Radiation Doses of Cerebral Blood Volume Measurements Using C-Arm CT: A Phantom Study


doi: https://doi.org/10.3174/ajnr.A3822
http://www.ajnr.org/content/35/6/1073
Radiation Doses of Cerebral Blood Volume Measurements Using C-Arm CT: A Phantom Study


ABSTRACT

BACKGROUND AND PURPOSE: Parenchymal blood volume measurement by C-arm CT facilitates in-room peritherapeutic perfusion evaluation. However, the radiation dose remains a major concern. This study aimed to compare the radiation dose of parenchymal blood volume measurement using C-arm CT with that of conventional CTP using multidetector CT.

MATERIALS AND METHODS: A biplane DSA equipped with C-arm CT and a Rando-Alderson phantom were used. Slab parenchymal blood volume (8-cm scanning range in a craniocaudal direction) and whole-brain parenchymal blood volume with identical scanning parameters, except for scanning ranges, were undertaken on DSA. Eighty thermoluminescent dosimeters were embedded into 22 organ sites of the phantom. We followed the guidelines of the International Commission on Radiation Protection number 103 to calculate the effective doses. For comparison, 8-cm CTP with the same phantom and thermoluminescent dosimeter distribution was performed on a multidetector CT. Two repeat dose experiments with the same scanning parameters and phantom and thermoluminescent dosimeter settings were conducted.

RESULTS: Brain-equivalent dose in slab parenchymal blood volume, whole-brain parenchymal blood volume, and CTP were 52.29 ± 35.31, 107.51 ± 31.20, and 163.55 ± 89.45 mSv, respectively. Variations in the measurement of an equivalent dose for the lens were highest in slab parenchymal blood volume (64.5%), followed by CTP (54.6%) and whole-brain parenchymal blood volume (29.0%). The effective doses of slab parenchymal blood volume, whole-brain parenchymal blood volume, and CTP were 0.87 ± 0.55, 3.91 ± 0.78, and 2.77 ± 1.59 mSv, respectively.

CONCLUSIONS: The dose measurement conducted in the current study was reliable and reproducible. The effective dose of slab parenchymal blood volume is about one-third that of CTP. With the advantages of on-site and immediate imaging availability and saving procedural time and patient transportation, slab parenchymal blood volume measurement using C-arm CT can be recommended for clinical application.

ABBREVIATIONS: PBV = parenchymal blood volume; s-PBV = slab parenchymal blood volume; w-PBV = whole-brain parenchymal blood volume; TLD = thermoluminescent dosimeter
the ischemic core and detect hyperperfusion phenomena per-
therapeutically in the angiography suite, facilitating endovascular
therapy without the transfer of patients to the CT room.16–15 In a
recent study, Royalty et al16 showed the feasibility of using C-arm
CT to measure perfusion parameters in an animal model. Never-
theless, the combination of DSA and flat panel parenchymal
blood volume raises concerns related to radiation exposure.17,18
Unintentional adverse effects due to overexposure to x-rays in CT
rooms or angiography suites should be avoided.17,19 Before the
one-stop imaging from diagnosis to imaging-guided endovas-
cular treatment and posttherapeutic evaluation is widely adopted in
clinical service, the dose measurement of C-arm CT in perfusion
parameter evaluation should be investigated. We, therefore, pres-
ent the current study.

MATERIALS AND METHODS

Radiation Dose Measurement

A radiation experiment by using an anthropomorphic phantom
(Rando-Alderson phantom; Radiology Support Devices, Long
Beach, California) was used for both PBV and CTP. The phantom
consisted of 35 sections of 2.5-cm thickness each. It simulated the
body of a 170-cm tall, 70-kg man. The phantom was composed of
a natural human skeleton embedded in a mass with the properties
of human soft tissue (mass attenuation, \(\rho = 0.985 \text{ kg/dm}^3\), effec-
tive atomic number, \(Z_{\text{eff}} = 7.3\)). The thorax of the phantom was
made of foam (\(\rho = 0.32 \text{ kg/dm}^3\); \(Z_{\text{eff}} = 7.3\)) to simulate human
lung tissue. Eighty lithium fluoride thermoluminescent dosime-
ters (TLD-100H; Bicron-Harshaw, Solon, Ohio) divided across
22 organ sites were embedded in the phantom (Table 1). Those
TLD-100Hs with coefficients of variation >3% were excluded.
The TLDs were made of a tissue-equivalent material with high
sensitivity and a linear response to radiation doses. Moreover,
after an adequate annealing process, the TLDs could be recycled,
which made them suitable for monitoring the delivery of radia-
tion with PBV and CTP imaging techniques. We followed the
guidelines of the International Commission on Radiation Protec-
tion number 103 to calculate the effective dose (ED)20 as follows:

\[
ED = \sum D_T \cdot W_R \cdot w_{T}\n\]

where \(D_T\) is the mean absorbed dose to the target organ, \(W_R\) is
the radiation-weighting factor, and \(w_{T}\) is the tissue-weighting factor.
Accordingly, the \(W_R\) for x-ray was 1. The absorbed dose obtained
from TLD in each specific organ was multiplied by the \(W_R\) to yield
the equivalent doses in each individual organ.

The values of the entrance skin dose/dose-area product of C-
arm CT and the dose-length product of multidetector CT as
shown by the consoles were recorded for comparison, while both
scanners were regularly calibrated following standard clinical ser-
vice requirements.

CT Perfusion

For comparison, CT scans on the same phantom and TLD distri-
bution were obtained on a 256-section multidetector CT scanner
(Brilliance iCT; Philips Healthcare, Best, the Netherlands). A clinical
CTP scanning protocol was used in accordance with the
American Association of Physicists in Medicine (AAPM).21
The acquisition parameters were 8-cm scan coverage identical to slab
PBV (s-PBV), 5-mm section thickness, 64 \times 1.25 mm collima-
tion, 20 \times 20 cm FOV, 80 kV(peak), and 250-mA tube current
with a rotation time of 0.4 seconds, equivalent to effective 100
mAs. The scan interval was 1.5 seconds, with a 1-minute duration.
No patient table movement was encountered throughout the CTP
data acquisition.

Parenchymal Blood Volume

PBV dose measurement was conducted with a biplane flat panel
detector–DSA suite (Axiom-Artis; Siemens, Erlangen, Germany).
A routine clinical imaging protocol (one 8-second rotational
mask run with 60 frames/second followed by another 8-second
rotational contrast-medium-filled run with the same frame rate)
for cerebral PBV measurement (syngo DynaPBV Neuro; Sie-
mens) was used. The scanning parameters were 73 kV, 483–555
mA, rotation angle of 200°, 0.5° per frame, and a 616 \times 480 ma-
trix. Two FOVs, full-size (30 \times 40 cm) and slab (8 cm at the
isocenter in a craniocaudal direction \times 40 cm in a right-left di-
rection), were used. The PBV measurements obtained were re-
spectively called whole-brain PBV (w-PBV) and slab PBV (rang-
ing from the sella turcica to high convexity). A repeat dose
measurement with same imaging protocol and scanning param-
eters was conducted.

RESULTS

The dose-area product and entrance skin dose were 2574.6
\(\mu\text{Gy}m^2/222 \text{ mGy} \) and 6850.4 \(\mu\text{Gy}m^2/238 \text{ mGy} \) for s-PBV
and w-PBV, respectively. As a comparison, the CTP dose-length pro-
duct was 1177.3–1232.9 \(\text{mGy} \cdot \text{cm} \), equivalent to an effective dose of
2.47–2.59 mSv calculated by the American Association of Physi-
cists in Medicine of k factor (k = 0.0021 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1} ).
The equivalent doses of different tissue organs in s-PBV, w-PBV,
and CTP measured from TLDs are listed in Table 2. Most TLDs
were located in the head, followed by the salivary glands and thy-
roid glands in all 3 protocols. s-PBV demonstrated a 62.5% ab-

| TLD-100Hs with coefficients of variation | 22 organ sites were embedded in the phantom (Table 1). Those TLD-100Hs with coefficients of variation >3% were excluded. The TLDs were made of a tissue-equivalent material with high sensitivity and a linear response to radiation doses. Moreover, after an adequate annealing process, the TLDs could be recycled, which made them suitable for monitoring the delivery of radiation with PBV and CTP imaging techniques. We followed the guidelines of the International Commission on Radiation Protection number 103 to calculate the effective dose (ED) as follows: 
\[
ED = \sum D_T \cdot W_R \cdot w_{T},
\]
where \(D_T\) is the mean absorbed dose to the target organ, \(W_R\) is the radiation-weighting factor, and \(w_{T}\) is the tissue-weighting factor. Accordingly, the \(W_R\) for x-ray was 1. The absorbed dose obtained from TLD in each specific organ was multiplied by the \(W_R\) to yield the equivalent doses in each individual organ.

The values of the entrance skin dose/dose-area product of C-arm CT and the dose-length product of multidetector CT as shown by the consoles were recorded for comparison, while both scanners were regularly calibrated following standard clinical service requirements.

CT Perfusion
For comparison, CT scans on the same phantom and TLD distribution were obtained on a 256-section multidetector CT scanner (Brilliance iCT; Philips Healthcare, Best, the Netherlands). A clinical CTP scanning protocol was used in accordance with the American Association of Physicists in Medicine (AAPM). The acquisition parameters were 8-cm scan coverage identical to slab PBV (s-PBV), 5-mm section thickness, 64 \times 1.25 mm collimation, 20 \times 20 cm FOV, 80 kV(peak), and 250-mA tube current with a rotation time of 0.4 seconds, equivalent to effective 100 mAs. The scan interval was 1.5 seconds, with a 1-minute duration. No patient table movement was encountered throughout the CTP data acquisition.

Parenchymal Blood Volume
PBV dose measurement was conducted with a biplane flat panel detector–DSA suite (Axiom-Artis; Siemens, Erlangen, Germany). A routine clinical imaging protocol (one 8-second rotational mask run with 60 frames/second followed by another 8-second rotational contrast-medium-filled run with the same frame rate) for cerebral PBV measurement (syngo DynaPBV Neuro; Siemens) was used. The scanning parameters were 73 kV, 483–555 mA, rotation angle of 200°, 0.5° per frame, and a 616 \times 480 matrix. Two FOVs, full-size (30 \times 40 cm) and slab (8 cm at the isocenter in a craniocaudal direction \times 40 cm in a right-left direction), were used. The PBV measurements obtained were respectively called whole-brain PBV (w-PBV) and slab PBV (ranging from the sella turcica to high convexity). A repeat dose measurement with same imaging protocol and scanning parameters was conducted.

RESULTS
The dose-area product and entrance skin dose were 2574.6 \(\mu\text{Gy}m^2/222 \text{ mGy} \) and 6850.4 \(\mu\text{Gy}m^2/238 \text{ mGy} \) for s-PBV and w-PBV, respectively. As a comparison, the CTP dose-length product was 1177.3–1232.9 \(\text{mGy} \cdot \text{cm} \), equivalent to an effective dose of 2.47–2.59 mSv calculated by the American Association of Physicists in Medicine of k factor (k = 0.0021 \text{ mSv} \cdot \text{mGy}^{-1} \cdot \text{cm}^{-1} ). The equivalent doses of different tissue organs in s-PBV, w-PBV, and CTP measured from TLDs are listed in Table 2. Most TLDs were located in the head, followed by the salivary glands and thyroid glands in all 3 protocols. s-PBV demonstrated a 62.5% ab-
Table 2: Radiation doses of individual organs/tissues in CTP, s-PBV, and w-PBV protocols measured from 2 repeated TLD exposure experiments.*

<table>
<thead>
<tr>
<th>Tissue or Organ</th>
<th>CTP</th>
<th>s-PBV</th>
<th>w-PBV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>163.55 ± 89.45</td>
<td>52.29 ± 35.31</td>
<td>107.51 ± 34.20</td>
</tr>
<tr>
<td>Salivary gland</td>
<td>13.94 ± 1.35</td>
<td>3.03 ± 0.61</td>
<td>137.75 ± 16.77</td>
</tr>
<tr>
<td>Thyroid</td>
<td>4.44 ± 1.64</td>
<td>1.20 ± 0.28</td>
<td>12.68 ± 2.48</td>
</tr>
<tr>
<td>Thymus</td>
<td>0.23 ± 0.08</td>
<td>0.10 ± 0.07</td>
<td>0.46 ± 0.15</td>
</tr>
<tr>
<td>Esophagus</td>
<td>1.18 ± 0.36</td>
<td>0.60 ± 0.08</td>
<td>2.61 ± 0.36</td>
</tr>
<tr>
<td>Breast</td>
<td>0.61 ± 0.17</td>
<td>0.19 ± 0.07</td>
<td>1.16 ± 0.17</td>
</tr>
<tr>
<td>Lung</td>
<td>0.50 ± 0.12</td>
<td>0.28 ± 0.09</td>
<td>1.19 ± 0.20</td>
</tr>
<tr>
<td>Stomach</td>
<td>0.06 ± 0.04</td>
<td>0.07 ± 0.06</td>
<td>0.16 ± 0.08</td>
</tr>
<tr>
<td>Liver</td>
<td>0.08 ± 0.03</td>
<td>0.05 ± 0.03</td>
<td>0.19 ± 0.07</td>
</tr>
<tr>
<td>Kidney</td>
<td>0.64 ± 0.74</td>
<td>0.05 ± 0.02</td>
<td>0.18 ± 0.03</td>
</tr>
<tr>
<td>Small intestine</td>
<td>0.03 ± 0.05</td>
<td>0.03 ± 0.05</td>
<td>0.04 ± 0.05</td>
</tr>
<tr>
<td>Colon</td>
<td>0.00 ± 0.00</td>
<td>0.01 ± 0.00</td>
<td>0.01 ± 0.01</td>
</tr>
<tr>
<td>Bladder</td>
<td>0.05 ± 0.03</td>
<td>0.05 ± 0.03</td>
<td>0.08 ± 0.05</td>
</tr>
<tr>
<td>Gonads</td>
<td>0.06 ± 0.03</td>
<td>0.03 ± 0.03</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>Bone marrow</td>
<td>0.43 ± 0.15</td>
<td>0.32 ± 0.13</td>
<td>1.12 ± 0.36</td>
</tr>
<tr>
<td>Skin</td>
<td>0.45 ± 0.29</td>
<td>0.12 ± 0.06</td>
<td>0.65 ± 0.11</td>
</tr>
<tr>
<td>Bone surface</td>
<td>0.42 ± 0.15</td>
<td>0.32 ± 0.15</td>
<td>1.12 ± 0.50</td>
</tr>
<tr>
<td>Effective doseb</td>
<td>2.77 ± 1.59</td>
<td>0.87 ± 0.55</td>
<td>3.91 ± 0.78</td>
</tr>
</tbody>
</table>

*Unless otherwise specified, data are in millisieverts.
†The sum of organ doses are weighted by the tissue-weighting factor recommended in the International Commission on Radiation Protection number 103.

DISCUSSION

The effective dose of CTP in the current study measured by TLD (2.77 ± 1.59 mSv) is close to that estimated from the dose-length product (2.47–2.59 mSv), calculated by the American Association of Physicists in Medicine of k factor, the reference effective dose estimation in a clinical setting. Nevertheless, we found some heterogeneity of dose distribution in the current TLD dose readouts. The heterogeneity is caused by multifactorial mechanisms. The elliptic shape of the Rando-Alderson phantom and limited rotation angles of the tube (200 °) make the attenuation distance of individual TLDs on the ventral side of the phantom longer than those on the dorsal side. Moreover, in the same section of the Rando-Alderson phantom, the attenuation distance of individual TLDs in the center is longer than that in the periphery. Therefore, dose values read in the ventral side and center are lower (Fig 1). This phenomenon is more profound in the area of the primary beam, such as in the brain and salivary glands. Narrower scan ranges (ie, s-PBV and CTP) cause higher dose variations than those in w-PBV. The latter received both primary and scatter beams of irradiation (Fig 3). Due to the vicinity of the inferior margin of the scanning range and lens in CTP and s-PBV modes, the lenses were partly within the primary beams and resulted in a large variation of equivalent dose (Fig 2). In a clinical scenario, we can adjust the patient’s head into the chin-
tuck position to avoid the lenses falling within the scan ranges in CTP or s-PBV.

CTP acquisition protocols were related to the scan interval, scan range, and tube potential. These variables were different across different brands and platforms of CT scanners. The effective doses, therefore, can range from 2.5 to 10 mSv.22-25 We chose the latest CT technique in our institution for the comparative study. The s-PBV (8-cm scanning range at the isocenter) was conducted for direct and equal comparison of radiation doses with CTP (8-cm coverage). Nevertheless, in contrast to the fixed and limited coverage of the brain for most CTPs, the scan range for PBV can be adjusted according to the operator’s preference. For example, coverage of the infratentorium is not mandatory for a patient with known acute MCA stroke, not only because of suboptimal quality infratentorially but also because of irrelevant vascular territory.26 In real practice, the coverage can be individually tailored to an optimal range on the basis of clinical needs. Although the s-PBV did not include the whole brain, it sufficiently covered most regions of interest, which are important for neurointerventional procedures. For example, vascular pathology that involves the distal anterior cerebral artery and MCA tributaries was usually too distal for endovascular intervention in acute stroke settings.26 Similarly, the imaging quality of infratentorial perfusion imaging was suboptimal due to beam-hardening artifacts; thus, its role in guiding thrombolytic therapy is limited.27

The comprehensive acute stroke imaging work-up usually includes noncontrast CT, CT angiography, and CT perfusion.28 Their main contributions are to exclude hemorrhage and large-territory infarction and to further quantify the thrombus burden and collateral circulations.1,29,30 Modern flat panel detector–CT imaging, to some extent, has a spatial and contrast resolution equivalent to that of multidetector CT.14,31 For those patients eligible for intra-arterial thrombolysis, DSA is far superior to CT angiography for evaluating vasculatures, occluded length, and collaterals. In addition to PBV, in-room assessment of the ischemic core and thrombus condition was feasible, thus reducing the door-to-puncture time and improving recanalization rates.10,32

Further reduction of the radiation dose is possible by lowering tube currents in CTP.33 A similar strategy might be applied in PBV. The optimal tube voltage of the PBV system among individuals was beyond the scope of our study. The radiation dose from fluoroscopy required to put patients into an appropriate scan position before PBV differs between operators. Although its contribution to the overall dose is trivial, it can be further reduced with improving skill in scanning practice. Wearing lens protection while undergoing PBV may be an alternative to further reduce the dose to the lens.

s-PBV decreases the radiation dose and keeps an efficient coverage for peritherapeutic monitoring of cerebral hemody-
CONCLUSIONS
The radiation dose measurement presented in this study is reliable and reproducible. Cerebral PBV measurement by using flat panel detector–DSA is a dose-saving imaging protocol. The effective dose with s-PBV is about one-third that of CTP. If one takes into account the advantages of on-site and immediate morphologic imaging availability and saving procedural time and patient transportation, flat panel DSA s-PBV may be recommended as an alternative peri-interventional imaging for evaluating intracranial hemodynamics of neurovascular disorders.

Disclosures: Wan You Guo—UNRELATED: Other: collaboration research contract between Taipei Veterans General Hospital and Siemens Healthcare. **Money paid to the institution.

REFERENCES