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Authors
Chan, Sheila
Josephson, S Andrew
Rosow, Laura
et al.

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A Quality Assurance Initiative Targeting Radiation Exposure to Neuroscience Patients in the Intensive Care Unit

Sheila Chan, MD[1], S. Andrew Josephson, MD[1], Laura Rosow, MD[1], and Wade S. Smith, MD, PhD[1]

Abstract

Background: Patients admitted to an intensive care unit (ICU) with a primary neurologic disorder often receive multiple radiation-based diagnostic studies of the head and neck. Although radiation exposure puts them at risk of intracranial and neck tumors, the amount of radiation received is largely unknown. **Methods:** We sought to accurately collect cumulative radiation exposure data from radiation-based studies in a retrospective cohort of patients admitted to the neuroscience ICU (NICU) at a single institution. Radiation doses of studies were converted to estimated effective doses in mSv via literature-published formulas. To impact ordering practices, we piloted an educational initiative on patient radiation exposure to a cohort of physicians caring for patients with a diagnosis of acute subarachnoid hemorrhage. Patients were randomized to have radiation exposure data posted at the bedside for physician viewing. **Results:** We identified 641 patients from July 2010 to March 2011 who had received at least 1 computed tomography-based study of the head. Patients received on average 18.4 mSv of radiation from head and neck imaging. Patients with subarachnoid hemorrhage received the highest average levels of radiation exposure (37.1 mSv). Attributable risk of carcinogenesis was estimated to be low. A pilot educational initiative did not reduce the total estimated effective dose per patient. **Conclusions:** Accurate reporting of estimated effective doses for NICU patients is feasible and can be provided to ordering physicians to assist with clinical decision making and potentially lower exposure risk. Further strategies are needed to reduce unnecessary radiation exposure at the physician ordering level.

Keywords

cerebral angiography/adverse effects, cranial irradiation/adverse effects, intensive care units, neuroradiography, radiation dosage, radiation injuries/prevention & control, risk assessment, subarachnoid hemorrhage/radiography

Introduction

Although radiation-based technologies continue to lead modern advances in medical care, the consequences of increasing radiation exposure are just starting to be recognized. Neuroscience intensive care unit (NICU) patients may receive a particularly high number of radiological studies that use ionizing radiation. A single-center study estimated that for patients admitted with a diagnosis of subarachnoid hemorrhage, the average total head radiation was 80 mSv, and the lifetime attributable cancer risk from medical radiation exposure averaged 1 in 125 persons.[1] In comparison, a review of 1187 patients admitted to the General Internal Medicine service in 2008 in Quebec, Canada, estimated that the median annual effective dose to the cohort was 8.7 mSv per year, imparting an estimated lifetime attributable cancer risk of 3.5 incident cancers per 10 000 patients.[2] Patients admitted with neurologic disorders tend to receive high, repetitive exposures to the head and neck, putting them at theoretical risk of intracranial tumors and thyroid malignancies as well as other noncancer health risks such as vasculopathy and damage to the skin and ocular lens.[3]

Despite these risks, most medical centers do not provide standardized reporting of the amount of radiation exposure to patients.[4] Furthermore, most studies that calculate per-patient radiation exposures use literature-derived estimates based on scan type, despite wide variation in computed

[1] Department of Neurology, University of California, San Francisco Medical Center, San Francisco, CA, USA

Corresponding Author:
Sheila Chan, Department of Neurology, University of California, San Francisco Medical Center, 505 Parnassus, Rm M830 box 0114, San Francisco, CA 94143, USA.
Email: sheila.chan@ucsfmedctr.org

tomography (CT) and angiography techniques between medical centers and scanners. One study attempted to obtain real-time data by applying dosimeter badges to the heads of patients admitted with a diagnosis of subarachnoid hemorrhage, but technical difficulties, lost badges, and a required large amount of staff training limited applicability.[5] Additional attempts to reduce unnecessary physician orders through educational and feedback initiatives have met with mixed results and have primarily targeted laboratory test ordering.[6,7]

We sought to pilot an initiative to accurately document the cumulative amount of radiation exposure in a cohort of NICU patients at a single tertiary-referral, nontrauma medical center hospital using estimates reported directly from scanners used to obtain imaging studies. In addition, we trialed a quality improvement (QI) education initiative to physicians caring for patients with subarachnoid hemorrhage admitted to the NICU. We provided real-time feedback on cumulative radiation exposure to these physicians on a per-patient basis in order to assess the feasibility of providing this education feedback to ordering physicians in the hopes of impacting physician-ordering behavior.

Methods

The Committee for Human Research at the University of California San Francisco (CHR at UCSF) approved the study. Medical records for all patients admitted to the NICU from July 2010 to March 2011 were obtained. Our radiology staff felt that radiation protocols were relatively uniform throughout this time period. We queried the radiology database for all CT brain and conventional brain angiogram studies performed on these patients during their admission. Patient diagnosis was mapped through a look-up table to general diagnostic categories.

The descriptions of each radiological study were extracted for uniqueness and then mapped through a look-up table to study categories. Actual reported dose-length products (DLP) and dose-area products (DAP) for CT brain scans and conventional brain angiograms, respectively, were converted to estimated effective dose in mSv using formulas extracted from the literature.[8,9] For nonreported studies, an average based on the reported cohort was used. Fluoroscopy times for conventional brain angiograms were also collected.

Each patient was assigned a total estimated brain radiation exposure by summing the estimated effective doses of all studies received during the admission. The mean, standard deviation (SD), minimum, and maximum estimated effective doses per patient by diagnosis category and by study type were tabulated. Fluoroscopy time was correlated with DAP by linear correlation statistic. Estimate of carcinogenesis was made using models derived from the Biological Effects of Ionizing Radiation (BEIR) VII report.[10]

Following this first phase of the study, a prospective, observational study on practitioners caring for patients admitted to the NICU with a diagnosis of acute nontraumatic subarachnoid hemorrhage was performed as a QI initiative from February 15, 2012, to May 15, 2012. The time interval was limited by practical considerations. Practitioners included neurology and neurosurgical attendings, fellows, residents, interns, and nurse practitioners as well as neurointerventional radiology attendings and fellows. Exclusion criteria were practitioners caring for patients on a nonneurological/neurosurgical attending service and patients below 18 years of age. Informed consent was obtained from all practitioners participating in the study. A retrospective control cohort of practitioners caring for patients admitted to the NICU from October 1, 2011, to December 31, 2011, was also identified for comparison. We did not seek informed consent from this latter group since these practitioners did not participate in the survey, and only information on the medical care of their patients was collected. The CHR at UCSF approved a waiver of consent for patients included in the study and for practitioners included in the retrospective cohort.

Practitioners consenting to the study completed a written examination of knowledge regarding radiation exposure from medical diagnostic equipment and reviewed a vignette on study ordering behavior regarding radiation-based procedures. Practitioners were given the answers to knowledge-based questions immediately upon completion of the survey. During the intervention portion of the study, all practitioners, regardless of consent status, received educational materials and a 5-minute lecture on radiation exposure and had access to estimated radiation exposure tallies displayed in the bedside charts for patients with a diagnosis of subarachnoid hemorrhage. Patients admitted on odd-numbered days to the NICU had exposures displayed in bedside charts, whereas patients admitted on even-numbered days did not. Tallies followed the patient charts out of the ICU until the patients were discharged from the hospital. Methods for estimating cumulative radiation exposure to the head and neck were as mentioned earlier.

Data collected on patients during the 3-month prospective and retrospective time periods included length of ICU stay, total hospitalization stay, ventilation status, attending service, age, gender, study types, mortality, tallies of radiation-based studies, and associated estimated effective doses.

The primary outcome of this study was reduction in total estimated radiation exposure to the head and neck, per patient during the intervention compared to the retrospective time period. Secondary outcomes were reduction in total estimated radiation exposure per patient whose radiation exposure tallies were posted at the bedside compared to the concurrent control cohort, reduction in estimated radiation exposure, length of ICU stay, length of hospitalization, mechanical ventilation, and morbidity. t-tests and chi-square tests were used to assess for significant differences. Significance tests were 2-tailed, with α set at .05.

Results

In the initial retrospective study, we extracted medical records of 1129 patients who met the inclusion criteria. Of the 1129 patients, 641 (56.8%) had at least 1 CT brain or conventional

Table 1. Estimated Effective Radiation Doses to Brain by Diagnosis.

Diagnosis	Number of Patients	Total Effective Dose, mSv	Mean Total Effective Dose[a], mSv	Min Total Effective Dose[a], mSv	Max Total Effective Dose[a], mSv	Standard Deviation, mSv
Neuromuscular	1	0.1	0.1	0.1	0.1	0
Congenital	1	5.7	5.7	5.7	5.7	0
Demyelinating	1	3.5	3.5	3.5	3.5	0
Skull-based neurosurgery	1	3.2	3.2	3.2	3.2	0
Toxic/metabolic	2	63.1	31.6	8	55.1	23.8
Degenerative	2	3.9	12.0	0.7	3.2	1.3
Encephalopathy	3	74.9	25.0	11.5	48.7	17.0
Traumatic brain injury	6	69.1	12.0	2.1	22.8	7.9
Pain/headache	7	57.6	8.2	1.8	20.2	6.1
General	7	31.4	4.5	1.6	13.4	3.7
Functional neurosurgery	9	126.1	14.0	2.8	47.9	13.0
Neuroinfection	9	195.7	21.7	0.1	111.1	33.6
Ventriloperitoneal shunt	9	105.7	11.7	4	22.3	5.8
Spine	11	51.4	4.7	1.7	13.2	3.4
Infection	17	223.6	13.2	1.5	36.4	12.6
Skull	20	185.7	9.3	2	47.2	9.7
Epilepsy	26	134.6	5.2	1.3	19.5	5.1
Neurovascular	34	554.6	16.3	1.4	58.3	12.4
Intracerebral hemorrhage	45	818.6	18.2	1.6	58.3	14.4
Stroke	58	909.1	15.7	0.1	44.1	9.6
Aneurysm	84	1571.4	18.7	2.5	51.2	9.2
Tumor	142	1164.1	8.2	0.1	48.9	8.0
Subarachnoid hemorrhage	146	5413.3	37.1	0.1	103.8	23.2
Total	641	11766.5	18.4	0.1	111.1	

Abbreviations: Min, minimum; Max, maximum.
[a] Per Patient.

angiogram brain study (Table 1). Dose-area products and DLPs were reported for 612 of 2046 studies: 19.6% of cerebral angiograms, 28.3% of cerebral angiograms with intervention, 8% of CT portable studies, 26.2% of CT brain protocols, 84.5% of CT brain with and without contrast protocols, 100% of CT stroke protocols, 84.5% of CT angiogram brain studies, and 0% of CT angiogram/perfusion (CTA/CTP) brain protocols. For CTA/CTP brain protocol, an average dose based on CTA/CTP studies obtained during the subsequent month of October 2011 was used. Highest doses of radiation were in patients with subarachnoid hemorrhage (primarily nontraumatic at this institution, mean 37.1 $\pm$ 23.2 mSv), followed by toxic/metabolic disturbance (mean 31.6 $\pm$ 23.8 mSv), encephalopathy (mean 25.0 $\pm$ 17.0 mSv), neuroinfection (mean 21.7 $\pm$ 33.6 mSv), unruptured aneurysm (mean 18.7 $\pm$ 9.2 mSv), intracerebral hemorrhage (mean 18.2 $\pm$ 14.4 mSv), other neurovascular (16.3 $\pm$ 12.4 mSv), and ischemic stroke (mean 15.7 mSv, SD 9.6 mSv). The number of radiological studies and descriptive statistics of effective dose by study category is shown in Table 2. The range of effective estimated doses for each protocol was wide. Fluoroscopy times reported for conventional cerebral angiograms are linearly correlated with estimated effective dose, with a correlation coefficient of $r = .73$. The coefficient of determination, $r^2 = .53$, indicates that 53% of the variation in estimated effective dose can be explained by fluoroscopy time.

Patient characteristics for the QI initiative are shown in Table 3. A total of 53 patients with acute nontraumatic subarachnoid hemorrhage were identified in the 3-month retrospective control cohort compared with 30 patients identified during the intervention time period. Of the 30 patients in the intervention cohort, 19 were admitted on odd-numbered days of the month and had radiation exposure data posted at the bedside. There were no significant differences between the intervention and the retrospective control cohorts by attending service, gender, mortality, mechanical ventilation, mean age, and mean length of stay. This was also true of comparisons between patients in the intervention cohort who had data posted at the bedside and those who did not, with the exception of gender.

There was no significant difference in mean total estimated effective dose for radiation studies in the prospective cohort

Table 2. Estimated Effective Radiation Doses to Brain by Study Protocol.

Examination Category	Description	Number of Studies	Min Effective Dose, mSv	Max Effective Dose, mSv	Mean Effective Dose, mSv	Total Effective Dose, mSv
CT stroke protocol	Noncontrast, perfusion, and postcontrast scans of head, angiogram study of head and neck vessels	67	0.5	10.6	6.2	420.8
CT brain s/c contrast	Noncontrast and postcontrast scan of head	97	0.7	11.1	3.6	355.4
CT angiogram/ perfusion brain	Noncontrast, perfusion, angiogram, and post contrast scan of head	157	6.3	6.3	6.3	989.1
CT angiogram brain	Angiogram study of head	173	0.9	13.9	7.6	1317.0
Cerebral angiogram	Diagnostic conventional angiogram of the head and neck	219	1.91	24.24	11.27	2468.0
Cerebral angiogram intervention	Diagnostic conventional angiogram of the head and neck with interventional procedure	233	3.48	63.92	14.66	3415.7
CT portable brain	Noncontrast scan using portable CT scanner of head	441	0.1	6.1	2.7	1213.1
CT brain	Noncontrast scan of the head	659	0.1	19.3	2.4	1587.4

Abbreviations: CT, computed tomography; max, maximum; min, minimum; s/c, without.

Table 3. Patient Characteristics, Intervention Versus Retrospective Control Cohort.

				Intervention Cohort, 30 Patients		
Characteristic	Intervention Cohort, 30 Patients	Retrospective Control Cohort, 53 Patients	*P* Value	Bedside Data, 19 Patients	No Bedside Data, 11 Patients	*P* Value
Attending service, % neurology	27	30	0.77	21	36	0.40
Gender, % female	70	57	0.23	58	91	0.03
Mortality, % died	7	8	0.87	11	0	0.14
% Mechanical ventilated	47	51	0.73	53	36	0.38
Age, mean in years	62	59	0.34	62	63	0.74
Length of stay, mean in days	13	10	0.11	13	12	0.52
Total effective dose, mean in mSv	30.23	30.17	0.99	33.67	24.48	0.24

versus the retrospective (30.23 mSv vs 30.17 mSv, $P = .99$) There was also no significant difference for the intervention cohort who had data posted at the bedside versus those who did (33.67 mSv vs 24.48 mSv, $P = .24$).

Mean numbers and estimated doses per patient for the most common CT-based studies are shown in Table 4. There were no significant differences in either the retrospective versus intervention time period or in the retrospective cohort who had radiation data posted at the bedside versus those who did not. No patients were estimated to receive over 100 mSv to the head and neck.

Discussion

This study was a unique attempt to accurately and systematically document total radiation exposure to a large number of patients based on actual reported exposures imparted by individual studies to the head and neck. Within our NICU population, patients receive multiple doses of radiation to the head and neck in the form of diagnostic studies or as imaging modalities during therapeutic procedures. The BEIR VII report acknowledges excess cancer risk at exposures over 100 mSv. Three patients in our retrospective cohort were exposed to brain radiation estimates exceeding 100 mSv (Table 5). Two of these patients presented with a diagnosis of subarachnoid hemorrhage, and the principal source of radiation exposure was from conventional cerebral angiography. These patients were particularly young with ages of 44 and 57 years. Based on average life expectancy, these patients are expected to survive 15 to 20 years longer, well within the range of developing radiation-induced cancers.[11]

The BEIR VII estimates lifetime attributable risk of incidence and mortality for solid cancers for exposure to 100 mSv as 8 male and 13 female excess cases of malignancy, and 4.1 male and 6.1 female excess deaths, per 1000 exposed persons. Based on our current rates of admission and radiation-based studies, cases of excess solid tumor from neuroimaging in our neuroscience ICU would occur once every 1125 months for men and once every 692 months for women. Excess deaths would occur once every 2195 months for men and once every 1475 months for women. Although our estimates indicate little increased risk of carcinogenesis, other studies have shown

Table 4. Radiological Procedures Per Patient, Intervention Versus Retrospective Control.

Procedure	Intervention Cohort, 30 Patients	Retrospective Control Cohort, 53 Patients	*P* Value	Intervention Cohort, 30 Patients		
				Bedside Data, 19	No Bedside data, 11	*P* Value
Dose, mSv						
Cerebral angiogram	4.65	6.22	0.21	4.45	4.99	0.71
Cerebral angiogram intervention	10.06	8.28	.46	10.37	9.53	0.87
CT portable brain	3.67	3.28	0.70	3.53	3.92	0.82
CT brain	2.82	2.36	0.55	3.64	1.58	0.11
CT angiogram/perfusion brain	3.58	2.88	0.48	4.54	1.92	0.11
Mean total	30.23	30.17	0.99	33.67	24.48	0.24
Number of procedures performed						
Cerebral angiogram	1.03	0.79	0.24	1.00	1.00	1.00
Cerebral angiogram intervention	1.21	0.92	0.23	1.26	1.27	1.27
CT portable brain	1.17	1.06	0.73	1.11	1.27	1.27
CT brain	1.07	1.00	0.73	1.32	0.73	0.73
CT angiogram/perfusion brain	0.45	0.32	0.26	0.53	0.27	0.27
Mean total	4.93	4.09	0.19	5.21	4.55	4.55

Abbreviation: CT, computed tomography.

Table 5. Characteristics of Patients With Total Estimated Dose Exceeding 100 mSv.

Patient	1	2	3
Diagnosis	Neuroinfection	SAH	SAH
Attending service	Neurosurg	Neurosurg	Neurosurg
Died	No	No	No
Length of stay, days	124	13	30
Mech vent	No	Yes	Yes
Age, yrs	59	57	44
Sex	M	M	F
Cerebral angiogram[a]	0	20	11.3
Cerebral angio intervention[a]	0	63.9	73.3
CT portable brain[a]	41.7	3	8.6
CT brain[a]	39.9	2.8	0
CT brain s/c contrast[a]	22	0	0
CT Stroke[a]	0	0	0
CT angiogram brain[a]	7.5	7.7	4.1
CT angiogram/perfusion brain[a]	0	6.3	6.3
Total effective dose, mSv	111.1	103.8	103.6

Abbreviations: CT, computed tomography; Mech Vent, mechanical vent; s/c, without; M, male; F, female; SAH, Subarachnoid hemorrhage

[a] Total estimated effective dose, mSv.

higher rates perhaps related to differences in population selection, methods for estimating radiation dose, CT protocol, and physician-ordering behavior.[1,12] A protocol to accurately quantify and target reduction is feasible.

Little literature exists on cumulative radiation exposure to hospitalized neuroscience patients. Similar studies have typically derived estimates from the literature based on CT protocol type. At our institution, actual radiation exposure documentation is still far from comprehensive and is reported for only 30% of dictated studies. Reasons for this are diverse. For CT-based studies, the DLP entry is prone to error since these are hand entered by technicians. For conventional angiograms, the DAPs are stored manually, and therefore are not available in a searchable database. Additionally, our analysis shows that the estimated effective doses vary widely among scans performed within the same protocol. For example, the estimated effective dose of CT stroke protocols at our institution ranges from 6.2 to 10.6 mSv. In the literature, ranges are reported from 4.7 to 9.5 mSv,[13] 7.52 to 10.6 mSv,[14] and 11.8 to 27.3 mSv[15] at various institutions. Accurate documentation of individual radiation exposure should not rely on literature estimates or even medical center estimates but rather on actual reported exposures per study.

Our attempt at providing radiation exposure education and feedback to ordering physicians showed no discernible effect on estimated radiation exposure or the number of radiation-based studies performed. A previous study found that a standard ordering algorithm for patients with diagnosis of subarachnoid hemorrhage resulted in a 12.1% decrease in cumulative estimated radiation exposure.[16] Other methods of notifying physicians of patient radiation exposure at the time of ordering may be more effective and further research is needed to determine the best approach. For example, real-time cumulative radiation exposure information might be more effectively delivered via alerts at the computerized order entry level since electronic medical records are increasingly the main method by which practitioners access patient-level information.

There are multiple limitations to our study. The nature of a retrospective study limits the accuracy of data reporting. Many of our patients are transferred from other hospitals, and our records of the studies they received prior to transfer are incomplete; therefore, we may be underestimating radiation exposure. Additionally, the initial diagnostic evaluation is nondiscretionary relative to subsequent radiation-based studies obtained during hospitalization, and inclusion of these studies may have decreased the observed effects of our interventions on total radiation dose estimates. Variation in hospital care of subarachnoid patients prior to arrival at our institution, as well as variation in clinical context, precluded accurate, standardized assessments of each study's clinical nondiscretionary status. Physicians may choose even initial diagnostic studies based on radiation risk and dosing if this information was to be available to them at the time. Since all studies have an associated radiation dose and potentially influence ordering behavior, we chose not to remove any studies from the analysis.

The pilot status and related practical limitations of the QI initiative prevented us from including a larger number of patients to the intervention portion of the analysis. Small sample sizes limited the statistical power of our study.

Finally, methods used to derive estimated effective dose from DAP and DLP and to convert dose to cancer risk are conjectural, and conversions are prone to faults and variance in measurement technique, machine technology, and calculation assumptions. Ongoing longitudinal prospective studies of patients over the next few decades will help clarify cancer risk.

Patients treated in our neuroscience ICU receive a considerable amount of radiation to the head and neck, but the excess risk of development of solid tumors is likely low in most cases. Accurate reporting of radiation doses for these patients is feasible and should be provided to ordering physicians to assist with clinical decision making. Computerized alerts at order entry, education initiatives, and standardized ordering algorithms are potential methods for targeting excess risk.

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Declaration of Conflicting Interests

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References

1. Gelfand AA, Josephson SA. Substantial radiation exposure for patients with subarachnoid hemorrhage. *J Stroke Cerebrovasc Dis*. 2011;20(2):131-133.
2. Martineau-Beaulieu D, Lanthier L. Low-dose ionising radiation from medical imaging in patients hospitalised in Internal Medicine. *Intern Med J*. 2012;42(5):547-553.
3. Moskowitz SI, Davros WJ, Kelly ME, Fiorella D, Rasmussen PA, Masaryk TJ. Cumulative radiation dose during hospitalization for aneurysmal subarachnoid hemorrhage. *AJNR Am J Neuroradiol*. 2010;31(8):1377-1382.
4. Smith-Bindman R. Is computed tomography safe? *N Engl J Med*. 2010;363(1):1-4.
5. Mamourian AC, Young H, Stiefel MF. Cumulative radiation dose in patients admitted with subarachnoid hemorrhage: a prospective study using a self-developing film badge. *AJNR Am J Neuroradiol*. 2010;31(10):1787-1790.
6. Bunting PS, Van Walraven C. Effect of a controlled feedback intervention on laboratory test ordering by community physicians. *Clin Chem*. 2004;50(2):321-326.
7. Axt-Adam P, van der Wouden JC, van der Does E. Influencing behavior of physicians ordering laboratory tests: a literature study. *Med Care*. 1993;31(9):784-794.
8. Huda W, Ogden KM, Khorasani MR. Converting dose-length product to effective dose at CT. *Radiology*. 2008;248(3):995-1003.
9. Sarycheva S, Golikov V, Kalnicky S. Studies of patient doses in interventional radiological examinations. *Radiat Prot Dosimetry*. 2010;139(1-3):258-261.
10. National Research Council (U.S.). Committee to Assess Health Risks from Exposure to Low Level of Ionizing Radiation. *Health Risks from Exposure to Low Levels of Ionizing Radiation: BEIR VII Phase* 2. Washington, DC: National Academies Press; 2006.
11. Berrington de Gonzalez A, Iulian Apostoaei A, Veiga LH, et al. RadRAT: a radiation risk assessment tool for lifetime cancer risk projection. *J Radiol Prot*. 2012;32(3):205-222.
12. Pearce MS, Salotti JA, Little MP, et al. Radiation exposure from CT scans in childhood and subsequent risk of leukaemia and brain tumours: a retrospective cohort study. *Lancet*. 2012; 380(9840):499-505.
13. Cohnen M, Wittsack HJ, Assadi S, et al. Radiation exposure of patients in comprehensive computed tomography of the head in acute stroke. *AJNR Am J Neuroradiol*. 2006;27(8):1741-1745.
14. Diekmann S, Siebert E, Juran R, et al. Dose exposure of patients undergoing comprehensive stroke imaging by multidetector-row CT: comparison of 320-detector row and 64-detector row CT scanners. *AJNR Am J Neuroradiol*. 2010;31(6):1003-1009.
15. Mnyusiwalla A, Aviv RI, Symons SP. Radiation dose from multidetector row CT imaging for acute stroke. *Neuroradiology*. 2009;51(10):635-640.
16. Loftus ML, Minkowitz S, Tsiouris AJ, Min RJ, Sanelli PC. Utilization guidelines for reducing radiation exposure in the evaluation of aneurysmal subarachnoid hemorrhage: A practice quality improvement project. *AJR Am J Roentgenol*. 2010; 195(1):176-180.