Tailoring Contrast Media Protocols to Varying Tube Voltages in Vascular and Parenchymal CT Imaging

Tailoring Contrast Media Protocols to Varying Tube Voltages in Vascular and Parenchymal CT Imaging

The 10-to-10 Rule

Bibi Martens, MD,† Babs M.F. Hendriks, MD,*†*
Casper Mihl, MD, PhD,† and Joachim E. Wildberger, MD, PhD*†*

Abstract: The latest technical developments in CT have created the possibility for individualized scan protocols at variable kV settings. Lowering tube voltages closer to the K-edge of iodine increases attenuation. However, the latter is also influenced by patient characteristics such as total body weight. To maintain a robust contrast enhancement throughout the patient population in both vascular and parenchymal CT scans, one must adapt the contrast media administration protocols to both the selected kV setting and patient body habitus. This article proposes a simple rule of thumb for how to adapt the contrast media protocol to any kV setting: the 10-to-10 rule.

Key Words: computed tomography, contrast media, radiation dosage, abdomen, pulmonary artery, coronary vessels, aorta

(*Invest Radiol* 2020;55: 673–676)

Since the invention of the first computed tomography (CT) scanner in 1971, CT technology has improved substantially.[1] The advent of powerful x-ray tubes, multiple detector rows, and dual-source technology has led to short acquisition times and excellent temporal and spatial resolution.[2]

These days, CT is a widely available, versatile, and fast medical imaging method, which has revolutionized radiology and the field of medicine as a whole.[3] In this era of personalized medicine, "one size fits all" protocols are increasingly substituted by individually tailored (CM) injection protocols.

This article summarizes the elements of CM injection protocols that are most relevant for optimal attenuation in parenchymal CT and CT angiography (CTA). It proposes an easy-to-use rule of thumb for tailoring CM injection protocols to different kV settings: the 10-to-10 rule.[4–6]

Individualized Scan Protocols

A comprehensive overview of the latest technical developments in CT has recently been published by Lell and Kachelrieß.[3] Two advances are especially pertinent to individualized scan protocols. First, the latest tube technology can generate a higher photon flux during longer acquisition times, which allows lower kV scanning and results in lower radiation dose for most patients.[2] Second, ATCM (automated tube current modulation) and ATVS (automated tube voltage selection) techniques are now available. These advances in CT technology create the opportunity for radiation dose tailoring to each individual patient.[7,8] Whereas good image quality may be achieved at 120 kV for a large adult; a tube voltage as low as 70 or 80 kV may be sufficient for a smaller person, as long as the tube current is adjusted accordingly. Thus, similar image quality may be achieved at lower radiation dose due to higher iodine attenuation at lower kV. When low kV photons that do not contribute to the image are filtered out via beam filtration, low kV scanning is advantageous for lowering the hypothetical radiation-induced cancer risk for patients and follows the "as low as reasonable achievable" (ALARA) principle.[9]

Individualized Contrast Media Protocols

In organ studies, the total iodine volume is most important for reaching optimal parenchymal enhancement, whereas iodine delivery rate (IDR, in g I/s) is the decisive factor for intravascular enhancement.[10] The latter has been proven for CTA of the pulmonary arteries, coronary CTA, and CTA of the aorta.[11–14] The relationship between IDR, flow rate, and CM concentration can be described using the following formula: IDR (g I/s) = [CM] (g I/mL) × flow rate (mL/s). Normalizing IDR is a straightforward method for making different injection protocols comparable. As seen in the formula, IDR can be modified either by adapting flow rate or changing CM concentration.

Several patient-related factors influence attenuation levels of both vascular and parenchymal structures. Patient body weight is a well-known, robust basis for tailoring individual CM protocols.[15] In coronary and pulmonary arteries as well as in liver parenchyma, adapting CM parameters to the patients' body weight has proven to be beneficial (see Fig. 1).[13,16,17] Compared with a "one size fits all" approach, the total body weight (TBW)–adapted CM protocols have been shown to yield more homogeneous attenuation of pulmonary and coronary arteries and liver parenchyma, between patients. Furthermore, individualized CM injection protocols have been shown to reduce CM usage in general, while still reaching optimal enhancement levels.[13,16,17]

CM injection protocols can be tailored using TBW as mentioned previously, but lean body weight may be preferable.[18] Lean body weight, which is TBW minus the amount of fat in the body, was introduced because fat is relatively poorly perfused and will therefore not participate as much in CM distribution.[10] Lean body weight can be calculated by using either the James or the Boer formula, the latter being the first choice for obese patients.[19]

Combining Scan and Contrast Media Protocols for Optimal Image Quality

With lower tube voltages and therefore the x-ray output drawing closer to the 33 keV k-edge of iodine, the photoelectric effect increases, which in turn increases the attenuation of iodine.[10] This provides new opportunities for CM individualization in both arterial and parenchymal studies. The benefits of lower kV scanning are 2-fold. First, as

Received for publication January 8, 2020; and accepted for publication, after revision, March 29, 2020.
From the *Department of Radiology and Nuclear Medicine, and †CARIM School for Cardiovascular Diseases, Maastricht University Medical Center, Maastricht, the Netherlands.
Martens Bibi and Hendriks Babs M.F. have equal contributions.
This manuscript has not received any funding. The authors report no conflicts of interest. However, the authors declare relationships with the following companies: Mihl C. receives personal fees (speakers bureau) from Bayer. Martens B. receives personal fees (speakers bureau) from Bayer. Wildberger J.E. reports institutional research grants from Agfa, Bayer, GE, Philips, Optimed, and Siemens, and personal fees (speakers bureau) from Siemens and Bayer, all outside the submitted work.
Correspondence to: Bibi Martens, Department of Radiology and Nuclear Medicine, Maastricht University Medical Centre, P. Debyelaan 25 PO Box 5800, 6202 AZ Maastricht, the Netherlands. E-mail: bibi.martens@mumc.nl.

ISSN: 0020-9996/20/5510–0673
DOI: 10.1097/RLI.0000000000000682

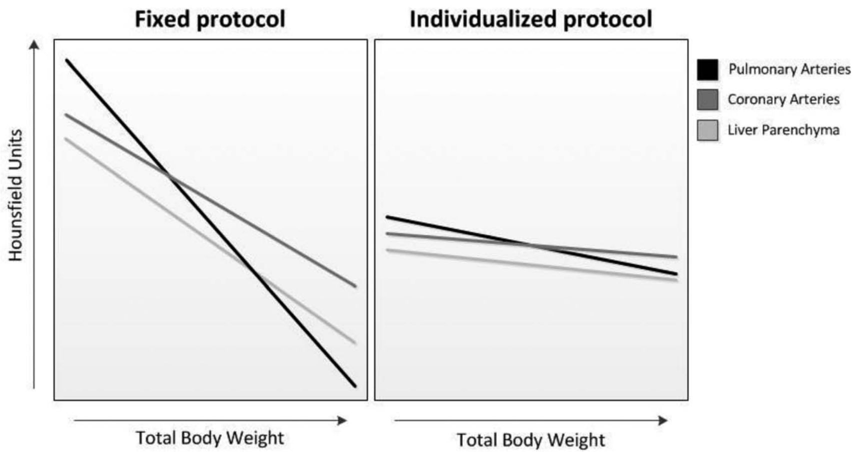

FIGURE 1. Individualized, body weight–based contrast media injection protocols, compared with a fixed injection protocol in the pulmonary arteries, the coronary arteries, and in the liver parenchyma. Individualized protocols yield a more similar and robust enhancement of vascular and parenchymal structures (modified from Hendriks et al,[13] Mihl et al,[16] and Martens et al,[17] and presented schematically).

previously mentioned, lower kV scanning results in overall radiation dose reduction for many patients.

Second, lower kV settings enable CM volume reduction, which may be beneficial for preventing contrast-induced nephropathy.[20,21] Some controversy remains on whether intravenous administration of CM causes the sometimes observed and mostly reversible dip in renal function.[22,23] Nevertheless, there is simply no need to give patients more CM than necessary, especially as the underlying physiological effects are still not fully understood.

With the arrival of ATCM and ATVS techniques, the use of variable, individualized kV settings has become readily feasible in clinical practice, but this comes with a new challenge. The variety in kV settings used has a substantial impact on the attenuation of iodine. If the iodine k-edge effect is not taken into account, CT attenuation numbers and image quality become very heterogeneous in a patient population scanned with different tube voltage settings.[11] Furthermore, radiologists incorporate attenuation characteristics when drawing conclusions from CT images. For example, the assessment of whether lesions are more likely benign or malignant depends on attenuation patterns.[24,25] The large variety of tube voltages and CM volumes used in daily clinical practice, together with varying patient characteristics, make it ever more important to reach a constant and comparable enhancement of target structures. Only when attenuation is similar and robust between patients and scans can reliable conclusions be drawn from contrast-enhanced CT scans.

Several groups have investigated the effect of low kV scanning on attenuation values during CTA and parenchymal CT.[7,11,17] The possibilities of lowering the kV setting and the methods of concordantly adapting CM parameters as well as patient-specific individualization of CM protocols have been widely studied.[16,18,26–28] The results can be combined into a practical, easy to remember, rule of thumb: the 10-to-10 rule.

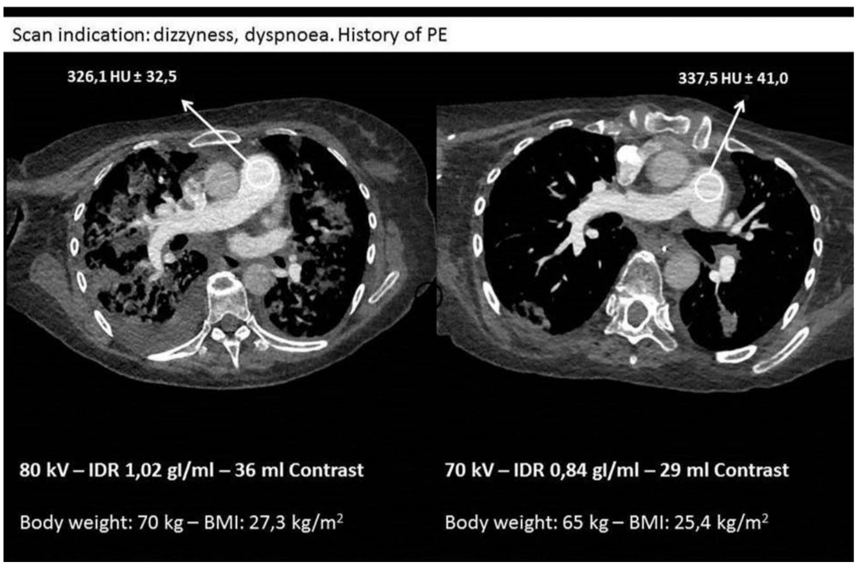

FIGURE 2. Two pulmonary angiography CT scans performed in the same patient suspected of pulmonary embolism. The iodine delivery rate (IDR) was adapted to the different kV settings; 80 kV with an IDR of 1.02 g I/s for scan A; 70 kV with an IDR of 0.84 g I/s for scan B. The region of interest (circle) shows the comparable attenuation (Hounsfield units) despite the different kV settings. IDR was reduced more than the 10% reduction, because the patient lost about 5 kg in body weight between scans A and B, for which the IDR was also adapted.[4]

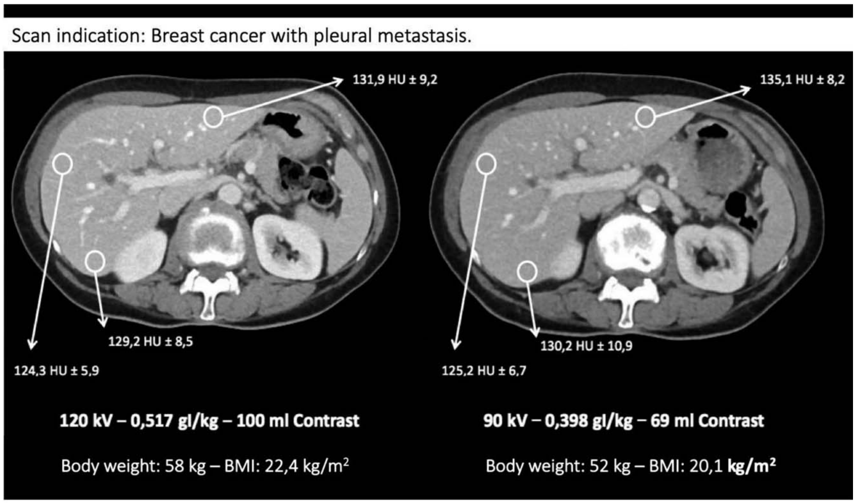

FIGURE 3. Two abdominal CT scans of the same patient in portal venous phase, performed on the same scanner at different kV settings within 1 year of each other. The scan was performed on a third-generation dual-source CT scanner at 120 kV (left) and at 90 kV (right).[6] As a result of adaptation of the CM protocol to kV setting and patient body weight, the attenuation of both scans is the same.

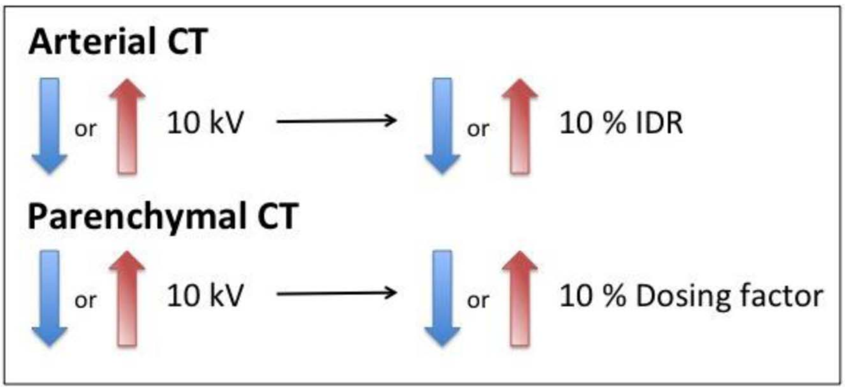

FIGURE 4. The 10-to-10 rule of thumb.

Rule of Thumb: The 10-to-10 Rule

Several IDR reduction percentages have been proposed for adapting vascular CT protocols to different tube voltages and some have been validated in a clinical setting.[4,28–30] Close scrutiny of the available literature reveals that the described methods in fact amount to a single rule of thumb: in CTA deduct 10% of the IDR per 10 kV reduction and vice versa.

A straightforward way to adapt IDR is by changing the flow rate; however, the same can be achieved by adapting CM iodine concentration. This rule has been validated in clinical practice for CTA of the pulmonary arteries and coronary CTA,[4,5] for an example, see Fig. 2.

In parenchymal studies, a reduction of 10 kV should result in a 10% reduction in total iodine load.[30] The landmark article by Heiken et al from 1995 stated that an attenuation increase of ≥50 HU of the liver parenchyma is necessary to ensure appropriate visibility of low-attenuating lesions, based on a tube voltage of 120 kV.[31,32] To achieve this attenuation, a dosing factor of 0.521 g I/kg can be calculated.[31] A recent study showed that a 10-kV reduction should lead to a 10% decrease of the dosing factor and vice versa, to be able to individualize the parenchymal CT based on both patient and scanner characteristics[6,30] (Fig. 3). This rule can easily be applied to any existing patient tailored protocol, thereby adjusting the CM protocol for any kV setting and individual patient characteristic (see Fig. 4).

CONCLUSIONS

The 10-to-10 rule is an easy to use rule of thumb to adapt CM injection protocols to varying tube voltages. This rule, used in conjunction with personalized CM injection protocols, will aid in keeping image quality constant and homogeneous throughout the patient population.

REFERENCES

1. Goodman LR. The Beatles, the Nobel prize, and CT scanning of the chest. *Radiol Clin North Am*. 2010;48:1–7.
2. Lell MM, Wildberger JE, Alkadhi H, et al. Evolution in computed tomography: the battle for speed and dose. *Invest Radiol*. 2015;50:629–644.
3. Lell MM, Kachelrieß M. Recent and upcoming technological developments in computed tomography: high speed, low dose, deep learning, multienergy. *Invest Radiol*. 2020;55:8–19.
4. 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.

5. Eijsvoogel NG, Hendriks BMF, Willigers JL, et al. Personalization of injection protocols to the individual patient's blood volume and automated tube voltage selection (ATVS) in coronary CTA. *PLoS One*. 2018;13:e0203682.
6. Martens B, Wildberger JE, Hendriks BM, et al. A solution for homogeneous liver enhancement in computed tomography: results from the COMpLEx trial. *Investigative Radiology*.
7. Mayer C, Meyer M, Fink C, et al. Potential for radiation dose savings in abdominal and chest CT using automatic tube voltage selection in combination with automatic tube current modulation. *AJR Am J Roentgenol*. 2014;203:292–299.
8. Papadakis AE, Damilakis J. Automatic tube current modulation and tube voltage selection in pediatric computed tomography: a phantom study on radiation dose and image quality. *Invest Radiol*. 2019;54:265–272.
9. Kalra MK, Sodickson AD, Mayo-Smith WW. CT radiation: key concepts for gentle and wise use. *Radiographics*. 2015;35:1706–1721.
10. Bae KT. Intravenous contrast medium administration and scan timing at CT: considerations and approaches. *Radiology*. 2010;256:32–61.
11. Kok M, Mihl C, Seehofnerova A, et al. Automated tube voltage selection for radiation dose reduction in CT angiography using different contrast media concentrations and a constant iodine delivery rate. *AJR Am J Roentgenol*. 2015;205: 1332–1338.
12. Kok M, Mihl C, Hendriks BM, et al. Patient comfort during contrast media injection in coronary computed tomographic angiography using varying contrast media concentrations and flow rates: results from the EICAR trial. *Invest Radiol*. 2016;51:810–815.
13. Hendriks BM, Kok M, Mihl C, et al. Individually tailored contrast enhancement in CT pulmonary angiography. *Br J Radiol*. 2016;89:20150850.
14. Mihl C, Wildberger JE, Jurencak T, et al. Intravascular enhancement with identical iodine delivery rate using different iodine contrast media in a circulation phantom. *Invest Radiol*. 2013;48:813–818.
15. Bae KT, Tao C, Gurel S, et al. Effect of patient weight and scanning duration on contrast enhancement during pulmonary multidetector CT angiography. *Radiology*. 2007;242:582–589.
16. Mihl C, Kok M, Altintas S, et al. Evaluation of individually body weight adapted contrast media injection in coronary CT-angiography. *Eur J Radiol*. 2016;85: 830–836.
17. Martens B, Hendriks BMF, Eijsvoogel NG, et al. Individually body weight-adapted contrast media application in computed tomography imaging of the liver at 90 kVp. *Invest Radiol*. 2019;54:177–182.
18. Kondo H, Kanematsu M, Goshima S, et al. Body size indices to determine iodine mass with contrast-enhanced multi-detector computed tomography of the upper abdomen: does body surface area outperform total body weight or lean body weight? *Eur Radiol*. 2013;23:1855–1861.
19. Caruso D, De Santis D, Rivosecchi F, et al. Lean body weight-tailored iodinated contrast injection in obese patient: Boer versus James formula. *Biomed Res Int*. 2018;2018:8521893.
20. Hou SH, Bushinsky DA, Wish JB, et al. Hospital-acquired renal insufficiency: a prospective study. *Am J Med*. 1983;74:243–248.
21. Khwaja A. KDIGO clinical practice guidelines for acute kidney injury. *Nephron Clin Pract*. 2012;120:c179–c184.
22. McDonald RJ, McDonald JS, Bida JP, et al. Intravenous contrast material-induced nephropathy: causal or coincident phenomenon? *Radiology*. 2013;267:106–118.
23. Nijssen EC, Rennenberg RJ, Nelemans PJ, et al. Prophylactic hydration to protect renal function from intravascular iodinated contrast material in patients at high risk of contrast-induced nephropathy (AMACING): a prospective, randomised, phase 3, controlled, open-label, non-inferiority trial. *Lancet*. 2017; 389:1312–1322.
24. Kang SK, Huang WC, Pandharipande PV, et al. Solid renal masses: what the numbers tell us. *AJR Am J Roentgenol*. 2014;202:1196–1206.
25. Dyer R, DiSantis DJ, McClennan BL. Simplified imaging approach for evaluation of the solid renal mass in adults. *Radiology*. 2008;247:331–343.
26. Kondo H, Kanematsu M, Goshima S, et al. Body size indexes for optimizing iodine dose for aortic and hepatic enhancement at multidetector CT: comparison of total body weight, lean body weight, and blood volume. *Radiology*. 2010;254: 163–169.
27. Bae KT, Shah AJ, Shang SS, et al. Aortic and hepatic contrast enhancement with abdominal 64-MDCT in pediatric patients: effect of body weight and iodine dose. *AJR Am J Roentgenol*. 2008;191:1589–1594.
28. Kok M, Mihl C, Hendriks BM, et al. Optimizing contrast media application in coronary CT angiography at lower tube voltage: evaluation in a circulation phantom and sixty patients. *Eur J Radiol*. 2016;85:1068–1074.
29. Lell MM, Jost G, Korporaal JG, et al. Optimizing contrast media injection protocols in state-of-the art computed tomographic angiography. *Invest Radiol*. 2015; 50:161–167.
30. Canstein C, Korporaal JG. *Reduction of contrast agent dose at low kV settings*. Forchheim, Germany: Siemens WP; 2015.
31. Heiken JP, Brink JA, McClennan BL, et al. Dynamic incremental CT: effect of volume and concentration of contrast material and patient weight on hepatic enhancement. *Radiology*. 1995;195:353–357.
32. Brink JA, Heiken JP, Forman HP, et al. Hepatic spiral CT: reduction of dose of intravenous contrast material. *Radiology*. 1995;197:83–88.