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Original article

Conversion coefficients calculation of mono-energetic photons from air-kerma using Monte Carlo and analytical methods

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ABSTRACT

This study is aimed to calculate the conversion coefficients $H^*(10)/\Phi$ form air-kerma for beams of mono-energetic photons, which incident on ICRU sphere diameter 30 cm of ICRU tissues material with a density of 1 g/cm^3 four-element tissue and a weight composition of 76.2% oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen (ICRU 57, 1997). The conversion coefficients are calculated using two methods: the DOSRZnrc based on EGSnrc code (Kawrakow et al., 2017) and our developed FORTRAN subroutine which evaluates the analytical expression available from a fit to Monte Carlo calculations (Veinot and Hertel, 2011). Our results have been carried out for absorbed dose and kerma approximations, for mono-energetic photons from 15 keV to 10 MeV. The results obtained were compared to those published by ICRU reports (ICRP Publication 74, 1996; ICRU 57, 1997). A good agreement with reference data with a local difference less than 2% was found.

1. Introduction

The conversion coefficients $H^*(10)$ form air-kerma, is the quantity that recommended by the International Commission on Radiation Units and Measurements (ICRU) to be used as an approximation of the protection quantity effective dose (ICRU 57, 1997). The International Commission on Radiation Units and Measurements, ICRU, and the International Commission on Radiological Protection, ICRP, are entities responsible to develop and promulgate internationally accepted recommendations on radiation related and units, measurement procedures and reference data used on radiation protection of individuals and populations (Valentin et al., 2005). The ambient dose equivalent, $H^*(10)$, is defined at a point in a radiation field, is the dose equivalent, which would be produced by the corresponding expanded and aligned field in the sphere of International Commission on Radiation Units and Measurements (ICRU) at a depth of 10 mm on the radius opposing the direction of the field (Valentin et al., 2005). ICRU sphere is 30 cm in diameter and its density equals to 1 g/cm^3. This sphere consists of 4-elemental compositions of 76.2% oxygen (O), 11.1% carbon (C), 10.1% hydrogen (H), and 2.6% nitrogen (N) (ICRP Publication 74, 1996; ICRU 57, 1997). The irradiation source is a photon beam parallel section 30 $*$ 30 cm^2. In this work, the conversion coefficients $H^*(10)/K_{air}$ calculated for mono-energetic photons from 15 keV to 10 MeV using DOSRZnrc based on EGSnrc code in absorbed dose mode and the kerma approximation and those calculated with our developed FORTRAN subroutine which evaluates the analytical expression available from a fit to Monte Carlo calculations (Veinot and Hertel, 2011, 2012).

2. Materials and methods

DOSRZnrc based on EGSnrc code (Mont Carlo) is used to calculate $H^*(10)/K_{air}$ in absorbed dose mode and the kerma approximation and calculated K_{air}/Φ values for mono-energetic photons from 15 keV to 10 MeV, which incident on ICRU sphere diameter 30 cm of ICRU tissues material with a density of 1 g/cm^3 four-element tissue and a weight composition of 76.2 % oxygen, 11.1% carbon, 10.1% hydrogen and 2.6% nitrogen. The irradiation source is a photon beam parallel section 30 $*$ 30 cm^2. We also calculated $Kair/\Phi$ with our developed FORTRAN subroutine which evaluates the analytical expression available from a fit to Monte Carlo calculations (Veinot and Hertel, 2011; Santos et al., 2016; Veinot and Hertel, 2012), as well K_{air}/Φ, which is given by Eq. (1) in (Gy.cm^2) .

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$$f(x) = \frac{a}{1+(b+cx)^2} + \frac{d}{1+(f+gx)^2} + \frac{h}{1+(j+kx)^2} + \frac{l}{1+\exp(m+nx)} + \frac{o}{1+\exp(p+qx)} \quad (1)$$

where f(x) is the logarithmic (base 10) value of the conversion coefficients and x equals $\log_{10}(E)$ with E numerically coincident with the energy expressed in MeV. Analytical fit values for K_{air}/Φ conversion coefficients are summarized in Table 1. The results obtained have compared with those calculated by Eq. (2) and those published in ICRP74, CEA-R-6235. The results show in the Table 2 and the curves show in Fig. 1 (Table 3).

The K_{air}/Φ values can be calculated from the mass energy-transfer coefficients $(\mu_{tr}/\rho)_{air}$ by applying the following Eq. (2) (Antoni and Bourgois, 2013; Mayles et al., n.d):

$$\frac{K_{air}}{\Phi} = E\frac{\mu_{tr}}{\rho} \quad (2)$$

where $\frac{\mu_{tr}}{\rho}$ is the mass–energy transfer coefficients in (cm^2/g), E is the photon energy in Joule.

Equation (3) represents the analytical function proposed by ICRU 47 to fit the mean conversion coefficients showed in Figs. 2, 3 in units of Sv/Gy (Medicine and 1993, n.d.; Santos et al., 2016).

$$\frac{H*(10)}{K_{air}} = \frac{x}{ax^2+bx+c} + d.\arctan(gx)....(Sv/Gy) \quad (3)$$

where a = 1.465, b = −4.414, c = 4.789, d = 0.7006, g = 0.6519, arctan is in radians, and x = ln(E/E_o), where E = photon energy (keV) and E_o = 9.85 keV.

Finally, the three equations are processed with a FORTRAN to develop a new approach to calculate the conversion coefficients (Appendix).

3. Results

3.1. Kair determination

Table 2 shows K_{air}/Φ values calculated with DOSRZnrc based on EGSnrc code, analytical fits Eq. (1), by the Eq. (2) and then compared with those published in ICRP74 and CEA-R-6235 (ICRP Publication 74, 1996; Josiane Daures et al., 2009; Veinot and Hertel, 2011). The values are in good agreement, which are shown in Fig. 1.

3.2. Conversion coefficients H*(10)/Kair as a function of energy

We have calculated conversion coefficients H*(10)/K_{air} in absorbed dose mode and in kerma approximation with DOSRZnrc code and FORTRAN subroutine which evaluates the analytical expression available from a fit to Monte Carlo calculations (Veinot and Hertel, 2011). The obtained results are compared with those reported in ICRP74. As shown in Fig. 2, H*(10)/Φ values are increased for photon energies from 15 keV to about 20 keV due to the decreasing of the transmission factor that the energy increases in this area where the preponderant interaction is photoelectric. At 20 keV, the curve reaches maximum before bending and decreasing to 100 keV. This behavior is with the energy increases, of the increasing component of the Compton process, which is responsible for a tiny fraction of energy transferred to the secondary electrons. In this same area, this process is in competition with the photoelectric process for which all the energy of the photon is transferred to the medium. In the tissues the preponderant interaction is the Compton type. The energy of the photon incident is strong, the higher the one carried by the electron Compton is on average high: the energy

Table 1
Analytical fit values for K_{air}/Φ conversion coefficients (Veinot and Hertel, 2011).

Parameter	a	b	c	d	f	G	h	j	k	l	M	n	o	p	q	SSR
	34.01720	1.151140	0.364446	0.508067	1.473950	2.018200	0.103817	25.83640	14.76820	−46.30410	0.442619	0.441972	4.606090	−1.822660	−2.276015	0.008800

Table 2
Comparison of K_{air}/Φ calculated with DOSRZnrc based on EGSnrc code, analytical fits Eq. (1), Eq. (2) and with those published in ICRP74 and CEA-R-6235.

Energy	Analytical fits	EGSnrc	ICRP74	CEA-R-6235	By Eq. (2)
15	3.20799E−12	3.1100E−12	3.11E−12	3.110E−12	3.20160E−12
20	1.74402E−12	1.7319E−12	1.73E−12	1.729E−12	1.72512E−12
30	6.77979E−13	7.3997E−13	7.39E−13	7.400E−13	7.38240E−13
40	4.33289E−13	4.3840E−13	4.38E−13	4.388E−13	4.37504E−13
50	3.43555E−13	3.2728E−13	3.29E−13	3.288E−13	3.28000E−13
60	3.09607E−13	2.8965E−13	2.93E−13	2.924E−13	2.92032E−13
80	3.11558E−13	3.0375E−13	3.09E−13	3.088E−13	3.08224E-13
100	3.60691E−13	3.6829E−13	3.73E−13	3.724E−13	3.72160E−13
150	5.89739E−13	5.9187E−13	5.99E−13	5.989E−13	5.99280E−13
200	8.74043E−13	8.5230E−13	8.56E-13	8.541E−13	8.55680E−13
300	1.40330E−12	1.3846E−12	1.38E−12	1.380E−12	1.38000E−12
400	1.88627E−12	1.8916E−12	1.89E−12	1.890E−12	1.88992E−12
500	2.35515E−12	2.3853E−12	2.38E−12	2.380E−12	2.37680E−12
600	2.80988E−12	2.8156E−12	2.84E−12	2.842E−12	2.83968E−12
800	3.65912E−12	3.7098E−12	3.70E−12	3.703E−12	3.69792E−12
1000	4.42148E−12	4.4849E−12	4.47E−12	4.473E−12	4.47520E−12
1500	6.02851E−12	6.1441E−12	6.13E−12	6.137E−12	6.13680E−12
2000	7.37301E−12	7.5407E−12	7.54E−12	7.547E−12	7.54880E−12
3000	9.70947E−12	9.9490E−12	9.95E−12	9.952E−12	9.96480E−12
4000	1.18536E−11	1.2261E−11	1.21E−11	1.211E−11	1.21216E−11
5000	1.39285E−11	1.3936E−11	1.41E−11	1.414E−11	1.41600E−11
6000	1.59798E−11	1.6293E−11	1.61E−11	1.613E−11	1.61568E−11
8000	2.00819E−11	1.9902E−11	2.01E−11	2.008E−11	2.01088E−11
10,000	2.42286E−11	2.4099E−11	2.41E−11	2.405E−11	2.40960E−11

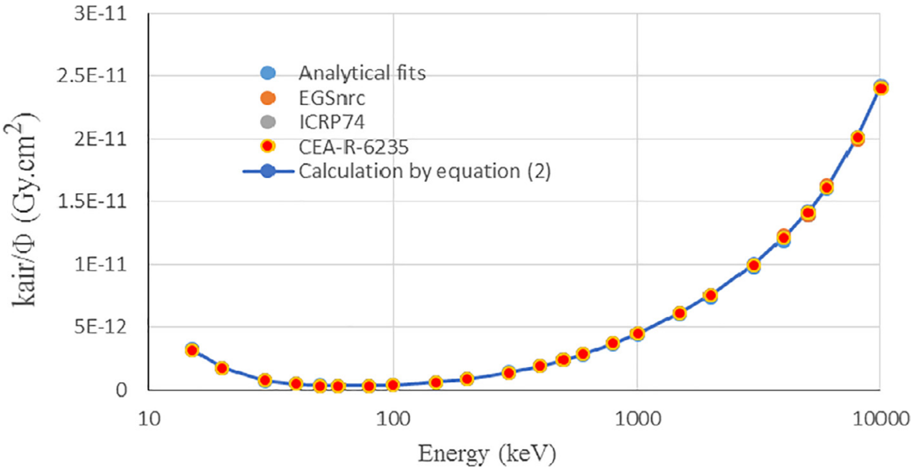

Fig. 1. Curves of K_{air}/Φ, which calculated using DOSRZnrc based on EGSnrc code, by Eq. (2), analytical fits Eq. (1) and with those published in ICRP74, CEA-R-6235.

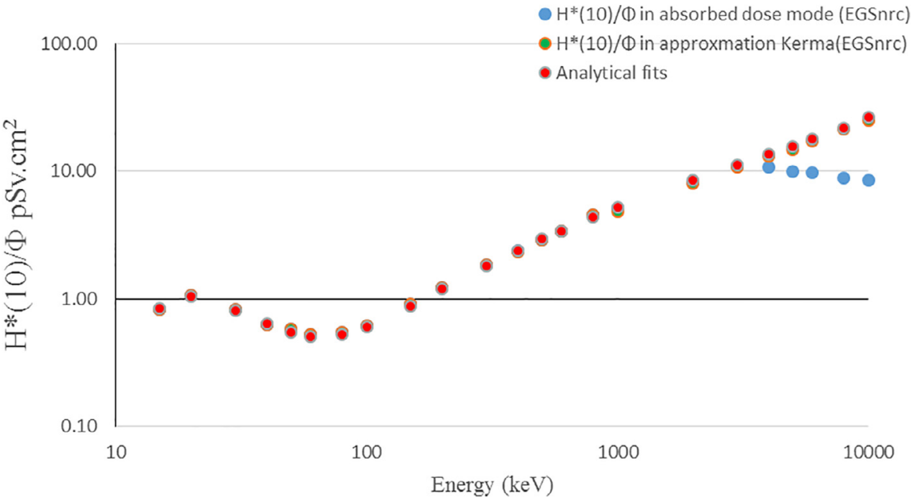

Fig. 2. Curves of the fluence ambient dose equivalent conversion coefficients for photons in absorbed dose mode and in kerma approximation using DOSRZnrc based on EGSnrc code.

Table 3
$H^*(10)/K_{air}$ conversion coefficients versus photon energy in absorbed dose mode and in kerma approximation.

	Absorbed dose mode	Kerma approximation		
E (keV)	EGSnrc	Analytical fits	EGSnrc	ICRP74
15	0.262182692	0.279252556	0.2621763	0.26
20	0.618280501	0.598447399	0.6427623	0.61
30	1.114747895	1.098908379	1.0871252	1.09
40	1.435697993	1.465295250	1.4004562	1.43
50	1.752658274	1.664596192	1.7433696	1.65
60	1.801242879	1.739207756	1.7892974	1.75
80	1.805004115	1.720418691	1.7882798	1.74
100	1.672866491	1.645354423	1.7174238	1.65
150	1.532380421	1.490686852	1.5122071	1.49
200	1.432711487	1.400305339	1.4375220	1.39
300	1.335403727	1.306653736	1.3390149	1.29
400	1.245136392	1.259204968	1.2262635	1.24
500	1.211587641	1.230427468	1.2618958	1.21
600	1.207380310	1.210989614	1.2530899	1.18
800	1.223462181	1.186167317	1.2188528	1.15
1000	1.131864702	1.170794667	1.1682294	1.14
2000	1.092033896	1.137703024	1.1510470	1.11
3000	1.104734144	1.125164616	1.1073475	1.09
4000	0.869994291	1.118264001	1.0933578	1.09
5000	0.714049943	1.113791677	1.0946470	1.08
6000	0.595237218	1.110610882	1.0930461	1.07
8000	0.446980203	1.106315875	1.1044116	1.06
10,000	0.354288560	1.103497331	1.0787170	1.05

yielded in the medium grows so as the energy increases (Antoni and Bourgois, 2013). As shown in Fig. 3, we notice that $H^*(10)/K_{air}$, for low energies from 15 keV to 20 keV, the deposited energy is lower than the transferred energy due to the photons transferring their energy totally into the region defined (10 mm). For energies more than 30 keV to 600 keV the energy deposited is greater than the energy transferred due to the increasing the stopping power as well the path of the electrons, (Attix, 1986). For energies higher than 600 keV and less than 1 MeV the conversion coefficients stabilizes around 1 because of the achievement of the electronic equilibrium. On the other hand, for the energies from 1 MeV $H^*(10)/K_{air}$ values determined in terms of absorbed dose are found fill down, in this energy range, the secondary electron created will depose their energies output volume of interest (Attix, 1986).

3.3. Variation of the conversion coefficients according to the energy and the depth

In this study, we vary the position of the point (P) along the sphere axis to find out the effect of the depth on the coefficients $H^*(d)/K_{air}$ as presented in Fig. 4.

For each energy, we found that the conversion coefficients decrease with increasing the depth, because the secondary electrons created by the photons will deposit a part of their energies before arriving the position of interest. For the curves corresponding the depths of 5 and 7 cm, we notice that after the 2 MeV energy the electronic equilibrium is realized and remains conserved for all other energies up to 10 MeV. For a depth greater than 7 cm the conversion coefficients take values lower than 1 due the secondary electrons lost their energies before arriving the point of interest.

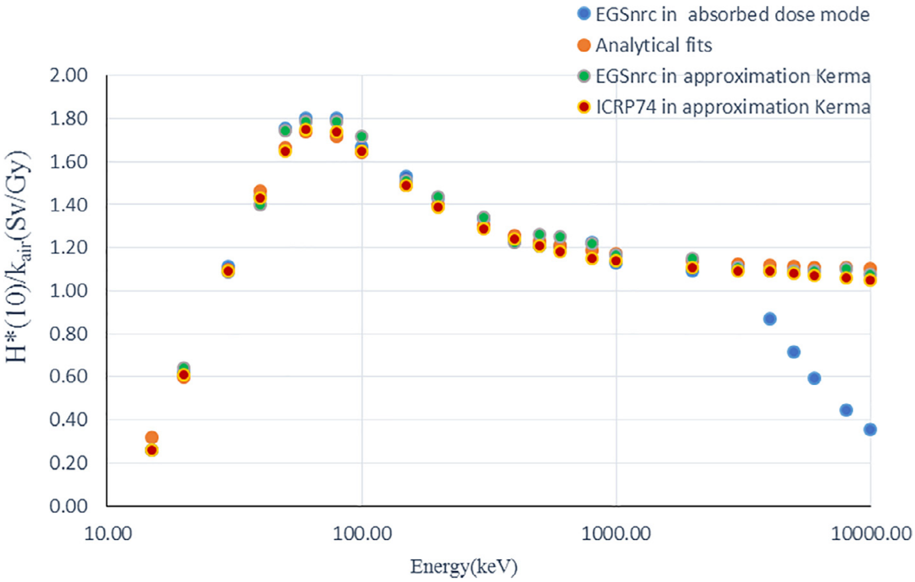

Fig. 3. Curves of $H^*(10)/K_{air}$ conversion coefficient versus photon energy in absorbed dose mode and in approximation kerma.

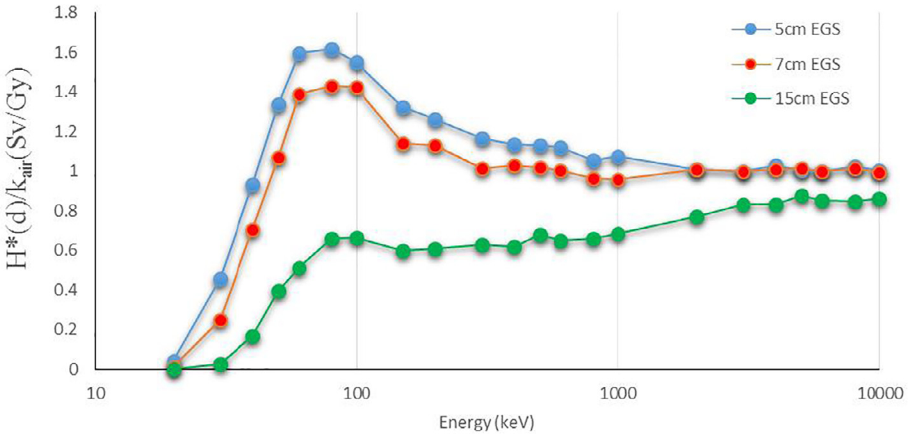

Fig. 4. Variation of the H*(d)/K_{air} conversion coefficient as a function of depth for energies from 20 keV to 10 MeV.

4. Conclusions

The H*(10)/K_{air} conversion coefficients have been calculated with DOSRZnrc based on EGSnrc code MC and FORTRAN program for mono-energetic photons from 15 keV to 10 MeV in kerma and absorbed dose terms. The ambient dose equivalent from air-kerma (H*(10)/K_{air}) values calculated are very close to those reported in ICRP74 report. At low photon energy, up to 3 MeV, the two sets of H*(10)/K_{air} conversion coefficients are consistent, Nevertheless, the differences increase at higher energy. This is mainly due to the lack of electronic equilibrium because the secondary electrons deposit a part of their energies before arriving at the position of interest. The main motivation for this study is to improve standards of protection for medical staff for procedure resulting in potentially high exposures and to develop methodologies for better assessing and for reducing exposures. Specifically, the numerical comparison was made to validate DOSRZnrc based on EGSnrc code for conversion coefficients calculations as well as testing the developed FORTRAN subroutine.

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Appendix A.

Program FORTRAN

```
! Conversion coefficients calculations of mono-energetic
  photons from air-Kerma Monte Carlo simulations
Program Hstar10
Implicit none
Integer::i
Real,dimension(24)::kairparfluence,Kairparfluencecalcula
  tion,Hstar10parkair,E,Utr
Open(unit = 2,file = ’These Results.txt’)
WRITE(2,3)
3 FORMAT(2X,“i”,9X,’E(i)’,6X,“kair/fluence(pSv.m2)”,3X,’Kair/
  fluenceCa(pSv.m2)’,3X,’H*(10)/kair(pSv)’)
Call Ambientdose(kairparfluence,Kairparfluencecalculation,H
  star10parkair,E,Utr)
Do i = 1,24
WRITE(2,4) i,E(i),kairparfluence(i),Kairparfluencecalculation
  (i),Hstar10parkair(i)
4 FORMAT(2X,i2,f16.0,2X,f16.9,10X,f16.9,10X,f16.9)
End do
Print∗,’see file These Results’
End program
Subroutine Ambientdose(kairparfluence,Kairparfluencecalcu
  lation,Hstar10parkair,E,Utr)
Real::ka,Hst
Real,dimension(24)::kairparfluence,Kairparfluencecalcula
  tion,Hstar10parkair,E,Utr
Integer::i
Open(unit = 1,file = ’Energy.txt’)
Do i = 1,24
Read(1,∗)E(i),Utr(i)
End do
Do i = 1,24
Kairparfluencecalculation(i) = E(i)∗Utr(i)∗1.602E-13/1.E-12
Hstar10parkair(i) = Hst(E(i))
kairparfluence(i) = ka(E(i))
End do
End subroutine
! The Function calculation kerma air
REAL FUNCTION ka(E)
Implicit none
real::Y,X,Z,Q,O,u,v,w,u1,v1,w1,i1,j,k,r,s,t,r1,s1,t1,E,sum
u = 34.0172;v = 1.15114;w = 0.364446;
u1 = 0.508067;v1 = 1.47395;w1 = 2.0182
i1 = 0.103817;j = 25.8364;k = 14.7682;r = –46.3041;s =
  0.442619;t = 0.441972
r1 = 4.60609;s1 = –1.82266;t1 = –2.76015
Y = u/(1 + (v + w∗LOG10(E/1000))∗∗2)
X = u1/(1 + (v1 + w1∗LOG10(E/1000))∗∗2)
Z = i1/(1 + (j + k∗LOG10(E/1000))∗∗2)
Q = r/(1 + EXP(s + t∗LOG10(E/1000)))
O = r1/(1 + EXP(s1 + t1∗LOG10(E/1000)))
Sum = Y + X + Z + Q + O
ka = 10∗∗(sum)
End function
! Conversion coefficients H*(10) from air-Kerma
Real function Hst(E)
Implicit none
Real::a,b,c,d,g,Eintial,F,N,M,E
```

```
a = 1.465;b = −4.414;c = 4.789;d = 0.7006;g = 0.6519;Eintial
   = 9.85
F = log (E/Eintial)
M = (a*F**2 + b*F + c)
N = d*atan (g*F)
Hst = (F/M) + N
End function
```

The Input file for the program.

Energy (keV)	The mass–energy transfer coefficients
15	1.334
20	0.5391
30	0.1538
40	0.06836
50	0.041
60	0.03042
80	0.02408
100	0.02326
150	0.02497
200	0.02674
300	0.02875
400	0.02953
500	0.02971
600	0.02958
800	0.02889
1000	0.02797
1500	0.02557
2000	0.02359
3000	0.02076
4000	0.01894
5000	0.0177
6000	0.01683
8000	0.01571
10,000	0.01506

The output file for the program.

i	E(i)	k_{air}/fluence (pGy.cm^2)	K_{air}/fluenceCa (pGy.cm^2)	H*(10)/ k_{air}(pSv)
1	15.	3.208004000	3.201600000	.319252500
2	20.	1.744019000	1.725120000	.598447400
3	30.	.677979900	.738240000	1.098908000
4	40.	.433289800	.437504000	1.465295000
5	50.	.343556100	.328000000	1.664596000
6	60.	.309608300	.292032000	1.739208000
7	80.	.311559000	.308224000	1.720419000
8	100.	.360692200	.372160000	1.645354000
9	150.	.589739600	.599280000	1.490687000
10	200.	.874045400	.855680000	1.400305000
11	300.	1.403302000	1.380000000	1.306654000
12	400.	1.886280000	1.889920000	1.259205000
13	500.	2.355154000	2.376800000	1.230428000
14	600.	2.809895000	2.839680000	1.210990000
15	800.	3.659127000	3.697920000	1.186167000
16	1000.	4.421490000	4.475200000	1.170795000
17	1500.	6.028514000	6.136800000	1.149257000
18	2000.	7.373024000	7.548800000	1.137703000
19	3000.	9.709488000	9.964800000	1.125165000
20	4000.	11.853610000	12.121600000	1.118264000
21	5000.	13.928510000	14.160000000	1.113792000
22	6000.	15.979790000	16.156800000	1.110611000
23	8000.	20.081980000	20.108800000	1.106316000
24	10000.	24.228550000	24.096000000	1.103497000

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