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Investigation of Radiation Exposure of Patients with Acute Ischemic Stroke during Mechanical Thrombectomy

Untersuchung der Strahlenexposition des Patienten mit akutem ischämischem Schlaganfall während der mechanischen Thrombektomie

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Key words

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ABSTRACT

Purpose In radiological interventions, the skin is the most exposed organ. The aim of this study was to investigate the local dose exposure and the resulting risk of deterministic radiation effects for patients who underwent mechanichal thrombectomy.

Materials and Methods The examination protocols of 50 consecutive stroke patients who underwent mechanical thrombectomy from September 2016 to April 2017 were evaluated in this study. All procedures were performed on a biplanar angiographic suite. The local skin equivalent dose $H_P(0.07)$ was calculated retrospectively using the recorded radiation data and previously measured conversion factors. The in-vitro determination of the conversion factors was performed with a silicon semiconductor detector on the surface of an Alderson-Rando head phantom depending on the radiation quality.

Results Vessel occlusion was located in the M1 and M2 segments of the cerebral artery media (n = 32), the internal carotid artery or carotid-T (n = 12) and the basilar artery (n = 6). The fluoroscopy times ranged from 5.7 minutes to 137.3 minutes with an average value of 39.5 ± 4.1 minutes. The determined skin equivalent dose values ranged from 0.16 ± 0.02 Gy to 4.80 ± 0.51 Gy, with the mean value being 1.00 ± 0.14 Gy. In 3 out of 50 cases (6 %), the threshold value for skin reactions of 3 Gy published by the German Radiation Protection Commission was exceeded. A further 15 patients (36 %) were exposed to a dose of 1–3 Gy. The highest dose values were achieved during long procedures with occlusions in the posterior circulation and carotid occlusions. In addition, a local dose reference level of 1.24 ± 0.15 Gy could be determined for the skin equivalent dose in mechanical thrombectomies for our center.

Conclusion Even during a modern neuroradiological intervention, such as mechanical thrombectomy, radiation doses to the patient are produced and can lead to deterministic radiation damage to the skin in approximately 6 % of cases. Systematic monitoring of local dose quantities, such as $H_P(0.07)$, seems appropriate. Possibilities for recording and reducing the local dose load should be developed by the interventional teams in cooperation with a medical physics expert.

Key Points:

- In 64 % of the thrombectomies the skin equivalent doses were in the harmless range (< 1 Gy).
- In 6 % of the patients higher $H_P(0.07)$ values were determined, which can lead to deterministic radiation damage to the skin.
- To avoid deterministic damage during neurointerventions, $H_P(0.07)$ should be recorded (combined measuring chambers).
- For longer interventions, precautions should be taken to reduce the radiation dose.

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ZUSAMMENFASSUNG

Ziel Bei radiologischen Interventionen ist die Haut auf der Strahleneintrittsseite das am stärksten exponierte Organ. In der durchgeführten Studie wurde am Beispiel der mechanischen Thrombektomie untersucht, wie hoch die lokale Exposition und die sich daraus ableitende Gefahr von deterministischen Strahlenwirkungen für Patienten ist.

Material und Methoden In dieser Arbeit wurden die Dosisprotokolle von 50 konsekutiven Schlaganfallpatienten ausgewertet, bei denen zwischen September 2016 und April 2017 eine mechanische Thrombektomie durchgeführt wurde. Alle Eingriffe wurden an einer biplanaren Anlage durchgeführt. Die lokale Haut-Äquivalentdosis $H_P(0,07)$ wurde retrospektiv mithilfe der protokollierten Strahlungsdaten und zuvor bestimmten Konversionsfaktoren berechnet. Die In-vitro-Ermittlung der Konversionsfaktoren erfolgte mithilfe eines Silizium-Halbleiterdetektors an der Oberfläche eines Alderson-Rando-Kopfphantoms in Abhängigkeit von der Strahlungsqualität.

Ergebnisse Die behandelten Verschlüsse betrafen das M1- und M2-Segment der A. cerebi media (n = 32), die A. carotis interna bzw. das Karotis-T (n = 12) sowie die A. basilaris (n = 6). Die Durchleuchtungszeiten reichten von 5,7 Minuten bis zu 137,3 Minuten bei einem Mittelwert von 39,5 ± 4,1 Minuten. Die ermittelten Werte der Haut-Äquivalentdosis reichten von 0,16 ± 0,02 Gy bis zu 4,80 ± 0,51 Gy, wobei der Mittelwert bei 1,00 ± 0,14 Gy lag. In 3 von 50 Fällen (6 %) kam es bei komplexen Eingriffen zu einer Überschreitung des von der Strahlenschutzkommission publizierten Schwellenwertes für Hautreaktionen von 3 Gy. Weitere 15 Patienten (36 %) wurden mit einer Dosis von 1–3 Gy exponiert. Die höchsten Dosiswerte wurden bei langwierigen Eingriffen mit Verschlüssen in der hinteren Zirkulation und bei Karotis-T-Verschlüssen beobachtet. Der aus diesen Daten ermittelte lokale Dosisreferenzwert unseres Zentrums für die Haut-Äquivalentdosis lag bei 1,24 ± 0,15 Gy.

Schlussfolgerung Auch bei einem modernen neuroradiologischen Eingriff wie der mechanischen Thrombektomie entstehen für den Patienten relevante Strahlendosen, die in circa 6 % zu deterministischen Strahlenschäden an der Haut führen können. Eine systematische Überwachung von lokalen Dosisgrößen, wie $H_P(0,07)$, erscheint angebracht. Möglichkeiten zur Erfassung und Reduktion der lokalen Exposition sollten von den interventionellen Teams in Zusammenarbeit mit einem Medizinphysikexperten erarbeitet werden.

Introduction

In their report (2007) on interventional radiology, the German Commission on Radiological Protection (SSK) concluded that no deterministic damage to the skin can be expected in interventional neuroradiology if interventions are performed at suitable neuroradiological centers by medical professionals with radiation protection experience [1]. However, the development of new treatment strategies and smaller instruments and the increasing digitalization of angiographic suites have allowed the development of new more complex interventions which can entail long fluoroscopy times. Consequently, it is necessary to check the validity of the SSK report with respect to current methods.

One of the most successful and most modern methods is mechanical thrombectomy for the treatment of acute ischemic stroke. Based on the positive clinical outcome and the high incidence rate of approx. 240 000 new cases per year in Germany with about 5 % being possible candidates for mechanical thrombectomy, the method has become one of the most common interventions in interventional neuroradiology [2].

The skin exposure of 50 patients during mechanical thrombectomy was determined in this study. The results of the study are intended to provide information regarding the frequency of harmful exposure and thus the need for systemic skin dose monitoring.

Materials and Methods

Patient group

The study included all consecutive patients who underwent mechanical thrombectomy between September 2016 and April 2017 due to occlusion of the internal carotid artery, middle cerebral artery, or vertebrobasilar territory. There were no exclusion criteria in relation to age, sex, or time of intervention after the start of symptoms. In addition to the retrospectively calculated patient skin dose, the fluoroscopy time, dose area product, reference air kerma and the number of DSA sequences were calculated.

Angiography suite

The interventions were performed on an "Artis zee biplane" angiography workstation (Siemens). This system allows digital subtraction angiography on two planes (plane A and plane B). In general, plane A is used for p. a. or undertable projections and plane B is used for lateral or overtable projections.

Voltages between 40 kV_p and 125 kV_p and copper filters ranging between 0.0 mm, 0.1 mm, 0.2 mm, 0.3 mm, 0.6 mm and 0.9 mm can be used to vary the radiation quality and are automatically activated by automatic dose regulation (ADR) under consideration of the parameters in the selected imaging/fluoroscopy program. The parameters of the imaging/fluoroscopy programs used in this study are shown in ▶ **Table 1**.

▶ **Table 1** Dose-influencing settings of the fluoroscopy (FL Neuro), DSA (LD Cerebral and Cerebral) and RoadMap (RM Neuro SF) programs.

parameter	FL neuro	cerebral	LD cerebral	RM neuro SF
kV plateau/kV	70	73	73	73
pulse width/ms	25	100	100	20
focus size/mm²	0.6 x 0.6	0.6 x 0.6	0.6 x 0.6	0.6 x 0.6
dose/image/µGy/fr	$3.20 \cdot 10^{-2}$	3.00	1.82	$4.50 \cdot 10^{-2}$
copper filter/mm	0.2–0.6	0.0–0.3	0.1–0.3	0.2–0.6
frame rate/1/s	10	4	4	10
kV ms/kV	125	96	96	77
kV dose/kV	125	102	102	109

Dose monitoring is performed by measuring the dose area product (DAP) with a DIAMENTOR K2S (made by PTW) directly behind the collimator. Moreover, a value for the reference air kerma at a focal distance of 60 cm determined indirectly from the measured DAP and collimator position is specified. All parameters are stored digitally after conclusion of an examination by generating an examination protocol.

Technical implementation of a thrombectomy

All thrombectomies were performed under general anesthesia by radiologists and neuroradiologists with interventional experience (> 50 thrombectomies). A long sheath (8F, Super Arrowflex, Teleflex Medical) was inserted via a transfemoral access into the affected common carotid artery/internal carotid artery and then an aspiration catheter (6F, Sophia-Plus, Microvention/Terumo) and a microcatheter (Rebar18, Ev3) were inserted using the coaxial technique to the intracranial occlusion. Thrombectomy was performed using a stent retriever system adapted to the vessel diameter (e. g. Solitaire, Medtronic) under distal aspiration.

Calculation of the skin equivalent dose $H_P(0.07)$

In the case of the photon energies of less than 150 keV usually used in radiology, exposure is greatest at the skin surface due to backscatter effects and the significant tissue attenuation so that skin exposure can be used as a measure for the risk of deterministic radiation damage.

Skin exposure is quantified according to DIN 6814–3 by the local skin equivalent dose $H_P(0.07)$. This corresponds to the organ equivalent dose averaged over a skin surface of 1 cm² at a depth of 0.07 mm. [3]

Only deterministic radiation effects are taken into consideration in the following so that $H_P(0.07)$ is specified in Gray (Gy) here instead of the usual unit for equivalent dose quantities (Sievert (Sv)) in order to rule out confusion with the effective dose. This is permissible since both the radiation weighting factor w_R and the quality factor Q for photon radiation are 1 and the numeric value does not change in the conversion from the energy dose to the equivalent dose. [4]

According to the data published by the German Commission on Radiological Protection, initial radiation-induced skin reactions, like temporary epilation and erythema, can be expected starting at a skin equivalent dose of 3 Gy [1].

Since direct measurement on the patient skin was not possible in this study, the local skin equivalent dose $H_P(0.07)$ was determined with the help of the data stored in the examination protocol and the following relation:

$$H_p(0{,}07) = \underbrace{\frac{DFP}{A_I} \times \left(\frac{r_I}{r_I - 9\,\text{cm}}\right)}_{K_E} \times f_{H_p(0{,}07)}(\Psi_E) \qquad (1)$$

Units: $[H_p(0{,}07)]$ = Gy; $[DFP]$ = cGy · cm²; $[A_I]$ = cm²; $[r_I]$ = cm; $[f_{H_p(0{,}07)}(\Psi_E)] = 10^2$

To convert the DAP specified in the examination protocol to entrance dose K_E (entrance kerma without consideration of backscatter and attenuation caused by positioning material), field size A_I in the reference point 15 cm above the table and focal distance r_I were taken from the "DICOM tags" of every stored fluoroscopy image or acquired image. For simplification, the head was approximated by a ball with a radius of 9 ± 3 cm (≙ radius of the head phantom, see below). A conversion factor $f_{H_p(0.07)}$ whose value depends on the spectral energy fluence Ψ_E (can be influenced by the tube voltage and prefiltering) and the beam direction was needed to convert entrance dose K_E to local skin equivalent dose $H_P(0.07)$. This takes into account backscatter effects and attenuation caused by material located in the beam path such as for patient positioning, and factors for converting from an air to a water energy dose.

The peak skin dose (maximum value of $H_P(0.07)$ during an intervention) was always assumed to be in the center of plane A on the beam entrance side since this was the primary work plane. Projections on plane B were only taken into consideration if their field size in the reference point was greater than 81 cm². In these projections it could be assumed that the presumed point of peak skin dose was located in the radiation field of plane B. Changes in angulation and the associated reduction in peak skin dose were not taken into consideration so that the values specified in the following are a conservative estimation of the peak skin dose. However, significant changes in angulation were also not observed.

In-vitro determination of the conversion factors $f_{H_p(0.07)}$

The conversion factors were determined with the help of a silicon semiconductor detector (DIADOS, made by PTW) on the surface

▶ **Fig. 1** Setup for measuring the conversion factors on the head phantom. Placement of the silicon semiconductor detector at **a** the undertable or p.-a. projection and **b** the overtable or lateral projection. Position of the head phantom relative to the C-arm at **c** the undertable or p. a. projection and **d** the overtable or lateral projection.

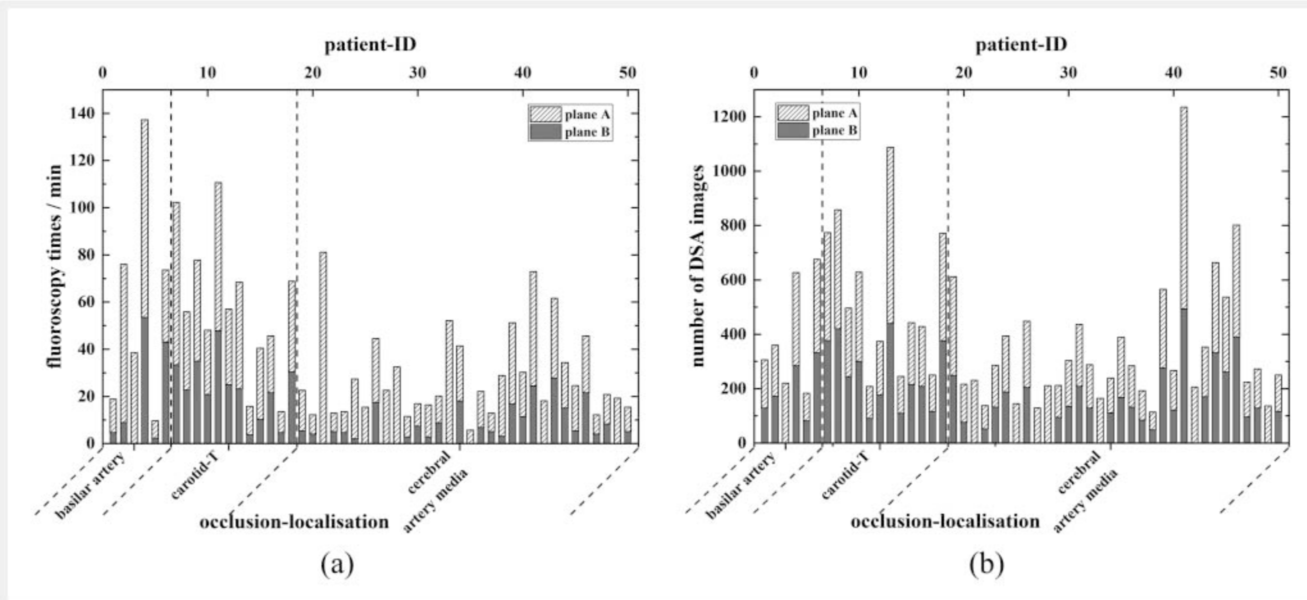
of an Alderson-Rando head phantom as a function of the tube voltage, copper filter, projection direction and field size (▶ **Fig. 1**). The dorsal placement of the detector (a and c) is representative of all p. a. and the lateral position (b and d) for all overtable projections.

It should be noted that the validity of conversion factors calculated in this way is limited to the head region and the beam entrance side. For geometric reasons the conversion factors for lateral projections were used for projections with angulations greater than 70° and less than -70°, while the conversion factors for p. a. projections were used in all other cases. It was not necessary to determine conversion factors for additional angulations since the head has approximately radial symmetry.

Statistics

The specified standard uncertainties were assessed according to DIN 13 005 [5] with an amplification factor of $k = 1$ (≙ the simple standard deviation), with the type-B uncertainty being 12 % due to the measurement setup.

The calculated dose values were evaluated in table form and using descriptive statistics methods ($\bar{x}$, $x_{min.}$, $x_{max.}$).



▶ **Fig. 2** **a** Fluoroscopy times (10 P/s) and **b** the number of DSA images (sum of images of all DSA series) for the respective planes, where plane A was used for undertable and plane B for overtable projections.

Results

Patient age at the time of the intervention ranged from 23 to 88 years and was on average 72.0 ± 2.2 years (median = 76 years). The treated occlusions affected the M1 and M2 segment of the middle cerebral artery (n = 32), the internal carotid artery, the carotid-T (n = 12) and the basilar artery (n = 6). The average dose area product was 12 810 ± 1.455 cGy·cm² and the average reference air kerma was 1.17 ± 0.17 Gy. Distributed to the two tubes, the average dose area product was 9112 ± 905 cGy·cm² and the average reference air kerma was 0.83 ± 0.10 Gy for plane A while for plane B the average dose area product was 3698 ± 669 cGy·cm² and the average reference air kerma was 0.34 ± 0.07 Gy.

▶ **Fig. 2a** shows the fluoroscopy times with classification as undertable (plane A) and overtable projections (plane B). The fluoroscopy times ranged from 5.7 to 137.3 minutes with an average value of 39.5 ± 4.1 minutes and a pulse rate of 10 P/s.

The value for plane A (on average 27.1 minutes) was significantly higher than that for plane B (on average 14.8 minutes). Only plane A was used for fluoroscopy in 8 of 50 patients (16 %) resulting in monoplanar imaging.

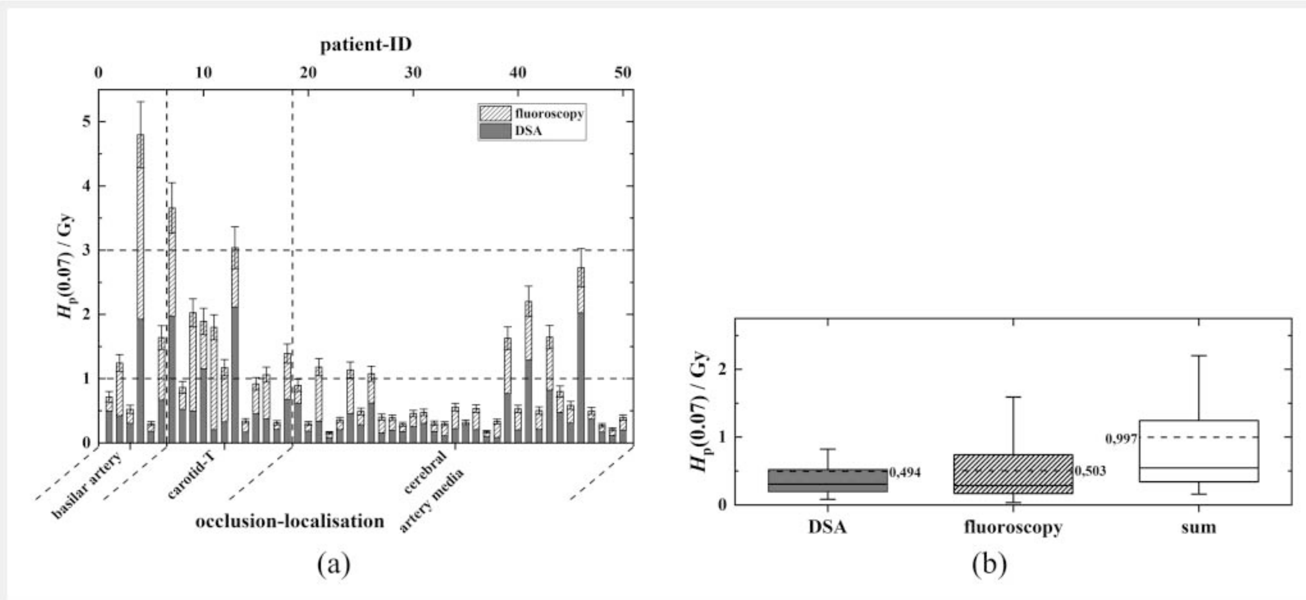
The number of DSA images acquired in the examinations (total images in all DSA series) is shown in ▶ **Fig. 2b**. Classification according to the two available planes was also performed here. There were 114 to 1236 DSA images and on average 398 + 36 DSA images per examination. Using the typical frame rate of 4 f/s and an average sequence duration of 6 s, up to 52 DSA series (26 per plane) per exmaniation were performed in extreme cases with an average of 16 series (8 per plane) per examination. In contrast to fluoroscopy, no significant dominance of one of the two planes in biplanar imaging was seen.

The calculated local skin equivalent doses and their statistical distribution are shown in ▶ **Fig. 3**. The values ranged from 0.16 ± 0.02 Gy to 4.80 ± 0.51 Gy, with an average value of 1.00 ± 0.14 Gy. According to ▶ **Fig. 3a**, the average threshold dose of 3 Gy for radiation-induced skin reactions was exceeded in 3 of 50 cases (6 %). The majority of patients (64 %) experienced harmless exposure of less than 1 Gy (median = 0.54 Gy, see ▶ **Fig. 3b**) with respect to deterministic skin reactions. Particularly high skin dose values were seen in occlusions located in the basilar artery and internal carotid artery or in the carotid-T while the dose values in occlusions of the middle cerebral artery were largely harmless. The cumulative values for fluoroscopy and DSA sequences with respect to the local skin equivalent dose are typically to be considered approximately equal. However, fluoroscopy has significantly higher maximum values (taking into account that significantly more fluoroscopy images than DSA images are acquired during an examination). The average local skin equivalent dose was 0.50 ± 0.08 Gy in the case of fluoroscopy and 0.49 ± 0.08 Gy in DSA sequences. A comparison of ▶ **Fig. 2a, 3a** also shows that the longest fluoroscopy times were seen in the patients with the highest skin dose values. Therefore, fluoroscopy time seems to be a good indicator of the total duration and complexity of an intervention.

Based on the results of this study, a local dose reference level for our center of 1.24 ± 0.15 Gy could be determined for the local skin equivalent dose $H_P(0.07)$ for patients undergoing mechanical thrombectomy. According to the recommendations of the International Commission on Radiological Protection (ICRP), this value corresponds to the upper quartile of the determined values [6].

Discussion

In a comparable study by J. Farah et al. (2018), the fluoroscopy times and the values for dose area product and reference air kerma were recorded in 319 mechanical thrombectomies [7]. In 80 %



▶ **Fig. 3** Maximum local skin equivalent dose values of a group of patients who underwent mechanical thrombectomy. **a** Bar chart of the investigated patients with drawn threshold for skin reactions at 3 Gy according to [1]. **b** Box plots of the applied local skin equivalent dose (the respective mean value segmented and the median compactly displayed). The size of the box is limited by the respective lower and upper quartiles. The maximum length of the whiskers is limited to 1.5 times the interquartile distance. The standard uncertainties estimated according to [5] are 12 %.

(DAP) and 56 % (K_a) of the cases in the study performed here, the values were less than the local dose reference levels specified for the dose area product (16 200 cGy·cm²) and the reference air kerma (0.85 Gy). In 62 % of cases, the fluoroscopy time was less than the specified reference level of 42 minutes. On the whole, both studies yielded comparable results (see ▶ **Table 2, 3**). The DRL for the DAP specified by the Federal Agency for Radiation Protection for thrombus aspiration after a stroke of 18 000 cGy·cm² [8] was undercut in 86 % of cases. A significant event as defined by the publication of the Federal Agency for Radiation Protection [9] did not occur during the study.

The threshold value of 3 Gy published by the German Commission on Radiological Protection for deterministic radiation effects on the skin (erythema, temporary epilation, dry desquamation) was exceeded in 3 of 50 cases (6 %). These cases included two patients requiring more than two thrombectomies and one patient in whom recanalization could not be achieved. However, the median value of 0.54 Gy shows that deterministic radiation damage is typically not to be expected. However, it must be taken into consideration that the threshold values are non-gender-specific and non-age-specific average values and according to [10, 11] age-dependent sensitivity of the skin to radiation can be expected. In addition, preceding acute diagnosis via CT, CT-angiography, and CT-perfusion prior to the intervention results in significant cumulative exposure for the patient. For this reason the use of a conservative monitoring dose of 1 Gy peak skin dose would be useful. If this value is exceeded, patients should be monitored with regard to deterministic skin reactions. This monitoring dose was exceeded in 18 of 50 cases (36 %) (see ▶ **Fig. 3**). Thus, the statement of the German Commission on Radiological Protection mentioned at the beginning could not be completely confirmed in the case of mechanical thrombectomy.

A comparison of ▶ **Fig. 2, 3** shows that with one exception a harmless skin dose of less than 0.6 Gy was achieved in all monoplanar thrombectomies. The study conducted by B. Friedrich et al. (2018) showed that clinical outcome is not affected by elimination of the use of the second plane if the thrombectomy is performed by an experienced radiologist [12]. Therefore, use of the second plane should always be carefully considered with respect to patient skin dose exposure. However, a possible increase in the amount of contrast agent needed and in the treatment duration must be taken into consideration.

Exposure values have not changed significantly despite the use of modern techniques in mechanical thrombectomy compared to earlier studies (see ▶ **Table 2**). This is primarily due to the high complexity of the method. Since the comparison studies prior to 2007 were still performed on analog X-ray image intensifiers, the common view that "digital systems result in a dose reduction" is not necessarily correct. Instead digital flat panel detector technology allows increasingly complex interventions resulting in a possible increase in fluoroscopy time as in the case of mechanical thrombectomy (see ▶ **Table 3**). Due to the substantial heterogeneity of the results in the comparison studies, it would be helpful to conduct additional studies on skin exposure in mechanical thrombectomy at other locations since a dependence between operator experience and the imaging technology being used is to be expected. Moreover, verification of the measured conversion factors via direct measurement of the surface dose, e. g. using thermoluminescence dosimeters (TLD) placed in the head rest or using Monte-Carlo simulations, would be desirable.

▶ **Table 2** Comparative studies on exposure in various neurointerventions. DRL = dose reference level.

source	surface dose/Gy			average DAP/cGy·cm²		application
	min.	max.	mean			
Federal Agency for Radiation Protection 2018 [8]	N/A	N/A	N/A	18 000 (DRL)		thrombus aspiration
Mooney et al. 2000 [13]	N/A	4.00	N/A	N/A		embolization
Struelens et al. 2005 [14]	N/A	5.40	N/A	N/A		embolization
Kemerink et al. 2002 [15]	0.17	2.33	0.87	22 800		coiling and embolization
Farah et al. 2018 [7]	0.07	4.52	0.70 ± 0.59	12 300 ± 9500		mech. thrombectomy
	(reference air kerma)					
Friedrich et al. 2018 [12]	N/A	N/A	N/A	11 456 (monoplanar)	20 566 (biplanar)	mech. thrombectomy
conducted study	0.16 ± 0.02	4.80 ± 0.51	1.00 ± 0.14	12 810 ± 1455		mech. thrombectomy

▶ **Table 3** Comparative studies of fluoroscopy time (without documentation, DSA series, etc.) for various neurointerventions.

Source	fluoroscopy time/min				application
	min.	max.	mean		
Theodorakou and Horrocks 2003 [16]	N/A	50.0	28.0		embolization
Seifert et al. 2000 [17]	N/A	N/A	17.2		embolization
Kemerink et al. 2002 [15]	16.0	66.0	34.8		coiling and embolization
Farah et al. 2018 [7]	7.0	226.0	35.0 ± 27.0		mech. thrombectomy
Friedrich et al. 2018 [12]	N/A	N/A	30.0 ± 20.0 (monoplanar)	34.0 ± 24.0 (biplanar)	mech. thrombectomy
conducted study	5.7	137.0	39.6 ± 4.1		mech. thrombectomy

Nonetheless, recording a local dose, such as $H_P(0.07)$ in this case, seems appropriate for assessing the risk for deterministic radiation damage during mechanical thrombectomy.

An estimation of the local dose based on the typically recorded dose area product is not useful due to the variability of the field size and distance between the patient and source in the individual case. Fluoroscopy time and the number of DSA images (see ▶ **Fig. 2, 3**) can at best serve as an indicator and are not suitable for the quantitative assessment of local exposure. A combined measuring chamber consisting of a DAP-DIAMENTOR and a smaller measuring chamber in the center could be used to assess deterministic radiation damage. This allows simultaneous direct measurement of the dose area product and air kerma that can be converted to the entrance dose using an additionally measured distance (e. g. via a laser). Using the entrance dose and corresponding conversion factors, the risk for deterministic radiation damage was able to be quantitatively assessed. This could be automatically recorded in connection with dose management systems.

Conclusion

The results of this study show that mechanical thrombectomy typically (64 %) results in harmless skin dose exposure of ≤ 1 Gy regarding deterministic radiation effects. However, dose values at which deterministic radiation damage to the skin of the patient, e. g. temporary epilation and erythema, cannot be ruled out can occur in individual cases. In addition to the assessment of the stochastic radiation risk based on the dose area product, measures for recording and reducing the local exposure of the patient must be discussed. Therefore, for example, due to the increased exposure, biplanar imaging should only be performed if required by the angiographic conditions, and a need-oriented reduction of the pulse frequency should be considered. The development and implementation of such measures for evaluating and reducing patient and examiner exposure while maintaining the necessary image quality are the responsibility of medical physics experts.

CLINICAL RELEVANCE OF THE STUDY

- A local dose reference level of 1.24 ± 0.15 Gy could be determined for the local skin equivalent dose $H_P(0.07)$ for patients during mechanical thrombectomy.
- Measures for recording and reducing local exposure in interventional neuroradiology should be implemented (e. g. combined measuring chambers).
- A suitable medical physics expert should be consulted for this purpose.

Conflict of Interest

The authors declare that they have no conflict of interest.

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