Physica Medica 32 (2016) 176–181

Contents lists available at ScienceDirect

Physica Medica

journal homepage: http://www.physicamedica.com

Original Paper

Patient and staff doses in paediatric interventional cardiology derived from experimental measurements with phantoms

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ARTICLE INFO

Article history:
Received 22 August 2015
Received in revised form 1 November 2015
Accepted 23 November 2015
Available online 11 December 2015

Keywords:
Interventional cardiology
Paediatric patient doses
Staff doses
Eye doses

ABSTRACT

The aim of this paper was to determine experimentally the entrance surface air kerma (ESAK) and kerma-area product (KAP) levels to patients and scatter doses at the cardiologist's eyes during paediatric interventional cardiology (IC) procedures for Chile, on the basis of measurements taken from X-ray systems characterization for different thicknesses of polymethyl methacrylate, together with the average values of fluoroscopy time and number of cine frames for ten paediatric IC procedures. The range of cumulative ESAK values when the different clinical procedures were simulated was from 2 to 1100 mGy. KAP values ranged from 0.30 to 150 Gy cm^2. Scatter doses at cardiologist's eyes for the simulated procedures ranged from 0.20 to 116 µSv per procedure. Large differences between the X-ray systems were found in our study. Standardized guidelines in terms of X-ray system setting and protocols should be developed for hospitals that perform paediatric IC procedures in Chile.

Introduction

It is known that interventional cardiology (IC) procedures may produce high doses of radiation for both patients and staff [1–3].

Radiation dose is particularly important for paediatric patients because, according to a recent UNSCEAR report, estimates of lifetime cancer risk for exposed children were uncertain but might be a factor of 2–3 times as high as estimates for a population exposed at all ages [4].

Moreover, during paediatric IC procedures interventional cardiologists need to remain closer to the patient than in adult procedures. Sometimes procedural complexity requires lengthy fluoroscopy time and multiple numbers of cine frames. As such, a careful evaluation of scatter dose levels for staff involved in these procedures is appropriate [5]. Evaluating the dose to the eye lens holds particular significance due to both cataract or opacity being one of the major deterministic effects for staff [6] and the ICRP having reduced the dose limit for workers from 150 to 20 mSv year^{-1}, averaged over a defined period of 5 years [7].

Evaluation of radiation doses received by patients and staff should be considered an important part of quality assurance programmes for IC procedures [8,9] and can, in part, be estimated from the experimental measurements performed within characterization of an X-ray systems [5,10].

This paper aims to determine experimentally some dosimetric parameters related with dose levels to patients and scatter doses at cardiologist's eyes in ten common types of paediatric IC procedures.

Materials and methods

The X-ray systems of four paediatric interventional cardiology services were characterized using modified DIMOND and SENTINEL protocols in terms of dose and image quality [11–13]. Six X-ray systems were evaluated, representing 100% of the paediatric cardiac angiography laboratories in Chile (a country with 18 million inhabitants) [14]. Three systems used image intensifiers and three used flat panel detectors. The systems were numbered from 1 to 6 (numbers 1–3 with flat panel detector and numbers 4–6 with image intensifier, see Table 1).

Polymethyl methacrylate (PMMA) slabs of 25 cm × 25 cm × 0.5 cm were used as phantoms in thicknesses from 4 cm to 16 cm, equivalent to paediatric patient chest thicknesses of around 6 cm and 24 cm thick, respectively, according to Rassow et al. [15]. These

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http://dx.doi.org/10.1016/j.ejmp.2015.11.009
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Table 1
X-ray systems evaluated in the survey.

ID no.	Manufacturer	Model	Image detector	Name of protocols used	Year of installation
1	Siemens	Axiom Artis dBC, Biplane	Flat detector	Paediatric 20 kg	2008
2	Philips	Allura Xper FD20, monoplane	Flat detector	5 kg, child 5–15 kg and child 15–40 kg	2005
3	Philips	Allura Xper FD20, biplane	Flat detector	5 kg, child 5–15 kg and child 15–40 kg	2012
4	General Electric	Advantx, biplane	Image intensifier	Cardio Ped	2009
5	Siemens	Axiom Artis BC, biplane	Image intensifier	Newborn, infant and child	2005
6	General Electric	Advantx, monoplane	Image intensifier	Cine A, B, C and D	1994

thicknesses may be considered as the range of the typical sizes of paediatric chest patients in antero-posterior X-ray beam direction. We assumed that 4 cm of PMMA represent patients aged below 1 year, 8 cm of PMMA represent patients aged below 5 year, 12 cm of PMMA represent patients aged below 10 year and 16 cm of PMMA represent patients aged below 15 years. A test object (Leeds TOR 18-FG) [16] was positioned at the isocentre and in the middle of the PMMA thickness during all measurements to evaluate image quality.

Measurements taken during the experiments used the default settings to simulate the most common paediatric examination protocols used in each X-ray system (see Table 1). During these simulations, no extra collimation was applied to the radiation field, its size being automatically collimated according to the image intensifier or flat panel detector field-of-view (FOV) format.

In accordance with the International Commission on Radiological Units (ICRU) Report 74 [17], the dosimetric quantities for patient dosimetry used were incident air kerma (IAK) or entrance surface air kerma (ESAK) (with backscatter) and kerma-area product (KAP) or dose-area product. For staff, the dosimetric quantity expressed as personal dose-equivalent Hp(0.07) was used to estimate eye doses. ICRP Publication 103 suggests that the monitoring of eye lens exposure is sufficiently reliable using Hp(0.07) [18]. Other studies show that to assess the equivalent dose to the eye lens of Hp(3) in IC, a passive whole-body dosimeter calibrated at Hp(10) or Hp(0.07) can be used satisfactorily. Numerically, Hp(10) is close to Hp(0.07) in IC and both can be used to assess Hp(3) [19].

IAK was measured using an Unfors Xi (model 8201010-A) system with a solid-state detector (model 82020030-AXi) [20] in contact with the PMMA slabs. The backscatter factor used to estimate ESAK from IAK values was 1.3 [17]. The Unfors Xi detector was positioned inside the radiation field, out of the automatic exposure control area. To simulate clinical conditions, the image detectors of the evaluated X-ray systems were always in antero-posterior projection and positioned at 5 cm from the phantom. Although other projections could be used, the evaluation of different C-arm angulations has been overlooked because in paediatric IC procedures using biplane systems, antero-posterior projections were used in around 85%–90% of the cases [10]. The focus-to-detector distances were ~74 cm to ~68 cm for the PMMA thicknesses studied (4 cm, 8 cm, 12 cm and 16 cm). In order to measure the dose at the cardiologist's eye lens position (~77 cm from isocentre and ~170 cm from floor), an Unfors EED-30 detector, model 8131010-C [20] was used, consisting of a solid-state sensor and an independent display. Dosimetric systems were duly calibrated, traceable to official calibration laboratories (RaySafe laboratory).

From the experimental measurements for all PMMA thicknesses during the characterization of each X-ray system, we selected ESAK rates for low rate fluoroscopy mode and ESAK per frame for cine acquisition and their respective scatter dose rates at simulated eye position (details of settings used are shown in Table 2). We also used the average values for fluoroscopy time (FT) and number of cine frames (CF) obtained in one of our previous papers [21]. Different dosimetric quantities such as ESAK, KAP (using the PMMA phantom) and scattered dose at cardiologist's eye lens position were estimated using the operational data (fluoroscopy time, number of cine frames, etc) collected for ten different types of paediatric IC procedures (see Table 3).

Table 4 presents ESAK rate and scatter dose rate values for all X-ray systems and PMMA thicknesses, evaluated in low rate fluoroscopy and cine acquisition modes.

We have not made several measurements of each of the values (ESAK and scatter dose), but this has been done in previous experiments and the reproducibility was always good, with the geometry conditions being most critical if changed during the experiments. The intrinsic "uncertainty" of the used solid-state detectors (Unfors Xi 10% and Unfors EDD 6%) was the highest and was assumed as the uncertainties for our single measurements. The significant figures in our table haves been adjusted accordingly. However, when referring to global results with several fluoroscopy and cine series, and as highlighted in the conclusions section, the total error estimation of these figures should be increased by a factor of about 3, depending of the age of the X-ray system, the geometry factors, and the automatic exposure control.

Results

Table 5 shows ESAK values for all X-ray systems and estimated for the ten procedures simulated with 4, 8, 12 and 16 cm of PMMA, respectively. Each value refers to a single procedure.

Table 2
Selected configurations in each X-ray systems (ID no.) for low rate fluoroscopy and cine modes and field of view (FOV) used.

ID no.	Manufacturer	Low rate fluoroscopy (pulses s^{-1})	Cine (frame s^{-1})	FOV (cm)
1	Siemens	8	15	25
2	Philips	8	15	22
3	Philips	13	15	22
4	General Electric	15	30	17
5	Siemens	10	15	22
6	General Electric	25	25	23

Table 3
Average fluoroscopy time and average number of cine frames for each type of procedure simulated [21].

ID	Procedure	Fluoroscopy time (min)	Number of cine frames
A	Diagnostic normal	7.3	770
B	Diagnostic complex	17.9	1114
C	Aortic angioplasty	13.7	1053
D	Pulmonary angioplasty	23.4	979
E	Pulmonary angioplasty with stent	29.4	1333
F	Atrial septal defect closure	21	479
G	Aortic valvuloplasty	11.5	563
H	Pulmonary valvuloplasty	14.2	507
I	Patent ductus arteriosus closure with coil	9	337
J	Patent ductus arteriosus closure with device	11.7	605

Table 4
Entrance surface air kerma (ESAK) and scatter dose for all X-ray systems (ID no.) evaluated with 4, 8, 12 and 16 cm of polymethyl methacrylate (PMMA) in low rate fluoroscopy (LF) and cine acquisition (CI) modes.

ID no.	Acquisition mode	4 cm of PMMA (0 to <1 years)		8 cm of PMMA (1 to <5 years)		12 cm of PMMA (5 to <10 years)		16 cm of PMMA (10 to <15 years)	
		ESAK (mGy/min)	Scatter dose (μSv/h)	ESAK (mGy/min)	Scatter dose (μSv/h)	ESAK (mGy/min)	Scatter dose (μSv/h)	ESAK (mGy/min)	Scatter dose (μSv/h)
1	LF	0.43	<0.2	1.0	<0.2	2.3	36	6.9	93
	CI	2.7	30	7.3	75	28	225	70	520
2	LF	0.62	<0.2	1.4	27	2.5	45	5.3	93
	CI	2.4	36	8.8	115	15.2	200	56	740
3	LF	0.62	<0.2	1.4	50	2.9	48	5.5	96
	CI	2.2	28	8.8	125	28	340	54	670
4	LF	0.37	<0.2	0.9	33	2.0	71	6.2	170
	CI	0.90	160	6.6	290	28	840	93	2030
5	LF	0.11	<0.2	0.24	22	0.58	50	1.4	102
	CI	5.3	330	14	920	20	1450	58	3100
6	LF	2.0	<0.2	3.8	37	11.5	130	33	210
	CI	8.0	510	9.3	165	21	380	104	1000

KAP values at the PMMA phantom thicknesses of 4, 8, 12 and 16 cm are presented in Table 6 for the ten simulated procedures. Each value refers to a single procedure.

Table 7 shows staff scattered dose values at cardiologist's eye position (personal dose equivalent, Hp(0.07)) for all X-ray systems and estimated for the ten procedures simulated from 4 to 16 cm of PMMA. Each value refers to a single procedure.

Discussion

The ESAK rate values and scatter dose rate values are summarized in Table 4 for the different X-ray systems, phantom thicknesses and acquisition modes used. Differences found between the various PMMA thicknesses for these two quantities in respect of ESAK and scatter dose rate values are derived from wide range of operating point and the different settings used locally for the X-ray systems, including automatic exposure control curves, number of pulses per second, pre-selection of tube potential, pulse time, tube current and added filter, etc. [13,22]. This wide variation in the settings or radiographic techniques employed to carry out similar IC procedures in Chile was also recently reported by McFadden et al. [23] in the UK and Ireland, which study also proposed that standardized guidelines should be developed.

To our knowledge, there are no international recommendations on the range of ESAK values for use in paediatric cardiac systems at different patient sizes. However, some publications do offer values for adult patient settings. Faulkner [24] refers to ESAK rate values recommended by national and international bodies measured for 1 or 1.5 mm copper filter, while Padovani et al. [1,25] report 13 mGy/min as a reference rate value for low fluoroscopy mode, but measured at the entrance of a 20 cm PMMA phantom. It is appropriate to propose certain ESAK values as investigation levels (ILs) [9] for the different fluoroscopy modes when values could be too high for the current technology of paediatric cardiac systems. The default clinical dose setting should be optimized to ensure that it is as low as reasonably achievable. In our national survey, for 4 cm of PMMA, our measured values ranged from 0.11 to 2.0 mGy/min (a factor of 18); for 8 cm of PMMA, values ranged from 0.24 to

Table 5
Entrance surface air kerma (ESAK) values estimated for the ten procedures (A to J) simulated with 4, 8, 12 and 16 cm of polymethyl methacrylate (PMMA) for all evaluated X-ray systems (ID no.).

		ESAK procedures (mGy)									
ID no.	PMMA (cm)	A	B	C	D	E	F	G	H	I	J
1	4	5.5	11	9.1	13	17	11	6.6	7.6	4.9	6.8
	8	13.5	27	22	32	40	25	16	18	11.7	17
	12	41	76	64	89	110	64	44	49	31	46
	16	111	210	180	250	310	180	120	140	88	130
2	4	6.5	14	11.2	17	22	14	8.6	10	6.4	8.8
	8	18	35	29	43	53	33	21	24	15.6	22
	12	31	63	52	77	96	60	38	44	28	39.3
	16	87	160	140	190	240	140	96	110	69	100
3	4	6.4	14	11	17	22	14	8.5	10	6.4	8.8
	8	18	36	30	44	55	34	22	25	16.1	23
	12	45	87	73	100	130	76	51	57	37	53
	16	86	160	140	190	240	140	97	110	69	100
4	4	4.2	8.8	7.2	11.0	14	8.8	5.4	6.3	4	5.5
	8	9.1	19	16	24	30	20	12	14	9	12.3
	12	27	54	44	65	81	50	32	37	24	33
	16	85	170	140	200	250	150	100	110	73	103
5	4	3.1	5.3	4.7	6	7.3	3.8	3	3.1	2	3.1
	8	7.8	13	12	14	18	8.8	7.2	7.4	4.8	7.5
	12	12.8	23	20	26	32	17	13	14	8.9	13.5
	16	35	61	53	69	84	45	34	36	24	36
6	4	19	42	33	53	66	45	26	31	20	27
	8	32	75	58	95	120	82	47	57	36	48
	12	94	220	170	280	360	250	140	170	108	143
	16	290	670	530	850	1100	730	420	500	322	430

Table 6
Kerma-area product (KAP) values estimated for the ten procedures (A–J) simulated with 4, 8, 12 and 16 cm of polymethyl methacrylate (PMMA) for all evaluated X-ray systems (ID no.).

KAP procedures (Gy cm^2)											
ID no.	PMMA (cm)	A	B	C	D	E	F	G	H	I	J
1	4	1.2	2.4	2.0	3.0	3.7	2.3	1.5	1.7	1.1	1.5
	8	2.7	5.4	4.5	6.5	8.1	5.0	3.2	3.7	2.4	3.3
	12	7.5	14	12	16	20	12	8.1	9.0	5.8	8.4
	16	19	35	30	42	51	31	21	23	15	21
2	4	1.1	2.4	1.9	3.0	3.7	2.4	1.5	1.7	1.1	1.5
	8	2.7	5.5	4.5	6.7	8.3	5.2	3.3	3.8	2.4	3.4
	12	4.4	9.0	7.4	11	14	8.6	5.4	6.2	4.0	5.6
	16	11	21	18	25	31	18	12	14	8.9	13
3	4	1.1	2.4	1.9	3.0	3.7	2.4	1.5	1.7	1.1	1.5
	8	2.8	5.7	4.7	6.9	8.6	5.4	3.4	3.9	2.5	3.5
	12	6.4	12	10	15	18	11	7.3	8.2	5.2	7.5
	16	11	21	18	25	31	19	13	14	9.0	13
4	4	0.30	0.70	0.60	0.9	1.1	0.70	0.40	0.50	0.30	0.40
	8	0.70	1.4	1.1	1.8	2.2	1.4	0.90	1.0	0.70	0.9
	12	1.8	3.6	3.0	4.4	5.4	3.4	2.2	2.5	1.6	2.2
	16	5.1	10	8.4	12	15	9.4	6.1	6.9	4.4	6.3
5	4	0.40	0.70	0.60	0.80	1.0	0.50	0.4	0.40	0.30	0.40
	8	1.0	1.6	1.4	1.8	2.1	1.1	0.90	0.90	0.60	0.90
	12	1.4	2.5	2.2	2.9	3.6	1.9	1.4	1.5	1.0	1.5
	16	3.6	6.2	5.4	7.0	8.6	4.6	3.5	3.7	2.4	3.7
6	4	3.5	6.2	4.9	7.8	12	6.6	3.8	4.6	2.9	3.9
	8	5.5	10	7.8	13	20	11	6.3	7.6	4.8	6.4
	12	15	27	21	35	55	30	17	21	13	17
	16	42	75	59	95	150	81	47	56	36	48

3.8 mGy/min (factor of 16); for 12 cm of PMMA, values ranged from 0.58 to 11.5 mGy/min (a factor of 20); and for 16 cm of PMMA, values ranged from 1.4 to 33 mGy/min (a factor of 24). For CI mode, these value ranges were the following: for 4 cm of PMMA, from 0.90 to 8.0 mGy/min (a factor of 9); for 8 cm of PMMA, from 6.6 to 14 mGy/min (a factor of 2); for 12 cm of PMMA, from 15.2 to 28 mGy/min (a factor of 2); and for 16 cm of PMMA, from 54 to 104 mGy/min (a factor of 2). According to the results published by Vaño et al. [26] for adult IC procedures, the ESAK rate values can vary from 63 to 191% for the different C-arm angulation, if antero-posterior projection is used as reference.

Generally, no point on the patient's skin is constantly irradiated by radiation beams. A more detailed evaluation requires knowledge of the exact distribution of the radiation fields on the patient's skin and this has not been examined in the present survey. Table 5 only shows the full range of cumulative dose values. This range of values of cumulative ESAK when the different clinical procedures were simulated was from 2 to 1100 mGy (factor of 550 for all the thicknesses). The highest value of skin dose was reported for the pulmonary angioplasty with stent procedure (66 and 1100 mGy, respectively), simulated with X-ray system ID no. 6. The lowest value of skin dose was reported for the patent ductus

Table 7
Scatter dose (Hp(0.07)) values estimated for the ten procedures (A–J) simulated with 4, 8, 12 and 16 cm of polymethyl methacrylate (PMMA) for all evaluated X-ray systems (ID no.).

Hp(0.07) procedures (μSv)											
ID no.	PMMA (cm)	A	B	C	D	E	F	G	H	I	J
1	4	0.40	0.60	0.60	0.50	0.70	0.30	0.30	0.30	0.20	0.30
	8	1.10	1.6	1.5	1.4	1.9	0.70	0.80	0.70	0.50	0.80
	12	7.6	15	13	18	23	14.5	9.2	11	6.8	10
	16	19	38	31	46	58	37	23	27	17	24
2	4	0.50	0.80	0.70	0.70	0.90	0.30	0.40	0.30	0.20	0.40
	8	5.0	11	8.5	13	16	11	6.4	7.5	4.8	6.6
	12	8.3	18	14	21	27	17	11	12.5	8	11
	16	22	43	36	50	64	39	26	29	19	27
3	4	0.40	0.60	0.50	0.50	0.70	0.20	0.30	0.30	0.20	0.30
	8	7.8	17	14	22	27	19	11	13	8.2	11
	12	11	21	18	25	32	20	13	15	9.4	13
	16	21	43	35	50	64	40	25	29	19	26
4	4	1.1	1.6	1.5	1.4	1.9	0.70	0.80	0.70	0.50	0.90
	8	6.0	13	10	15	20	13	7.8	9.1	5.8	8
	12	15	30	24	35	45	29	18	21	13	19
	16	35	71	58	83	107	67	43	40	31	44
5	4	2.4	3.4	3.2	3.0	4.1	1.5	1.7	1.6	1	1.9
	8	9.3	16	14	17	22	12	9.1	10	6.2	10
	12	16	30	26	33	43	24	17	19	12	18
	16	35	62	54	68	88	49	36	39	25	37
6	4	4.4	6.4	6.0	5.6	7.6	2.7	3.2	2.9	1.9	3.5
	8	5.9	13	10.0	16	20	14	8	10	6.1	8.2
	12	19	44	35	56	71	49	28	34	21	29
	16	34	74	59	92	116	78	46	55	35	47

arteriosus closure with coil procedure (2 and 24 mGy, respectively), simulated with X-ray system ID no. 5. The ESAK values in our study were lower than the threshold for deterministic effects for skin or transient erythema (2 Gy) [27].

According to the IAEA [28], the KAP quantity was originally introduced to determine energy imparted to patient, since it is a quantity that is related to the stochastic risk of cancer induction. The KAP quantity is also recommended for the establishment and use of diagnostic reference levels for patients subjected to IC procedures [17]. In the current study (see Table 6), KAP values ranged from 0.30 to 150 Gy cm^2 (a factor of 500 for all the thicknesses). As with skin dose, the highest and lowest KAP values corresponded to pulmonary angioplasty with stent (simulated with X-ray system ID no. 6) and patent ductus arteriosus closure with coil (simulated with X-ray system ID no. 5) procedures, respectively.

Table 7 illustrates the scattered dose values at cardiologist's eye position. These values reported allow an estimation of staff doses received in paediatric cardiac laboratories if a ceiling-suspended screen is not used. The scattered doses at cardiologist's eye lens for the ten kinds of simulated procedure ranged from 0.20 to 116 µSv (factor of 580). If we assume a typical workload of twenty procedures per month, exclusively examining patients aged between 0 to <1 years could mean a scattered dose from 4 to 152 µSv per month. In the case of patients aged between 10 to <15 years, the monthly range may be from 340 to 2320 µSv. The use of personal protective shielding is clearly necessary in paediatric IC procedures. Occupational doses, including operator eye dose, can be reduced to very low levels with proper use of ceiling-suspended lead shields, if they are positioned correctly during the procedure. Leaded eyewear is recommended if ceiling-suspended shields cannot be used continuously during the entire procedure [29]. Vano et al. [26] also reported that the scatter dose rates to the lens of the cardiologists vary substantially depending on the different angulations used for adult IC procedures. Using the antero-posterior projection as normalisation value (100%), the scatter dose rates may change between 40 and 233%. For moderate angulations (the ones used in some paediatric procedures with biplane systems) the changes in scatter dose are between 61 and 123% compared with the antero-posterior projection.

Study limitations

The limitations of this study were the use of values for fluoroscopy time and number of cine frames of one hospital and assume that the other services worked with the same parameters. In future work, the impact of using both C-arms simultaneously and other angulations should be taken into account but this will require the access to the patient dose reports in all the centres and this was not possible for most of the X-ray system currently used in our country.

Conclusions

From the ESAK values and scatter dose values obtained during characterization for all X-ray systems used in Chile for paediatric IC procedures, and taking the typical FT and CF values for ten such procedures from the largest paediatric hospital in Chile, the dose levels to patients and scattered dose at cardiologist's eyes were derived. The cumulative skin dose and KAP values for the different procedures ranged from 2 to 1100 mGy and from 0.30 to 150 Gy cm^2, respectively. However, when referring to cumulative skin dose and KAP values during full procedures with several fluoroscopy and cine series, the total error estimation of these figures should be increased by a factor of about 3, depending on the age of the X-ray system, the geometry factors, and the automatic exposure control. Note that IEC standard 60601-2-43 says that the overall uncertainty of the displayed values of the cumulative KAP shall not exceed 35% [30]. For the ten common procedures selected, scattered dose at cardiologist eye lens ranged from 0.20 to 116 µSv per procedure. Large differences between the X-ray systems were found in our study. Standardized guidelines or reference levels in terms of X-ray system setting and protocols should be developed for hospitals that perform paediatric IC procedures in Chile.

Funding

This research was partially supported by the Direction of Research at the Tarapaca University, through senior research project No. 7710-14.

Acknowledgments

The current work has been carried out under the framework of the International Atomic Energy Agency regional project RLA/9/075, "Strengthening National Infrastructure for End-Users to Comply with Regulations and Radiological Protection Requirements".

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