Individualization of computed tomography protocols for suspected pulmonary embolism: a national investigation of routines

Berit Dymbe, Elisabeth Vespestad Mæland, Jorunn Rønhovde Styve and Albertina Rusandu

Abstract
Objective: Given the extensive use of computed tomography (CT) in radiation-sensitive patients such as pregnant and pediatric patients, and considering the importance of tailoring CT protocols to patient characteristics for both the radiation dose and image quality, this study was performed to investigate the extent to which individualization of CT protocols is practiced across Norway.

Methods: This cross-sectional study involved collection of CT protocols and administration of a mini-questionnaire to obtain additional information about how CT examinations are individualized. All public hospitals performing CT to detect pulmonary embolism were invited, and 41% participated.

Results: Tailoring a standard protocol to different patient groups was more common than using dedicated protocols. Most of the available radiation dose-reduction approaches were used. However, implementation of these strategies was not systematic. Children and pregnant patients were examined without using dedicated CT protocols or by using protocol adjustments focusing on radiation dose reduction in 30% and 39% of the hospitals, respectively.

Conclusion: Practice optimization is needed, especially the development of dedicated CT protocols or guidelines that tailor the existing protocol to pediatric and pregnant patients. Practice might benefit from a more systematic approach to individualization of CT examinations, such as inserting tailoring instructions into CT protocols.
Keywords
Pulmonary embolism, computed tomography, patient-centered imaging, protocol individualizing, radiation dose, pulmonary computed tomography angiography

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Introduction
The substantial increase in computed tomography (CT) use despite concerns about a potential increase in the risk of radiation-induced cancer is evidence of the value of CT in medical care. An increase in CT use has also been documented in Norway. Radiation doses for CT examinations vary considerably among patients, institutions, and countries, and the variation is mostly attributable to the way in which CT scanners are used (i.e., the technical parameters of the CT scanning protocols). The greatest variation (15-fold) is observed in CT examinations for suspected pulmonary embolism (PE).

CT pulmonary angiography (CTPA) is the first-choice method for diagnosing PE because of its accuracy, speed of diagnosis, and accessibility. The threshold for referral for CT because of suspected PE is low because of the high mortality (30% reported mortality when untreated) and PE is the third most frequent cause of death among cardiovascular diseases after myocardial infarction and stroke and nonspecific symptoms (such as chest pain and shortness of breath, which are common in many pulmonary and cardiac conditions). The main challenge associated with the use of CT for suspected PE is its frequent use in young female patients because of the higher risk of PE associated with oral contraceptives, pregnancy, and the postpartum state. The rate of CT use in pregnant patients has markedly increased during the last decade, and most of these examinations were performed for suspected PE.

The incidence of PE in children appears to be quite low, but it is often underestimated. However, the use of hormonal contraceptives among adolescents is increasing, especially among younger adolescents (12 to 15 years old), and contraceptives are prescribed to patients as young as 10 years old for various medical reasons such as excessive or irregular menstruation or treatment of acne. This increases the risk of PE in pediatric patients and the use of CTPA in this patient group. Despite the quite low incidence of PE, this patient group needs special attention because radiation-induced cancer in girls is estimated to result from every 330 to 480 chest CT examinations.

The use of CTPA in radiation-sensitive patients such as pregnant patients and female adolescents makes tailoring the CT protocol to the patient crucial to achieve the highest cost–benefit ratio in terms of the radiation dose and amount of contrast agent needed to obtain the required image quality. This goal can be achieved by patient-centered imaging which involves the use of patient-tailored CT scan protocols. Tailoring the imaging protocol to the patient is crucial for providing accurate information to the physician. Additionally, one of the most strongly emphasized advantages of protocol tailoring is the consistency of image quality across various patient sizes.

CT protocols should be tailored based on patient age, size, and clinical
condition, and dedicated pediatric protocols are often needed. Both the International Atomic Energy Association and the International Commission on Radiological Protection strongly recommend that only pediatric protocols should be used in children. Increased use of CT in pediatric patients together with a variation in radiation doses reinforces the need for optimization. Individualization of pediatric CT protocols can result in radiation dose reductions ranging from approximately 50% to 90% without compromising diagnostic image quality. Along with pediatric patients, another group who might benefit from radiation dose reduction are pregnant patients because of the rapid cell multiplication in both the fetus and mother.

Various approaches have been used to reduce radiation doses, such as reducing the scan length, lowering the kilovoltage peak settings, using automatic tube current modulation (ATCM), and using iterative reconstruction. ATCM is a widespread dose-reduction measure that allows the use of different tube currents (mA) along the z-axis depending on patient size and different attenuations depending on body regions. Organ dose modulation is a more advanced technique that reduces the tube current over the anterior aspect of the body and reduces the irradiation of the breast tissue. This technique was shown to be more efficient than ATCM in reducing the total radiation dose. A simple and highly effective dose-reduction approach is scan range reduction. A mean scan range reduction of 30% to 33% in the CTPA protocol can result in a 23% to 27% effective dose reduction. This benefits pregnant patients by allowing an 83% estimated radiation dose reduction to the fetus (explained by the increased distance between the fetus and the scanned volume). Another effective dose-reduction measure that is especially suitable for CTPA is the use of a lower tube potential. Previous studies have shown the feasibility of reducing the tube potential to 80 kVp. Reducing the tube potential also provides the possibility of lowering the amount of iodinated contrast agent. Automatic kilovoltage peak selection in relation to patient size is an available function on newer CT scanners and has been shown to reduce the radiation dose. In one study, the use of this function in CTPA resulted in a selected tube potential of 70 to 90 kVp (80 kVp in most cases). The use of dual energy in CTPA reportedly provides similar image quality at lower radiation doses.

Considerable differences among CT scanners (geometry, filtration, detector efficiency, and reconstruction algorithms) result in considerable differences in image quality obtained at given exposure parameters on different CT scanners. Both the possibility for use of iterative reconstruction and the adapted dose shield stand out among the scanner-related features because of their notable radiation dose-saving potential. Radiology departments quite commonly have two or more CT scanners of different models, and the choice of the CT scanner used for a clinical indication and/or a particular patient group might also be employed as a dose-reduction strategy.

Regularly reviewing CT protocols is essential to ensure that all protocols are correctly configured so that the image quality and dose are being optimized. Protocol reviewing and optimizing requires a team-based approach, and the team should comprise a radiologist, physicist, and radiographer.

Given the extensive use of CT in radiation-sensitive patient groups such as pregnant and pediatric patients, and considering the importance of tailoring CT protocols to patient characteristics in terms of both radiation dose and image quality, this study was performed to determine to what extent individualization of
currently used CTPA protocols is practiced. The investigation focused on how CT protocols are tailored when examining radiation-sensitive patients such as pediatric and pregnant patients and what radiation-saving approaches are used to tailor the protocols to those patients across hospitals in Norway. Our hope is that a review of current practices will be valuable for identifying any optimizing potential.

Methods

This cross-sectional study involved collection of the CT protocols used to investigate PE from Norwegian hospitals along with administration of a mini-questionnaire to obtain additional information about the departments’ practices regarding individualization of CT examinations. All public hospitals that perform CTPA examinations were invited to participate (n = 41). An email was sent to each hospital’s senior CT radiographer and included free text response questions focusing on routines for tailoring the CT examination to different patient groups and routines for CT protocol optimization along with a request to send us all the protocols they use for PE. Because of the limited number of replies after the first mailing round, a second mailing round was conducted 3 weeks later.

Triple rule-out (a protocol used for simultaneous examination of the coronary arteries, thoracic aorta, and pulmonary arteries) and other combined protocols used to assess other conditions in addition to PE were excluded from the study.

Among the collected material, we analyzed the number of protocols the hospital uses to detect PE, to which patient groups these protocols are dedicated, differences between the standard protocols and the protocols used for pediatric or pregnant patients in the same hospital, and the presence or absence of radiation dose-reducing approaches (e.g., the use of automatic kilovoltage peak, dual energy, iterative reconstruction, and other approaches). The data were first registered in an Excel file (Microsoft Corp., Redmond, WA, USA) and then exported to SPSS version 24 (IBM Corp., Armonk, NY, USA). The collected data were analyzed using descriptive statistics.

Ethical considerations

The participants were informed about the aim of the study and received the research protocol, which had been approved by the university. They were also informed that participation in this study was voluntary and that an email reply containing attached CT protocols would be regarded as implied consent to participate. Moreover, the participants were informed that the name of the person replying to the email would not be registered at all and that the name of the hospital would not be disclosed. The need for approval from the Regional Committee for Medical and Health Research Ethics and the Norwegian Centre for Research Data was waived because the project did not involve any health-related or personal information.

Results

Response rate

The overall response rate after the two emails were sent was 41% (17 of 41 hospitals). The participating hospitals represented 13 of the 20 health trusts in Norway from all four regional health authorities in the country. The total number of protocols used solely for PE was 41, and seven combined protocols were excluded. All participants answered the mini-questionnaire completely.
Protocol individualization practices

The data showed variation in the number of protocol variants used for PE. The most common situation was having solely a standard protocol (41%), followed by two protocols (29%). Other hospitals had four, six, or even eight protocols (6% each).

Almost all hospitals (with only one exception) reported tailoring their protocols using various criteria (Figure 1). The respondent who reported using the standard protocol without any adjustments stated that the use of ATCM was sufficient for tailoring the examination to different patient characteristics. The routines for tailoring protocols differed among the hospitals, and most of them used more than just one method (Figure 2).

ATCM was used in all CTPA protocols; 35% also used automatic kilovoltage peak selection, while 29% used dual energy. All hospitals that did not use automatic kilovoltage peak selection used a tube potential of ≤100 kVp except for one hospital that used a tube potential of 120 kVp in their standard CTPA protocol. Iterative reconstruction was used in 41% of the hospitals.

Protocol individualization practices for pregnant patients

In total, 12% of the hospitals reported that they never examined pregnant patients suspected to have PE. Similar to the situation regarding pediatric patients, it was more common to tailor one of the existing protocols than to have protocols dedicated to pregnant patients (Figure 4). Radiation-saving approaches used to tailor the protocol to pregnant patients were reducing the scan length, lowering the kilovoltage peak...
settings, and using the newest CT scanner. Additional practices were tailoring the amount of contrast agent and tailoring the injection flow rate.

**Practices for protocol reviewing and optimizing**

Most hospitals had no established procedures for CT protocol updating. Half of the senior CT radiographers reported that the date of the last protocol update was unknown, and the remaining radiographers reported that they reviewed the protocols periodically (every 18, 24, or 36 months). In contrast, almost all the departments updated the protocols when needed; in some cases, this was performed in addition to the periodic protocol review (Table 1). The hospitals that updated their protocols yearly reported using an electronic system to remind them when the time for the periodic protocol review is approaching.

The lead radiologist and the lead CT radiographer shared the responsibility for protocol reviewing and optimizing, and only 30% reported participation of a physicist in the process.

The mini-questionnaire included a question asking which resources are used to optimize the CT protocols. The results showed that the participants used multiple resources to optimize their protocols. The most common were protocols used by colleagues from other hospitals (88%), scientific publications (peer-reviewed journals and textbooks) (88%), courses (82%), and manufacturers’ recommendations (82%) followed by local protocol testing (53%). Many respondents specified that protocols recommended by the manufacturer were used as a starting point and that those protocols were later optimized by performing small changes based on small-scale testing.

**Discussion**

The present study showed that the most common situation among Norwegian hospitals was using a single standard protocol and tailoring this standard protocol based...
on different patient characteristics. Using the standard protocol in all patients without any adjustments was an exception. Relying solely on ATCM even when having optimized protocols (as in one of the cases in this study) still does not ensure that the examination is tailored to different patient groups, especially pediatric patients. As emphasized by the International Commission on Radiological Protection,\textsuperscript{42} the use of ATCM does not totally free the operator from selection of scan parameters. The various approaches to reduce radiation doses mentioned in the literature\textsuperscript{19,23,29–33} were used to different extents in the participating hospitals. The use of a lower tube potential was the most commonly used approach, with almost all hospitals using a tube potential of 100 kVp or even lower, probably because of the high number of studies confirming the effectiveness of this method in dose reduction without compromising image quality.\textsuperscript{23,35–38} The choice of the CT scanner was actively used as a radiation dose-reduction strategy by scanning radiation-sensitive patients such as pregnant and pediatric patients with the newest CT scanner, which usually has radiation dose-reducing features such as iterative reconstruction, dual energy, and automatic kVp selection.

Although the results of this study show knowledge of most of the available radiation dose-reduction approaches, implementation of these strategies was not systematic. Protocol tailoring based on ad-hoc assessment performed by the radiographer alone or in collaboration with the radiologist was still very common (Figure 2), even when more systematic approaches (such as the inclusion of tailoring instructions in the protocol) might be more efficient in providing consistency with best practice standards.\textsuperscript{46} A concerning finding of this study is that children might be examined using adult CT protocols without any adjustment in 30% of the hospitals, which is totally against the existing recommendations.\textsuperscript{26,27,42} Additionally, 39% of the pregnant patients were examined without using dedicated protocols or specific adjustments focusing on radiation dose reduction in this particular radiation-sensitive patient group. Using protocol tailoring based only on body weight categories might be detrimental to pregnant patients because they will be scanned with a higher radiation dose protocol because of gestational weight gain. Increasing the radiation dose by placing the pregnant patient in a higher weight category is totally unnecessary because only a low percentage of gestational weight gain is caused by breast enlargement or fat deposition in the upper body.\textsuperscript{47} Use of the
pregestational weight as a criterion for choosing the protocol might be a better alternative.35

The lack of systematic routines for protocol reviewing and optimizing in half of the hospitals indicates a need for practice improvement because regular reviewing is essential to ensure a correct balance between the radiation dose and image quality.25–27,42–46 Even in hospitals with systematic protocol-reviewing routines in the present study, the reviewing frequency was lower than the recommended yearly frequency.44,46 Another necessary improvement in some hospitals is the inclusion of a physicist in the protocol review and optimization team as recommended by most sources.26,42,44

Most of the participants reported use of scientific publications as a source of knowledge when optimizing their protocols. However, academic publications offer little general information on practical approaches for reviewing and optimizing protocols46 and no guidance on how to best apply the results to a particular CT scanner.45 Protocols cannot simply be transferred between different scanner models.42 The results of the current study confirm that staying up to date with the literature is beneficial but is not sufficient; this is because half of participants who declared using scientific literature had no established procedures for protocol updating and optimizing, and some of them tailored the examinations to only a small extent. Previous studies have shown that clinical practice improves when all radiographers are involved in auditing and optimizing processes.29,48 Feedback on doses used in CT examinations performed at the department might also be an effective measure because it was proven to cause significant dose reduction especially in combination with education on dose-reduction strategies.48 Practicing patient-centered imaging will require substantial changes in the current imaging culture, with key components being greater emphasis on implementing radiation dose-optimization strategies20 and support from the administration, especially allocation of sufficient amounts of dedicated time and resources.44,46

To the best of our knowledge, this is the first study to analyze practices regarding CT protocol individualization. The study included 41% of public hospitals representing all four regional health authorities in Norway, and it is therefore reasonable to consider the results as representative of the country.

The study has several limitations. First, the percentage of hospitals that perform CT examination of children with neither pediatric CTPA protocols nor routines for tailoring the existing protocols to children might have been overestimated because we cannot be sure that this was the case for all departments in which children were not examined (the mini-questionnaire did not include a specific question about what patient groups they examine). This might also apply to pregnant patients. Second, only the senior CT radiographer of the department answered the questions, and he or she might not have had extensive knowledge of all the ad-hoc protocol adjustments made by the other radiographers. As noted in a previous study, clinical practice is largely subjective and ad-hoc.49 The extent to which the scanning parameters of the CT protocol are adjusted when examining children or pregnant patients might therefore be higher than reported in the current study.

**Conclusion**

This study provides an overview of how CTPA examinations are tailored to different patient characteristics at Norwegian hospitals. The results reveal the need for practice optimization, especially with
regard to developing dedicated CT protocols for pediatric and pregnant patients or inserting tailoring instructions into the existing standard CT protocols. Practice might benefit from a more systematic approach to reviewing and optimizing the CT protocols (based on quantitative evaluation of the patient dose and image quality) and from formalizing the role of the protocol-optimizing team, which should always include a physicist. We anticipate that the present assessment of current practices reported by the participating hospitals will prove the interim value of future research on implementing patient-centered imaging.

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**ORCID iD**

Albertina Rusandu https://orcid.org/0000-0001-9784-6157

**References**

1. Burke LMB, Semelka RC and Smith-Bindman R. Trends of CT utilization in North America over the last decade. *Curr Radiol Rep* 2014; 3: 78.
2. Spelie D. The nationwide evaluation of X-ray trends, Part 2: US trends for CT. *J Am Coll Radiol* 2016; 13: 992–994.
3. Hess EP, Haas LR, Shah ND, et al. Trends in computed tomography utilization rates: a longitudinal practice-based study. *J Patient Saf* 2014; 10: 52–58.
4. Smith-Bindman R, Lipson J, Marcus R, et al. Radiation dose associated with common computed tomography examinations and the associated lifetime attributable risk of cancer. *Arch Intern Med* 2009; 169: 2078–2086.
5. Brenner DJ and Hall EJ. Computed tomography — an increasing source of radiation exposure. *N Engl J Med* 2007; 357: 2277–2284.
6. Borreten I, Lysdahl KB and Olerud HM. Diagnostic radiology in Norway—trends in examination frequency and collective effective dose. *Radiat Prot Dosimetry* 2007; 124: 339–347.
7. Parakh A, Euler A, Szucs-Farkas Z, et al. Transatlantic comparison of CT radiation doses in the era of radiation dose-tracking software. *Am J Roentgenol* 2017; 209: 1302–1307.
8. Smith-Bindman R, Wang Y, Chu P, et al. International variation in radiation dose for computed tomography examinations: prospective cohort study. *BMJ* 2019; 364: k4931.
9. Sadigh G, Kelly AM and Cronin P. Challenges, controversies, and hot topics in pulmonary embolism imaging. *Am J Roentgenol* 2011; 196: 497–515.
10. Araoz PA, Haramati LB, Mayo JR, et al. Panel discussion: pulmonary embolism imaging and outcomes. *Am J Roentgenol* 2012; 198: 1313–1319.
11. Henzler T, Barraza JM, Nance JW, et al. CT imaging of acute pulmonary embolism. *J Cardiovasc Comput Tomogr* 2011; 5: 3–11.
12. Mayo J and Thakur Y. Pulmonary CT angiography as first-line imaging for PE: image quality and radiation dose considerations. *Am J Roentgenol* 2013; 200: 522–528.
13. Bélohlávek J, Dytrych V and Linhart A. Pulmonary embolism, part I: epidemiology, risk factors and risk stratification, pathophysiology, clinical presentation, diagnosis and nonthrombotic pulmonary embolism. *Exp Clin Cardiol* 2013; 18: 129–138.
14. Kwan ML, Miglioretti DL, Marlow EC, et al. Trends in medical imaging during pregnancy in the United States and Ontario, Canada, 1996 to 2016. *JAMA Netw Open* 2019; 2: e197249.
15. Thacker PG and Lee EY. Pulmonary embolism in children. *Am J Roentgenol* 2015; 204: 1278–1288.
16. Rashed AN, Hsia Y, Wilton L, et al. Trends and patterns of hormonal contraceptive prescribing for adolescents in primary care in the U.K. J Fam Plann Reprod Health Care 2015; 41: 216–222.

17. Krishnamoorthy N, Ekins-Daukes S, Simpson CR, et al. Adolescent use of the combined oral contraceptive pill: a retrospective observational study. Arch Dis Child 2005; 90: 903–905.

18. Miglioretti DL, Johnson E, Williams A, et al. The use of computed tomography in pediatrics and the associated radiation exposure and estimated cancer risk. JAMA Pediatr 2013; 167: 700–707.

19. Iezzi R, Larici AR, Franchi P, et al. Tailoring protocols for chest CT applications: when and how? Diagn Interv Radiol 2017; 23: 420–427.

20. Einstein AJ, Berman DS, Min JK, et al. Patient-centered imaging: shared decision making for cardiac imaging procedures with exposure to ionizing radiation. J Am Coll Cardiol 2014; 63: 1480–1489.

21. Depuey EG, Mahmarian JJ, Miller TD, et al. Patient-centered imaging. J Nucl Cardiol 2012; 19: 185–215.

22. Grimes J, Leng S, Zhang Y, et al. Implementation and evaluation of a protocol management system for automated review of CT protocols. J Appl Clin Med Phys 2016; 17: 523–533.

23. Zsolt Szucs-Farkas PV and Schindera ST. Low-dose pulmonary CT angiography: reduced radiation exposure and iodine load at low tube kilovoltage. Imaging Med 2010; 2: 696–705.

24. Ngo AV, Winant AJ, Lee EY, et al. Strategies for reducing radiation dose in CT for pediatric patients: how do we it. Semin Roentgenol 2018; 53: 124–131.

25. Kalra MK, Sodickson AD and Mayo-Smith WW. CT radiation: key concepts for gentle and wise use. RadioGraphics 2015; 35: 1706–1721.

26. (IAEA) IAEA. Radiation protection in paediatric radiology. Vienna: International Atomic Energy Agency, 2012.

27. ICRP. Radiological protection in paediatric diagnostic and interventional radiology. ICRP Publication 121. Ann ICRP 2013; 42: 1–63.

28. Brody AS, Frush DP, Huda W, et al. Radiation risk to children from computed tomography. Pediatrics 2007; 120: 677–682.

29. Hendriks BMF, Schnerr RS, Milanese G, et al. Computed tomography pulmonary angiography during pregnancy: radiation dose of commonly used protocols and the effect of scan length optimization. Korean J Radiol 2019; 20: 313–322.

30. Kalender WA, Buchenau S, Deak P, et al. Technical approaches to the optimisation of CT. Physica Medica 2008; 24: 71–79.

31. Kubo T, Lin PJP, Stiller W, et al. Radiation dose reduction in chest CT: a review. Am J Roentgenol 2008; 190: 335–343.

32. Moser JB, Sheard SL, Edyvean S, et al. Radiation dose-reduction strategies in thoracic CT. Clin Radiol 2017; 72: 407–420.

33. Hurwitz LM, Yoshizumi TT, Goodman PC, et al. Radiation dose savings for adult pulmonary embolus 64-MDCT using bismuth breast shields, lower peak kilovoltage, and automatic tube current modulation. Am J Roentgenol 2009; 192: 244–253.

34. Zhao Y, Zuo Z, Cheng S, et al. CT pulmonary angiography using organ dose modulation with an iterative reconstruction algorithm and 3D Smart mA in different body mass indices: image quality and radiation dose. Radiol Med 2018; 123: 676–685.

35. Rusandu A, Odegard A, Engh GC, et al. The use of 80 kV versus 100 kV in pulmonary CT angiography: an evaluation of the impact on radiation dose and image quality on two CT scanners. Radiography (Lond) 2019; 25: 58–64.

36. Szucs-Farkas Z, Kurmann L, Strautz T, et al. Patient exposure and image quality of low-dose pulmonary computed tomography angiography: comparison of 100- and 80-kVp protocols. Invest Radiol 2008; 43: 871–876.

37. Szucs-Farkas Z, Christie A, Megyeri B, et al. Diagnostic accuracy of computed tomography pulmonary angiography with reduced radiation and contrast material dose: a prospective randomized clinical trial. Invest Radiol 2014; 49: 201–208.
38. Viteri-Ramírez G, García-Lallana A, Simón-Yarza I, et al. Low radiation and low-contrast dose pulmonary CT angiography: comparison of 80 kVp/60 ml and 100 kVp/80 ml protocols. Clin Radiol 2012; 67: 833–839.

39. Hendriks BMF, Eijsvoogel NG, Kok M, et al. Optimizing pulmonary embolism computed tomography in the age of individualized medicine: a prospective clinical study. Invest Radiol 2018; 53: 306–312.

40. De Zordo T, von Lutterotti K, Dejaco C, et al. Comparison of image quality and radiation dose of different pulmonary CTA protocols on a 128-slice CT: high-pitch dual source CT, dual energy CT and conventional spiral CT. Eur Radiol 2012; 22: 279–286.

41. Vollmar SV and Kalender WA. Reduction of dose to the female breast in thoracic CT: a comparison of standard-protocol, bismuth-shielded, partial and tube-current-modulated CT examinations. Eur Radiol 2008; 18: 1674–1682.

42. ICRP. Managing patient dose in multi-detector computed tomography (MDCT). ICRP Publication 102. Ann ICRP 2007; 37: 1–79, iii.

43. Zacharias C, Alessio AM, Otto RK, et al. Pediatric CT: strategies to lower radiation dose. Am J Roentgenol 2013; 200: 950–956.

44. AAPM. AAPM Medical Physics Practice Guideline 1.a: CT Protocol Management and Review Practice Guideline. J Appl Clin Med Phys 2013; 14: 3–12.

45. Szczykutowicz TP, Bour RK, Pozniak M, et al. Compliance with AAPM Practice Guideline 1.a: CT Protocol Management and Review — from the perspective of a university hospital. J Appl Clin Med Phys 2015; 16: 443–457.

46. Kofler JM, Cody DD and Morin RL. CT protocol review and optimization. J Am Coll Radiol 2014; 11: 267–270.

47. Butte NF, Ellis KJ, Wong WW, et al. Composition of gestational weight gain impacts maternal fat retention and infant birth weight. Am J Obstet Gynecol 2003; 189: 1423–1432.

48. Miglioretti DL, Zhang Y, Johnson E, et al. Personalized technologist dose audit feedback for reducing patient radiation exposure from CT. J Am Coll Radiol 2014; 11: 300–308.

49. Zhang Y, Smitherman C and Samei E. Size-specific optimization of CT protocols based on minimum detectability. Med Phys 2017; 44: 1301–1311.