights are not specifically checked before each exposure and the technologists have some discretion in determining which exposure to use.

The images are obtained and processed on Agfa Healthcare's DXS CR system (Ridgefield Park, NJ, USA) and its NX technologist workstation and exposure-monitoring quality-assurance software. This software allows automatic storage of the exposure index for every image. It can also store identification of the technologist taking the image and the time and date of the acquisition. The data can be downloaded at any time for statistical analysis.

Our study was *not* designed to determine optimal exposure factors for neonatal portable chest radiographs. We continued to use our existing exposure factors. As an indictor of the actual dose from these exposure factors we imaged our neonatal phantom with similar factors (Table 3). The measured skin entrance air kerma was 34.6 μGy.

In order to calculate our deviation index, we set the target exposure index as the mean of our first 50 patients. The deviation index was calculated using the formula given in the introduction, and presented using the description in Table 2. The target exposure index for the phantom was calculated using the average exposure index from the first week.

The exposure index and the deviation index were calculated on 1,884 consecutive neonatal chest images acquired during a 3-month period, October—December 2009. The data were displayed for each acquisition over the entire time period as a means to evaluate for any temporal dose changes.

The Gammex Neonatal Chest Phantom (Gammex Corp., Middleton, WI, USA) is designed to simulate the chest of a 1,500-g baby. Exposure of this phantom was designed to act as a control. We used an exposure of 68 kVp and 0.8 mAs. Anode-plate distance was kept at 40 in. A total of 34 chest phantom exposures were done during the study, Oct. 1 to Dec. 31, 2009. The exposure index and deviation index values for the chest phantom exposures were calculated.

The Kolmogorov-Smirnov and Ryan-Joiner statistical tests were used to check normality of the data. To determine whether the patient data shifted during the study, the first 200 samples were compared to the last 200 samples using a two-sample *t* test with a *P*-value of 0.15.

Results

The daily individual patient exposure index is shown (Fig. 1). A graph of the mean weekly exposure index is also shown (Fig. 2). Although there is some variation among individual patients, the exposure index appears to be relatively stable during the 3-month study. The mean weekly exposure index for the patients is shown in Table 4. There is a very slight increase in the mean weekly exposure index during the 13 weeks of the study, as seen in the table and in Fig. 2. The calculated increase was less than 10%. This was not statistically significant, using a two-sample *t* test and with a *P*-value of 0.15.

The mean of the neonatal chest exposure index during the period was 371 and the standard deviation was 154. The target exposure index used was 338 based on the first 50 exposures. Ninety-three percent of the exposures fell between 169 and 676 (+ or −3 deviation units).

The histogram for the patient exposure index data is shown in Fig. 3. The distribution is not normal. The *P*-value is 0.005 and the Ryan-Joiner correlation coefficient is 0.93. The data appear to be log normal. The log transformed data (Fig. 4) produced a Ryan-Joiner correlation coefficient of 0.997, a definite case to accept normality. The *P*-value was 0.057 using the Kolmogorov-Smirnov test. The only deviation from normality was on the tails of the distribution. This deviation is most likely a result of assignable causes such as overexposure and mal-positioning, but further study needs to be done to confirm this. The distribution of the deviation index is log normal as well, since it is a mathematical (log) calculation from the exposure index and a fixed target exposure index. Since the exposure index data are skewed (log normal) the standard deviation might be somewhat misleading. The standard deviation of the deviation index would be a more accurate number to monitor.

For the phantom the measured exposure index is shown in Fig. 5, and the histogram for the measured values is

Table 3 Entrance dose for the phantom

Phantom entrance dose						
Site	kVp	mAs	Total filtration mm AL	HVL mm AL	Entrance air kerma μGy	Exposure index
Riley Children's	68 kVp	0.8	3.4	2.71	34.62	608

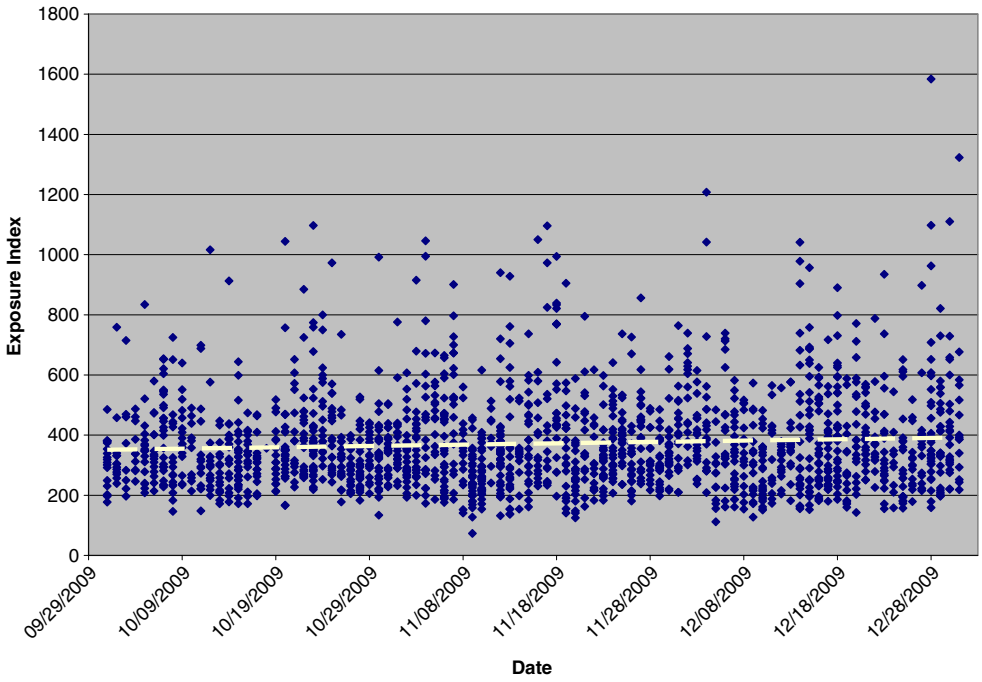

Fig. 1 Exposure index for 1,884 consecutive neonatal chest radiographs during a period of 3 months, from Oct. 1 to Dec. 31, 2009

shown in Fig. 6. The mean of the phantom exposure index during the study period was 436 and the standard deviation was 36. The target exposure index used based on the first week was 416. One hundred percent of the exposures fell between 330 and 524 (+ or −1 deviation unit).

The patient exposure index variation was much greater than that of the phantom. The phantom data show a *P*-value of greater than 0.10 and a Ryan-Joiner correlation coefficient of 0.99, a definite case to accept normality. The phantom exposure conditions were more closely controlled, using the same object, distance and exposure factors each day, and thus were less susceptible to error from assignable causes. Over time the weekly exposure index of the phantom increased 8%, a change similar to that of the patients (Fig. 2).

The deviation index histogram for the patients shows a normal bell-shape distribution (Fig. 7). The mean is 0.08 and the standard deviation is 1.67. The mean weekly deviation index results for the patients and for the phantom are given in Tables 4 and 5.

The distribution of patient deviation index was as follows: between −1 and 1, 46%, i.e., 46% of exposures were between 20% below and 26% above the target; between −2 and 2: 78%, i.e., 78% of exposures were

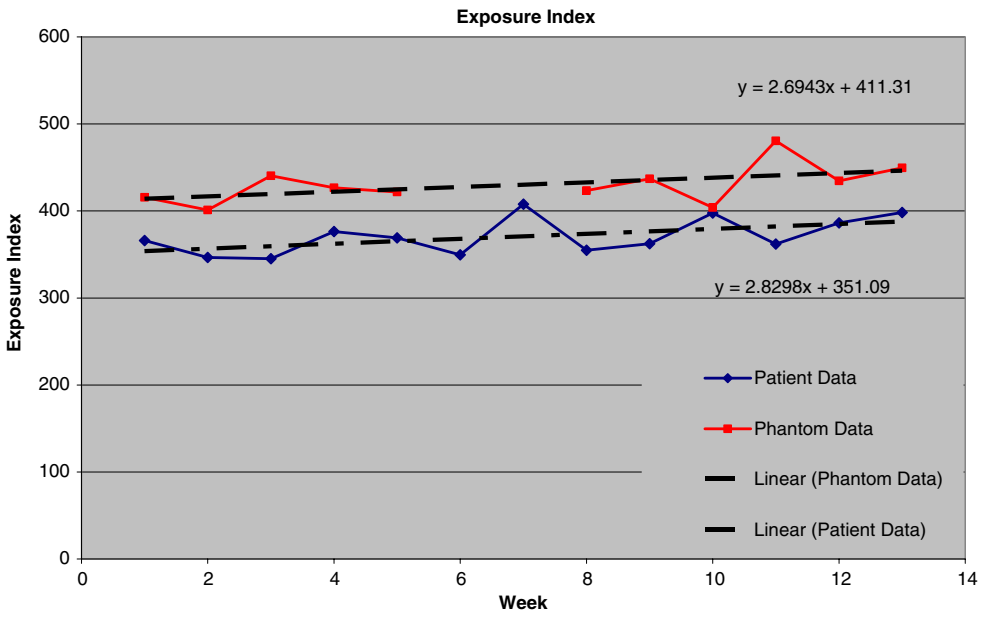

Fig. 2 Mean weekly patient and weekly phantom exposure indices during the 3-month period from Oct. 1 to Dec. 31, 2009

Table 4 Mean weekly patient exposure index and standard deviation from the target exposure for the 1,884 neonatal chest radiographs

	Weekly patient data			
Week	Patient exposure index	Target exposure index	Patient deviation index	Weekly EI st dev
1	366	338	0.35	127
2	347	338	0.11	146
3	345	338	0.09	123
4	376	338	0.47	151
5	369	338	0.38	146
6	350	338	0.15	147
7	408	338	0.81	199
8	355	338	0.21	131
9	362	338	0.30	123
10	398	338	0.71	172
11	362	338	0.30	175
12	386	338	0.58	150
13	398	338	0.71	210
Average	371	338	0.40	154

between 40% below and 60% above the target; between −3 and 3: 93%, i.e., 93% of exposures were between 50% below and 100% above the target.

Two percent of exposures were less than −3 deviation units or less than 50% of the target exposure. Five percent of exposures were more than +3 deviation units or greater than 100% above the target exposure. See Table 2 for explanation of the deviation index numbers.

The distribution of the phantom deviation index was much narrower, as follows: between−1 and 1: 100%, i.e., 100% of exposures were between 20% below and 26% above the target.

Discussion

With any digital imaging system excessive radiation dose might be utilized (dose creep) without the technologists or radiologists recognizing the problem. The risk of dose creep is especially important in premature babies, as these infants frequently have a large number of radiographs done, are immature and thus more susceptible to harm from radiation and, as they still have a long life to live, there is time for harmful effects from radiation to develop [6].

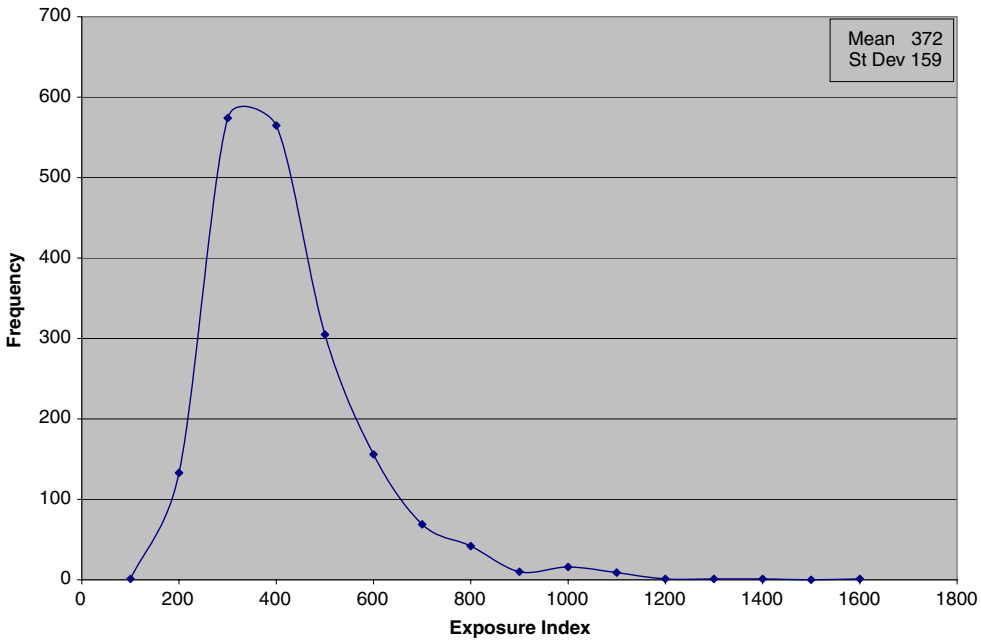

Fig. 3 Histogram for exposure index for 1,884 consecutive neonatal chest radiographs during the 3-month period from Oct. 1 to Dec. 31, 2009

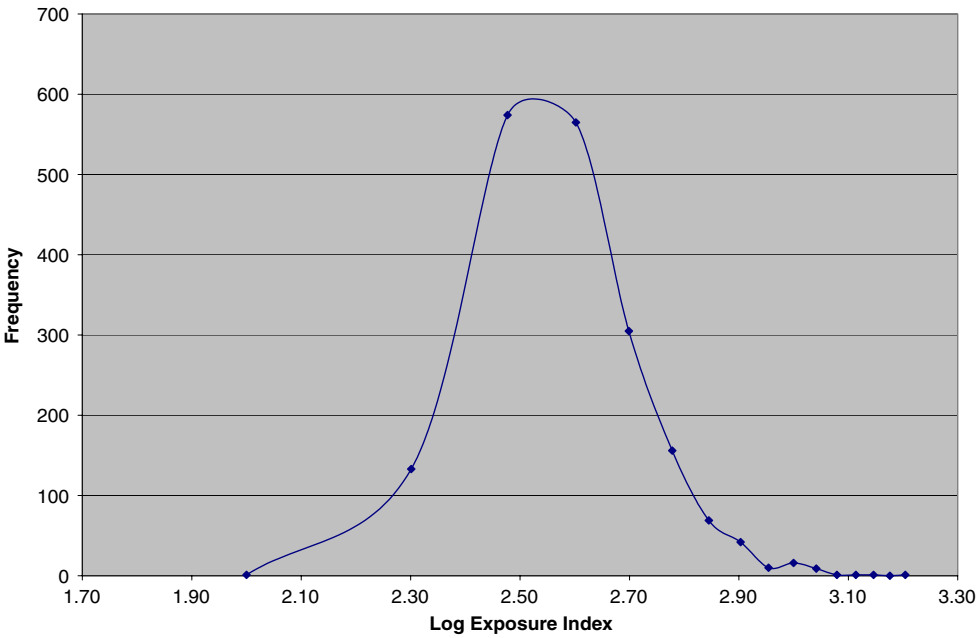

Fig. 4 Log plot of the histogram for exposure index for 1,884 consecutive neonatal chest radiographs during the 3-month period from Oct. 1 to Dec. 31, 2009

There are many cumbersome ways of trying to identify dose creep in a neonatal nursery. A department might have standard kV and mAs settings for the technologist. It could then track compliance with these protocols. As the kV and mAs do not appear on the final images, this requires manual tracking and logging of the data on a case-by-case patient basis. This is too time-consuming for a routine quality-assurance program. Tracking kV and mAs might not even be a good indicator of overall neonatal radiation exposure because it does not account for variations in distance from the patient to the radiation source, variations in tube output of the portable X-ray machine, and the size of the patient.

One of the key advantages of digital systems is the ability to record the exposure to the receptor. With CR systems, this value is stored and displayed as a number related to the amount of the X-ray exposure incident on the plate. Manufacturers have developed indices for this value that are unique to their systems (Table 1). Examples include the Fuji S number, Agfa LGM index, Canon REX value and various other types of exposure values [6, 8]. These values respond in different ways to changes in exposure,

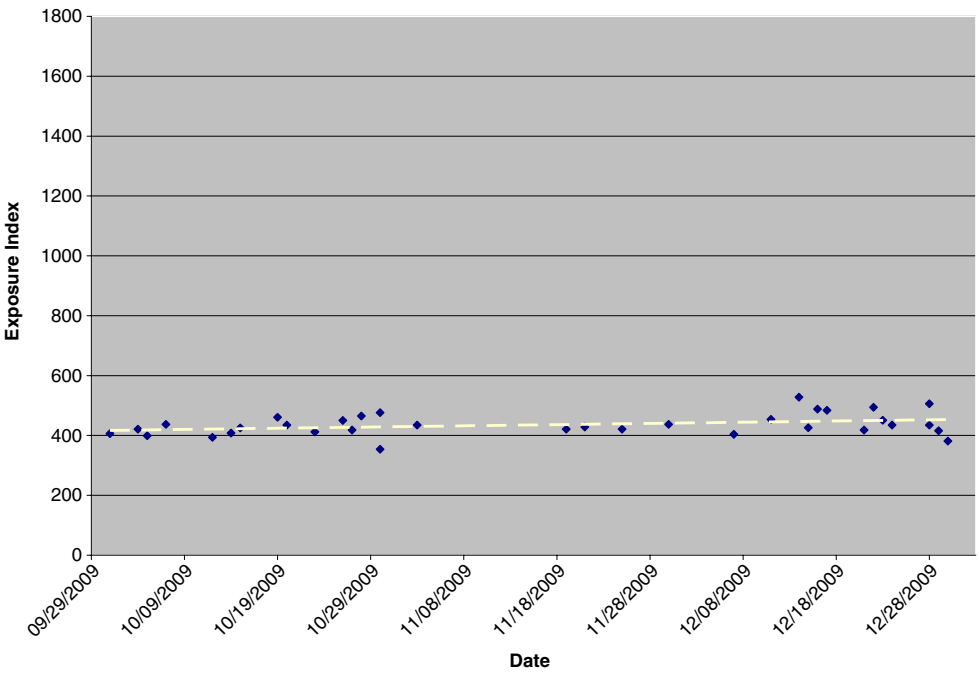

Fig. 5 Exposure index for 34 phantom exposures during the 3-month period from Oct. 1 to Dec. 31, 2009

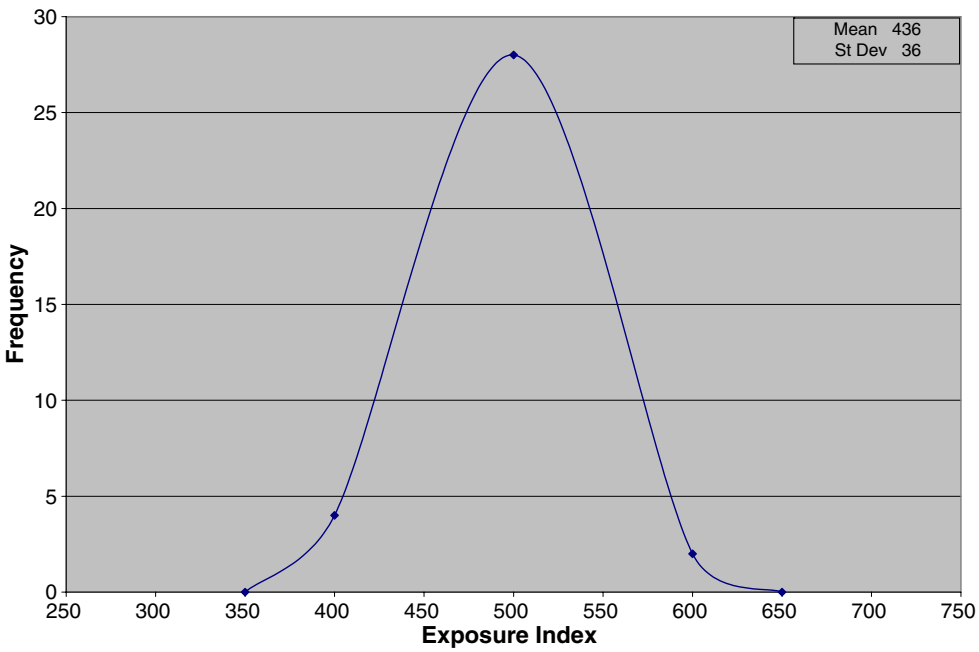

Fig. 6 Histogram of the Gammex phantom exposure index during the 3-month period from Oct. 1 to Dec. 31, 2009

some increasing with increased exposure and some decreasing with increased exposure.

For example, typical ranges of the "S number" developed by Fuji were 200 to 800 but the value decreased with increased exposure. Some of these indices change in a logarithmic fashion and some change in a linear fashion. Needless to say, there is a confusing variety of indices when multiple systems are used within a department. The result is that they might be ignored. Another reason these numbers have largely been ignored is that the data are acquired on a case-by-case basis. Acquiring a large number of data points for a valid QA program would require a tiresome manual method of tracking and recording the number for each patient.

The recently developed exposure index provides a standardized exposure value that responds in a similar fashion for all digital radiography systems, irrespective of the manufacturer. As applied on our Agfa CR system the exposure index for all patients is automatically recorded so that large datasets can easily be acquired and analyzed. Previously, exposure data lacked a standard definition to provide uniformity among vendors. The exposure data were

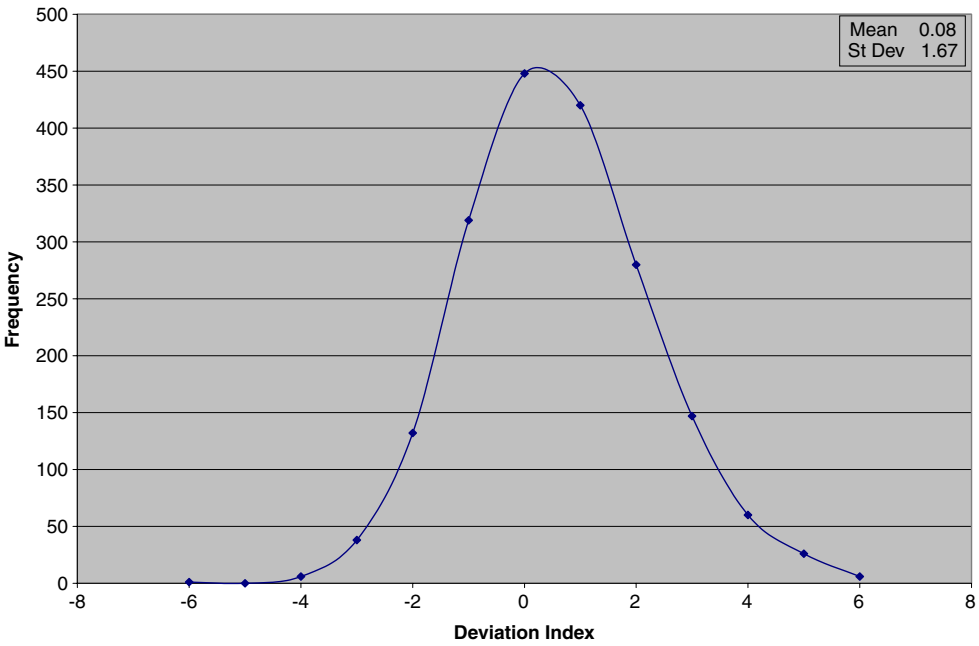

Fig. 7 Histogram for the deviation index for 1,884 consecutive neonatal chest radiographs during the 3-month period from Oct. 1 to Dec. 31, 2009

Table 5 Mean weekly phantom exposure index and deviation index

	Chest phantom data		
Week	Phantom exposure index	Target exposure index	Phantom deviation index
1	416	416	0.00
2	401	416	−0.16
3	440	416	0.25
4	427	416	0.11
5	422	416	0.06
6		416	
7		416	
8	423	416	0.08
9	437	416	0.21
10	404	416	−0.13
11	481	416	0.63
12	435	416	0.19
13	450	416	0.34
Average	430	416	0.14

difficult to analyze because the CR manufacturers did not provide software tools to allow easy access to the data. During routine daily work, the exposure index and deviation index are displayed for the technologist in numerical and graphical form. A summary chart showing a running average and the standard deviation for each exam is available at the workstation. DICOM tags are provided so the exposure index, deviation index and target exposure index values can be sent to the PACS and displayed with each image for the radiologist reading the study. In addition, large datasets acquired over time can be submitted for detailed analysis to identify trend changes and causes.

For our Gammex phantom, the mean exposure index was 430. There is a normal distribution histogram of the EI with 95% of values between 363 and 508. Our exposure settings and distances were constant for all exposures of the phantom. Phantom position was kept constant. The results show some mild variation in the exposure index over time. The cause for this is not known. It could be related to daily variations of output from the tube of our portable X-ray machine or to slight variations in the sensitivity of our phosphor plates.

There is a much wider variation in the exposure index for our patients. This wide distribution of patient data could be explained by many factors. The most important reason is believed to be the variation in patient size. We used only three sets of exposure factors to cover all of the different-size babies in our nursery. Other factors include variation in tube output, technologist errors and variation in anode-detector distances resulting from problems in positioning the portable X-ray machine around different incubators.

During the 3 months of our study, the exposure index indicated that we were not experiencing significant upward exposure drift. This conclusion is validated by the results of our phantom studies.

The patient exposure index distribution is skewed; however the exposure index distribution is logarithmic normal and the deviation index is normal. Because X-ray absorption is related exponentially to patient thickness, it would be expected that the exposure index would be skewed if the patient size distribution is normal. Of interest, Willis et al. [9] had previously shown that the Fuji S number was also log-normally distributed based on patient X-ray absorption.

As the exposure index is collected automatically, for all of our exposures, it will be easy to institute an ongoing QA program designed to detect any exposure drift. If this is detected then data can be further analyzed to determine whether the upward exposure drift is related to any technologist shifts, or even to an individual technologist. Thus not only can upward exposure drift potentially be identified, but appropriate corrective action can then be implemented.

The deviation index expresses the variation of the exposure index from the set target. It is a measurement of how far the exposure index for a given patient exposure is from a target exposure value. It provides a relative indication for under-exposure or over-exposure. The deviation index is very specifically defined, as shown in Table 2. Thus one deviation unit equals 26% increase (+1) or 20% decrease (−1) in exposure; and three deviation units equal 2× exposure or 1/2 exposure (+3 or −3).

Using the deviation index we can thus easily compare differences in deviations from a target exposure. The difficulty is that the target exposure index, from which the deviation index is calculated, must be somewhat arbitrarily determined.

We wished to study application of the deviation index and evaluate the extent of deviation. This study did not tell us whether our exposures are appropriate, too high or too low, but it did allow us to test the concept of using a calculated deviation index, in addition to the exposure index.

The deviation index distribution for the phantom images has a narrow distribution, with less than one deviation unit for 100% of the images. The distribution of the deviation index for the patient images was greater, with 95% of the images falling between −3 and 3, which represents a change in exposure of 2× or 1/2 x a target value. Considering the large variation in weight of the babies in our newborn nursery, this is an expected result. During each week of the study the mean deviation index for both the patient and phantom images was fairly consistent with very little drift. This would indicate that the exposure to the patient was relatively consistent during the time period of our study. The fact that the phantom and average patient deviation values track each other confirms this.

Exposure index disadvantages

At first glance it appears as though the exposure index can be used to track patient radiation exposure for all plain film imaging studies. Although it is true that the exposure index tracks in a linear fashion with changes in mAs, many other factors change the exposure index. These include beam conditions (kVp and beam filtration), grids, the patient anatomy and the screen phosphor structure used [8]. Different types of exams will have different target exposure index values based on the exposure to the body part, the sensitivity of the system and the final amount of radiation that ultimately reaches the detector. The response of exposure index to increased exposure is only linear if the kVp is constant. If kVp is increased and the exposure kept constant, the exposure index increases in a non-linear fashion (Fig. 8). Thus exposure index is an excellent method of tracking radiation exposure in a specific population (e.g., newborn infants), for a given body part (e.g., chest), for a specific imaging system and when the kVp is kept relatively constant. Because exposure factors such as kVp and filtration vary among institutions, the exposure index cannot be used to accurately determine variations in radiation exposure among institutions, even for a given study such as neonatal chest radiographs. It can, however, be used to identify possible outliers. To overcome some of these problems, the concept of setting a target exposure index was developed by the IEC and the AAPM [6, 8]. The target is very specific and is set for a body part, using a specific imaging system. The target exposure index is a value that represents a desired satisfactory exposure. It can be set based on historical knowledge or it can be determined by statistical averaging (e.g., of 50 exposures).

It is extremely important to appreciate that the exposure index is not a measure of patient radiation dose—it is only a method of tracking compliance with a predetermined satisfactory exposure.

Conclusion

A key goal in a newborn nursery is to establish the optimal exposure for each exam type, then to assure that

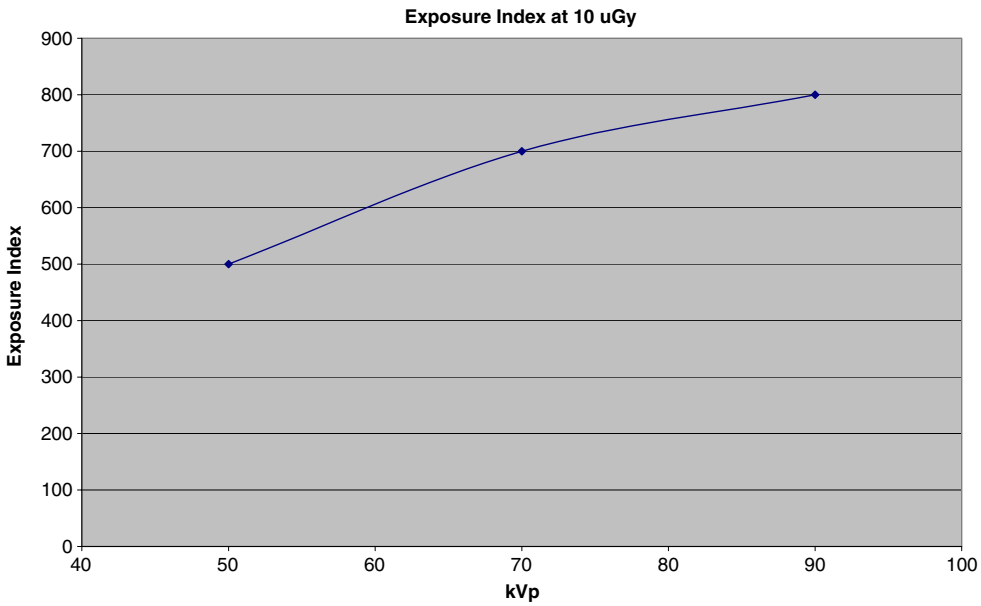

Fig. 8 Exposure index increases as kVp increases, when overall exposure is kept constant by adjusting mAs

exposure is consistent over time, without significant drift up or down in exposure index. In a perfect system, the deviation index should be close to 0. The exposure index and deviation index are excellent tools to monitor the consistency of patient exposures, as measured by exit dose to the detector, for chest radiographs, on large numbers of neonatal patients. The method is intuitive and easily implemented. When used in conjunction with the Gammex neonatal phantom, changes in exposure can be identified and corrective action can be taken before they become clinically significant. If very high deviation indices were to be found in the future, our system would allow us to track them to specific days of the week, specific technologist shifts, or even to one individual technologist.

Conflict of interest Quality Assurance: Using the Exposure Index and the Deviation Index to Monitor Radiation Exposure for Portable Chest Radiographs in Neonates

Mervyn Cohen has a conflict of interest. He received $2000.00 from Agfa to support the study.

Bruce Apgar works for Agfa corporation. He provided help with data collection and analysis

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