

RESEARCH ARTICLE

Reducing an already low dental diagnostic X-ray dose: does it make sense? Comparison of three cost-utility analysis methods used to assess two dental dose-reduction measures

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Objectives: To find a method that is suitable for providing an objective assessment of the cost effectiveness of a dose-reducing measure used for diagnostic dental X-ray exposures.

Methods: Three cost-utility analysis (CUA) methods were evaluated by comparing their assessments of two dose-reduction measures, a rectangular collimator and the combination of two devices that reduce the radiation dose received during orthodontic lateral cephalography. The following CUA methods were used: (1) the alpha value (AV), a monetary valuation of dose reduction used in the nuclear industry; (2) the value of a statistical life for valuation of the reduction in stochastic adverse effects; and (3) the time-for-time method, based on the postulate that risk reduction is effective when the number of years of life gained is more than the years that an average worker must work to earn the costs of the risk-reducing measure. The CUA methods were used to determine the minimum number of uses that was required for the dose-reducing device to be cost effective. The methods were assessed for coherence (are comparable results achieved for comparable countries?) and adaptability (can the method be adjusted for age and gender of specific patient groups?).

Results: The performance of the time-for-time method was superior to the other methods. Both types of dose-reduction devices tested were assessed as cost effective after a realistic number of uses with all three methods except low AVs.

Conclusions: CUA for the methods of X-ray dose reduction can be performed to determine if investment in low dose reduction is cost effective. The time-for-time method proved to be a coherent and versatile method for performing CUA.

Dentomaxillofacial Radiology (2015) **44**, 20150158. doi: [10.1259/dmfr.20150158](https://doi.org/10.1259/dmfr.20150158)

Cite this article as: Hoogeveen RC, Sanderink GCH, van der Stelt PF, Berkhout WER. Reducing an already low dental diagnostic X-ray dose: does it make sense? Comparison of three cost-utility analysis methods used to assess two dental dose-reduction measures. *Dentomaxillofac Radiol* 2015; **44**: 20150158.

Keywords: radiation protection; dental radiography; orthodontics; risk management

Introduction

The use of X-rays for diagnostic purposes in dentistry is well established, although the ionizing property of X-rays is potentially detrimental to the patient. The harm posed by radiography is why the radiation protection laws and regulations require justification

for every patient exposure. When an exposure is justified, it is supposed to be executed in accordance with the as low as reasonably achievable principle. “Reasonably” indicates that there are limits to the efforts required to reduce doses. Recommendations of the International Commission on Radiation Protection (ICRP) stipulate that financial and socioeconomical factors must be taken into account when dose-reducing measures are considered.¹ The dose of a dental diagnostic

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This article was funded by Academic Center for Dentistry Amsterdam, Amsterdam, Netherlands.

Received 2 May 2015; revised 11 June 2015; accepted 24 June 2015

radiographic exposure can be expressed in sieverts, which is the unit used for the “effective dose” (E) of a dental radiograph. E is a measure that was designed to express the risk of detrimental effects. E depends on the type of radiation and the radiosensitivity of the organ or tissue that receives the dose. Although the assumption has been debated, the field of radiation protection assumes that there is a linear relationship between dose and risk, even at the lowest dose levels. With the use of a risk factor (RF), E can be expressed in terms of total detriment, which means the induction of fatal cancers, hereditary effects and non-fatal cancers. The ICRP considers the detriment-adjusted RF to be $5.7 \times 10^{-2} \text{ Sv}^{-1}$ for the average population.² Radiation detriment is age and gender dependent, being higher for younger age groups and slightly higher for females. The RF should therefore be adjusted for specific patient groups. The RF is based on a multiplicative risk model, implying that a radiation exposure increases the existing “natural” cancer prevalence by a factor, after a latency period, during the remaining lifetime.³ When a population group is exposed to radiation, the doses to individuals can be aggregated and expressed as the collective dose using man-Sv as the unit. These collective doses can be converted to stochastic effects by the RF. In this way, a population dose can be quantified as the loss of the number of “statistical lives”. This term refers to anonymous fictitious members of a population and is useful for quantifying and comparing different risks to the public.

If a dental dose-reducing measure (DDRM) is developed, it should be evaluated regarding its effect in the socioeconomic perspective. However, no methods have been definitively identified for evaluating whether or not a DDRM is a sound investment. Practice guidelines encourage us to invest in dose-reducing measures, which include using rectangular collimation for intraoral radiography and limiting the field of view and shielding the thyroid for lateral cephalography.^{4,5} However, there have not been any evaluations that balance the costs of these measures with their utility.

Regarding radiological protection and risk management, there are different methods for performing cost–utility analysis (CUA) of dose- or risk-reduction strategies. One method uses the concept of the alpha value (AV). The AV is a monetary reference value that expresses how much money is reasonable to be spent for a collective dose reduction. It is expressed as € per man-Sv and is commonly used in the nuclear industry. AV can be used to assess the price of dose-reducing measures against the reduction of the collective dose. The Organization for Economic Co-operation and Development⁶ has published the AVs from various countries. Some countries apply a fixed AV; other countries use an AV that varies, depending on the remaining individual dose level, where a low remaining dose level results in a lower AV (Table 1). The cost–utility of a DDRM can be evaluated by this method. The AV can be used to convert the dose reduction per exposure into a financial benefit per exposure. The minimum number

of exposures needed to result in a cost-effective DDRM can be calculated when the price of the DDRM is known.

To illustrate this: let us assume that a fictitious device reduces the dose to the patient of an X-ray exposure with $10 \mu\text{Sv}$, and the national AV is $154 \text{ € man-mSv}^{-1}$. This means that after 100 exposures with the device, the reduction of the collective dose to the patients is ($100 \times 10 \mu\text{Sv} =$) 1 man-mSv . This reduction according to the AV can be valued as $\text{€}154$. Per exposure, the reduction can be valued as ($\text{€}154/100 =$) $\text{€}1.54$. Should the reducing device cost $\text{€}1000$, then after ($\text{€}1000/\text{€}1.54 =$) 650 times of its use its costs are balanced by its benefits.

Another method of performing CUA of a DDRM is to quantify the dose reduction as reduced loss of statistical lives and consecutively to express this reduction in a monetary value by the use of the value of a statistical life (VSL). The VSL has been the focus of many investigations. The VSL can be determined by surveying people about their willingness to pay for specific levels of risk reduction. Another method for determining the VSL is to calculate an implicit VSL. The cost of an actual risk-reducing measure is evaluated against its actual benefits for saving lives or is evaluated by analysing wage–risk data from the labour market.

The concept of the VSL has evolved since it was first formulated in 1962 by Drèze.⁷ Many articles on the VSL have been published since then. A recent meta-analysis has shown that a wide range of VSLs can be found in the literature, ranging from US \$0.5 to \$50 million.⁸ The wide range has been partially explained by differences in the age, income, and level and type of risk of the study population.^{9,10} The type of risk being reduced also plays a role in the wide range. The willingness to pay for reducing the risk of a fatal cancer has been found to be twice that of reducing the risk of sudden death.¹¹

Government bodies have incorporated the concept of the VSL into their policies. However, their use of the VSL to develop policy does not clarify the wide range in the VSL as was shown by Krupnick,¹² who reported that different government agencies in a single country use different VSLs. Doucouliagos *et al*⁹ have reported that the US Environmental Protection Agency recommended a VSL of US \$6.2 million in year 2000 prices; the Australian Department of Finance and Deregulation adopted a VSL of A\$ 3.5 million in 2007; and the Department of Transportation of the United Kingdom adopted a VSL of £1.64 million in 2009. The European Union published interim values for the VSL in 2001, with an upper and lower estimate of $\text{€}0.65$ million to $\text{€}2.5$ million in year 2000 prices.¹³ The European Union publication stipulated that a 50% premium should be added for reducing the risk of a fatal cancer. These numerous different values can be compared only after correction for exchange rates, inflation and differences in purchasing power, which is beyond the scope of this article. It is highly unlikely that a universally accepted VSL will ever be adopted. We

Table 1 Published alpha values (AVs)

Country that published AVs	Fixed or variable value	α -value in € man-mSv ⁻¹	Minimum α -value in € man-mSv ⁻¹	Maximum α -value in € man-mSv ⁻¹	n for rectangular collimator	n for anatomical cranial collimator/cephalographic thyroid protector
Finland	Fixed	77.21			170	2590
Romania	Fixed	570			23	351
Netherlands	Fixed	433.78			30	461
USA	Fixed	154.3			85	1296
Switzerland	Fixed	2481.39			5	81
Czech Republic	Variable		20.08	100.39	655	9960
Korea	Variable		13.13	1312.59	1002	15232
Slovakia	Variable		33.19	663.88	396	6026
Sweden	Variable		55.48	283.29	237	3605
UK	Variable		12.55	125.39	1048	15936
Average					365	5553
Median					203	3097

AVs in € man-mSv⁻¹ of 10 countries provided by the Organization for Economic Cooperation and Development.⁶ Minimum numbers of use (n) were calculated using the AV method. The values used for the calculations in this study are 1000 fold higher to convert to € man-mSv⁻¹.

conclude that an acceptable estimate of the VSL for reducing the risk of a fatal cancer must be somewhere in the range of €2 to €5 million in year 2013 prices. We used that range for calculations based on the VSL in this study.

We illustrate the VSL method of CUA with an example with our fictitious device that reduces the dose with 10 μ Sv: the ICRP RF describes that the chance of a stochastic effect is reduced by $10 \mu\text{Sv} \times 5.7 \times 10^{-2} = 5.7 \times 10^{-7}$. In fact this chance is the part of a statistical life that is saved by the reduction. By multiplying the reduced chance with the VSL, we get the monetary value of the reduction per exposure being ($5.7 \times 10^{-7} \times €2\text{--}€5 \text{ million} =$) €1.14 to €2.85. If the device costs €1000 then the cost-utility is broken even at ($1000/2.85 =$) 351 to ($1000/1.14 =$) 877 cycles of use.

The use of the VSL to put a price on a human life is not very elegant, difficult to explain to the general public and can be viewed as unethical.¹⁴ To overcome the problem of placing a monetary value on human lives, Lind¹⁵ proposed an alternative method in 2002 for performing a CUA of a resource used to reduce risk for the public. He proposed the “invested time theory of acceptable risk”. The theory is based on the assumption that a risk-reducing measure is beneficial to a community when the number of years of healthy life expectancy is greater than the years spent working to pay for the measure. Lind’s theory will be referred to in this report as the “time-for-time” principle. The time-for-time principle can be used for CUA of a DDRM by converting the reduced loss of statistical lives to reduction of lost lifetime (LLT). The reduced LLT per exposure can be compared to the working time (WT), which is equivalent to the investment for the DDRM, to determine the minimum number of times the DDRM must be used to become cost effective.

To illustrate this method of CUA, we use the example that was given for the VSL method where 5.7×10^{-7} statistical lives were saved per exposure. When assume that per stochastic effect 15 years of life lost, this amounts to a saved lifetime of 8.6×10^{-6} years per exposure. The time it costs to work for earning the

device can be calculated by dividing the price (say €1000) by the average income of a worker (say €30,000 year⁻¹) corrected for the part of life we spend working (1/8). This gives 4.2×10^{-3} years. After a minimum number of ($4.2 \times 10^{-3}/8.6 \times 10^{-6} =$) 484.5 cycles of use, the lifetime saved by the device is more than the time it cost to work for it.

To establish a standard for performing a CUA of a DDRM, the dental profession should identify a suitable CUA method. The aim of this study was to evaluate the applicability of the three CUA methods described in the Introduction section to DDRMs. The three methods were used to determine the minimum number of exposures performed with the DDRM that is needed for the DDRM to be cost effective. If the expected number of exposures performed with the DDRM is higher than the minimum number of required exposures, the investment in the DDRM can be regarded as sound from a cost-utility perspective. By comparing the outcomes of the three methods for coherence (values for comparable countries are in the same range) and adaptability (the CUA can be adapted to the characteristics of the patient population for whom the DDRM is applied), the value of a CUA method used to evaluate a DDRM can be established.

Methods and materials

Two DDRMs, rectangular collimation for intraoral radiography and reduction of the field of exposure during cephalography for orthodontic diagnostics, were subjected to three types of CUA. The use of a Rinn Universal Rectangular Collimator (RC; Dentsply Ltd, Addlestone, UK) was analysed (Figure 1). The Rinn RC reduces the 6- to 8-cm diameter field of exposure delivered by an intraoral radiography unit to a 4.5- to 3.5-cm rectangular field. Ludlow *et al*¹⁶ reported that the effective dose E of an average round, collimated intraoral exposure was 9.5 μ Sv, and a RC led to an 80% decrease in E (1.9 μ Sv), a reduction of 7.6 μ Sv per



Figure 1 Rinn® universal rectangular collimator (Dentsply Ltd, Addlestone, UK).

exposure. The cost of RC was determined from three different suppliers and was found to be approximately €100. The fact that the use of RC can lead to loss of diagnostic information through cone cutting and that, in a certain percentage of exposures, this leads to retakes has not been incorporated in the calculations in this article.

Reduction of the field of exposure during cephalography for orthodontic diagnostics can be achieved using two devices, the anatomical cranial collimator (ACC) and the cephalographic thyroid protector (CTP) (both GentleCeph BV, Rotterdam, Netherlands) (Figure 2). The ACC and CTP shield the thyroid gland and reduce the size of the irradiated area outside the diagnostic target during orthodontic lateral cephalography. These devices reduce the E of a lateral cephalographic exposure by 58.8% (from 8.5 to 3.5 μSv), which is a reduction of 5.0 μSv reduction per exposure.¹⁷ The combined cost of ACC and CTP was estimated by the manufacturer to be approximately €1000.

Alpha value cost–utility analysis

The reduction per exposure (ΔSv) was multiplied by the AV (α) to determine the monetary value of the reduction per exposure. The cost of the DDRM (c) was divided by the monetary value of the reduction per exposure to determine the minimum number (n) of use cycles required to reach the break-even point of cost effectiveness. [Equation (1)]

$$n = \frac{c}{(\Delta\text{Sv} \cdot \alpha)} \quad (1)$$

Table 1 shows the AVs of 10 countries. Calculations were performed using the AV of each country. A fixed

AV is used in some countries, and some countries have a maximum and minimum AV, depending on the remaining risk for the exposed population. Because of the low remaining dose of dental X-ray procedures, the minimum AVs were used for the calculations.

Value of statistical lives cost–utility analysis

The reduction in loss of statistical lives was determined by multiplying the dose reduction by the RF. The RF was adjusted to the age of the exposed patient population (RF_{adj}). To assess the RC, the average age of the population can be assumed (the “standard” ICRP value of 5.7% Sv^{-1}) because intraoral radiography is performed for patients of all ages. To assess the ACC and CTP, the average age of the orthodontic population was arbitrarily set at 12 years, which results in a higher RF. By interpolating the data from the ICRP 60 for children aged 12 years, the RF_{adj} for the orthodontic patients group was determined as being 17.5% Sv^{-1} . The reduction in loss of statistical lives was multiplied by the VSL to determine the monetary value of the dose reduction per exposure. As reported in the introduction, the VSL values of €2 and €5 million were used for the calculations. The cost (c) of the DDRM was divided by the monetary value of the reduction per exposure to determine n [Equation (2)].

$$n = \frac{c}{(\Delta\text{Sv} \cdot \text{RF}_{\text{adj}} \cdot \text{VSL})} \quad (2)$$

Time-for-time cost–utility analysis

The reduction of loss of statistical lives was expressed as reduction of LLT. Land and Sinclair¹⁸ calculated that the LLT per stochastic effect (LLT/SE) was 15 years for a population of average age. This value will be used for the CUA of RC. The LLT/SE for the younger orthodontic patients with an average age of 12 years can be assumed to be higher than that for the RC population. The difference in LLT/SE between these populations is not as large as the difference in their average age would suggest. According to the multiplicative model, the radiation risk increases the existing risk of cancer by a factor. Because the incidence of cancer increases with increasing age, only with increasing age the extra stochastic effects will occur. This means that the stochastic effects also for the orthodontic population occur relatively late in life. It seems justifiable for this reason to use a value of 20 years for the adjusted LLT/SE of the orthodontic population.

The reduced LLT (ΔLT) per use of the DDRM was determined using the adjusted RF and the adjusted LLT/SE [Equation (3)].

$$\Delta\text{LT} = \Delta\text{Sv} \cdot \text{RF}_{\text{adj}} \cdot \frac{\text{LLT}}{\text{SE}_{\text{adj}}} \quad (3)$$

The cost of a DDRM (c) was expressed as the WT required of an average worker to pay for the DDRM. The WT was determined by dividing c by GNI_c divided by the fraction of lifetime that was spent working (f) [Equation (4)]. To take into account the regional

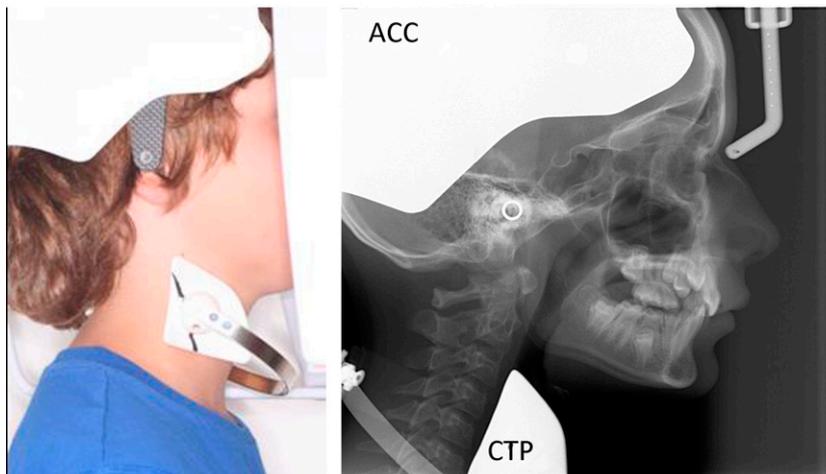


Figure 2 On the left, ACC and CTP shown positioned on the patient during exposure. On the right, the resulting cephalogram. Both devices are manufactured by GentleCeph BV, Rotterdam, Netherlands. ACC, anatomical cranial collimator; CTP, cephalographic thyroid protector.

differences in economies, two values for GNI_c , for high income economies and for upper–middle income economies, were used to calculate n ¹⁹ (Table 2). The value $1/8$ for f is used as substantiated by Lind.¹⁵

$$WT = \frac{c}{\left(\frac{GNI_c}{f}\right)} \quad (4)$$

To determine η , WT was divided by ΔLT [Equation (5)]

$$\eta = \frac{WT}{\Delta LT} \quad (5)$$

When in Equation (5) WT is replaced following Equation (4) and ΔLT is replaced as Equation (3) specifies, we can rewrite Equation (5) as [Equation (6)]

$$\eta = \frac{c \cdot f}{GNI_c \cdot \Delta Sv \cdot RF_{adj} \cdot LLT/SE_{adj}} \quad (6)$$

The three methods were compared by assessing coherence and adaptability. The coherence of a method was positive if it produced comparable results in for comparable economic regions. If a difference between the results was a factor less than two, the method was graded positive for coherence, a difference of 2–10 was mediocre (\pm), and >10 was negative. Adaptability was assessed in terms of RF (was it possible to adjust the RF to that of the exposed patient population?) and in terms of LLT/SE (was it possible to adjust the value for LLT/SE to the age of the patient population at exposure?).

Results

Alpha value method

The minimum numbers of use (η) of the two DDRMs are shown in Table 1, and ranged from 5 to 1048 for RC

(average 365, median 203) and from 81 to 15,936 (average 5553, median 3097) for the ACC/CTP; an almost 200-fold difference between the lowest and highest value.

Value of a statistical life method

The values for η for the two DDRMs for VSLs of €2 million and €5 million are shown in Table 3. The η values for RC ranged from 46 to 115, and for ACC/CTP from 229 to 571. There is a 2.5-fold difference between the low and high values, which is the same as the difference between €2 million and €5 million.

Time-for-time method

The values for η for the two DDRMs that were calculated for high income economies and upper–middle income economies are shown in Table 4. The η values for both DDRMs differed between the economic regions by a factor of 5.9, which is the ratio of the GNI_c s of the two economies.

Comparison of methods

The results of the evaluation of the three methods for coherence and adaptability to a specific patient group are summarized in Table 5. The AV method was negative for coherence, and for adaptability to group specific RF and LLT/SE; the time-for-time method was positive for all three parameters; and the VSL

Table 2 World Bank data for gross national income (GNI) per capita of two economic regions

Region	Number of countries	Number of inhabitants (2013) (billions)	GNI per capita (2013) €
High income economies	31	1.054	34,257
Upper–middle income economies	55	2.409	5850

World Bank data for GNI per capita 2013.¹⁸
The GNI per capita was converted from US\$ to € using the exchange rate of July 2013.

Table 3 Minimum number of uses determined by the VSL method

Device	\bar{n} VSL 2 million €	\bar{n} VSL 5 million €
Rectangular collimator	115	46
Anatomical cranial collimator/ cephalographic thyroid protector	571	229

\bar{n} , minimum numbers of use; VSL, value of a statistical life.

method had mediocre, positive and negative grades, respectively.

Discussion

The guidelines for dentists and dental specialists recommend measures to reduce the dental diagnostic X-ray dose to their patients. They are not required to reduce at all costs; the effort must be to reduce as low as “reasonably” achievable. Dental X-ray doses are generally lower than in other fields of medicine. The question arises whether the effort to reduce an already low dose is worthwhile. To answer this question, the dental community should decide on a method for performing CUA. In our study, we evaluated three CUA methods that were used to analyse two types of DDRMs. The results of our comparison of the methods of CUA indicated that the time-for-time method was best suited for performing the CUA, because of positive grades for all the factors used for comparison. The method is coherent because it determined comparable outcomes for comparable countries. The AV method was negative regarding coherence because comparable countries used very different AVs. The AV method should not be used for CUA because of the varying and apparently random AVs used by different countries. The VSL method is problematic because VSL is not an officially adopted value. The “official” VSL varies between comparable countries and even between different governmental bodies. Therefore, in our study we used a range of VSLs to perform our assessment of the method, which led to a range of \bar{n} values.

The VSL and the time-for-time method had positive grades for adaptability, because they can adjust for the characteristics of a patient group. The RF could be adjusted according to age and gender. The time-for-time method is more versatile, because it can also adjust the LLT/SE according to a specific patient group.

The time-for-time method of CUA enables a sound basis on which to decide if a dose-reduction measure is cost effective. For example, for a decision on developing a new intraoral sensor that reduces the E by $1 \mu\text{Sv}$ per exposure, while costing €3000 more than a conventional sensor, the minimum number of uses before this extra investment becomes sound can be calculated, given the GNI_c of the location and the characteristics of the patient group. In a high income economy for the average population, this new sensor would become cost effective after more than 12,800 cycles of use which in

most dental offices seems as an unrealistic high number. For another example, the time-for-time method can also be used to establish that a certain cost-effective measure for a paediatric dentistry clinic will not be cost effective for a geriatric dentistry clinic because of differences in the RF and LLT/SE for these different populations. For a final example, the time-for-time method can be used to recommend dose-reduction measures for locations where certain exposures are frequently performed, and to decide that they would be ineffective for locations where they are used less frequently.

The final example also illustrates the point that policies regarding radiation protection should not be based solely on CUA. Practitioners performing low numbers of exposures might argue that they can deliver a high radiation dose to their patients because investments for reducing the dose are not cost effective for their practice. This is where “dose reference levels” should play a role to eliminate the outliers.^{2,20,21} These reference values, together with the CUA, must be used by governing bodies to produce regulations and practice guidelines for establishing minimal standards; a CUA by itself is not enough.

The CUA methods in our study were evaluated for dental X-ray exposures, because large numbers of low-dose exposures are performed in dentistry, and the available dose-reduction measures must be evaluated for cost effectiveness. There is no particular reason why the time-for-time method cannot be used for medical diagnostic radiology. The radiation doses are higher, but so are the costs for dose reductions. For instance, evaluations of dose-reducing measures for mammography obviously must take into account the patient group, which consists of females of a specific average age. The age and gender of this group can be used to determine the adjusted RF. The method also allows adjustment of the LLT/SE for this group, which means that the time-for-time method can provide data for a well founded CUA.

CUA with the time-for-time method should be regarded with some restraint as it is based on three assumptions. The first assumption is that of the linear no-threshold theory (LNT). The LNT states that there is a linear connection between radiation dose and risk, even at the lowest dose levels. This assumption continues to be debated, but until the LNT is proved to be incorrect, it remains the basis of our radiation protection laws and regulations.²² Therefore, developing a method for CUA based on this assumption seems

Table 4 Minimum number of uses determined by the time-for-time method

Device	\bar{n} upper-middle income economies	\bar{n} high income economies
Rectangular collimator	329	56
Anatomical cranial collimator /cephalographic thyroid protector	1221	209

\bar{n} , minimum numbers of use.

Table 5 Coherence and adaptability of the three methods of cost-utility analysis

Method	Coherence		Adaptability	
	Relative range factor of η	Grade	For risk factor	For lost lifetime per stochastic effect
Alpha value	198	–	–	–
Value of statistical life	2.5	±	+	–
Time-for-time	1	+	+	+

η , minimum numbers of use.

Grades of the three methods in three domains.

valid. The second assumption is that of the accuracy of the use of RFs. Martin²² reported that the relative uncertainty of the use of RF might be as much as 40%. As the use of RFs is the established way of estimation risk resulting from radiation exposure, it seems logical to use them for CUA. The third assumption is that the time-for-time method is correctly based on the concept that lifetime gained by the reduction of risk must be more than the time society has to work for it. Lind¹⁵ states that the risk-reducing measure is effective when the ratio of extra years of life to the extra years of work to pay for the measure is greater than unity. If not, he states that “the life-saving project is actually a life-consuming project”. Although this assumption is probably intuitively valid, it carries the perception that time spent on working is *per se* something to be regarded as negative. Perhaps this is true for workers with little education, possibly for a majority of workers, but certainly not for all, as for instance, the time spent working on this study is perceived as time well spent. Based on data on job satisfaction and other non-material rewards of employment, the time-for-time ratio of unity could be perceived to need adjustment. If the ratio, for example, should be changed in a way that lifetime gained can cost twice the amount of time to work for it, a risk-reducing measure would be considered cost effective at half the number of uses.

Comparison of the three methods of CUA used to assess RC revealed that most results were comparable (Tables 1, 3 and 4). The median outcome of the AV method was in good agreement with the VSL €2M calculation and results of the upper-middle-income economies determined by the time-for-time method. The results of the time-for-time CUA for the high-income economies and the VSL method using €5M for calculations were very close for both DDRMs. Equations 2 and 6 both provide the same results when $VSL = [(LLT/SE) \cdot GNI_c] / f$. The time-for-time method implicitly assumes a VSL of €4.1 million for the average population in a high income economy, which explains the comparable outcomes of the two CUA methods.

The CUA with VSL method and the time-for-time method determined that RC is effective after a realistic

number of uses in a general practice. These methods also regard ACC/CTP effective after a few hundred uses, which seems to be a realistic number for an orthodontic office. The CUA with the AV method regards both DDRM effective after a realistic number of uses when the AVs are used of the countries with a single AV. The low AVs used in the countries with variable AV results in unrealistic high numbers of use before the DDRM are considered effective. These low AVs are remarkable as they do not seem to be in accordance with generally accepted principles of radiation protection, more specific with the LNT. The low AVs are specified to be applicable in case of low remaining dose levels for the individual member of the public. The medical X-ray burden of populations in modern societies is high and rising. In 2006, 48% of the total population dose in the USA was caused by medical exposures.²³ Therefore, it could be argued that the remaining dose level for the individual member of the public is not that low, and a higher AV should be applied. The results of the CUA with the AV method for these countries could then be more in line with the other CUA methods.

The benefits of dose reduction lie far in the future, as only then reduction in cancer incidence will become evident. Therefore, the cost of a dose-reduction measure precedes its utility. It could be argued that financing costs should be incorporated into the CUA. A contrary view is that the financing costs are the same as the increase in GNI_c until the benefits materialize, and that they should therefore not be incorporated. This shows that we are comparing unequal properties. Money can be saved and can earn interest, but no returns can be calculated for preserving health in the future.

In conclusion, the time-for-time CUA method was found to be superior in coherence and adaptability to two other CUA methods. A simple formula can be used to determine the minimum number of uses for a dose-reduction measure to become cost effective. This method can allow a valid assessment of the cost effectiveness of investments in dose-reduction devices. The CUA with the time-for-time as well as the VSL method in this study of two DDRMs showed that they were cost effective after a realistic number of uses.

Conflicts of interest

The first author has a financial interest in the company GentleCeph Ltd, which develops devices to reduce doses used for cephalometric radiography. GentleCeph manufactures and sells the ACC to the dental profession and strives to do so with the CTP.

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