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Estimate the Minimized Effective Dose and Critical Organ in Pediatric Nuclear Medicine

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Abstract Many techniques and research models on calculating and reducing the nuclear radiation dose on pediatric nuclear medicine procedure have been developed and reported in recent years. However, most those models either utilized simple shapes to present the organs or used more realistic models to estimate the nuclear dose applied on pediatric patients. The former are too simple to provide accurate estimation results, and the latter are too complicated to intensively involve complex calculations. In this study, a simple but practical model is developed to enable physicians to easily and quickly calculate and select the average optimal effective nuclear dose and critical organs for the given age and weight of the pediatric patients. This model is built based on one research result reported by Frederic Fahey et al., and it can be easily implemented in most common pediatric nuclear medicine procedures. This is the first research of using fuzzy inference system (FIS) to calculate the optimal effective dose applied in the nuclear medicine for pediatric patients.

Keywords*: fuzzy inference system, reduction of nuclear radiation dose, common pediatric nuclear medicine procedures, optimized nuclear radiation dose*

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1. Introduction

Nuclear medicine provides important and critical information that assists in the diagnosis, treatment, and follow-up of a variety of disorders on pediatric patients, including central nervous, endocrine, cardiopulmonary, renal, and gastrointestinal systems, as well as in the fields of oncology, orthopedics, organ transplantation, and surgery. Due to its high sensitivity, nuclear medicines can detect some disease in its earliest stages to enable it to be treated earlier. The noninvasive nature of nuclear medicine makes it an extremely valuable diagnostic tool for the evaluation of children. It provides useful diagnostic information that may not be easily obtained by using other diagnostic methods, some of them may be more invasive or contain some higher nuclear radiations [1,2].

Pediatric nuclear medicine includes the application of small amounts of radiopharmaceuticals that emit nuclear radiations such as γ-rays, β-particles, or positrons to patients during the diagnostic process. This emission exposes the pediatric patient to low levels of nuclear radiations that might be result in harmful health effects on pediatric patients. In most nuclear medicine procedures, the amounts of radiation (dose) applied on pediatric patients are limited to certain low levels, but they are contradictory to the mechanistic biologic observations. It had been difficult for most physicians to effectively assess the magnitude of exposure or potential risk due to implementation of nuclear radiations on pediatric treatments. The challenge job is how to make a trade-off between the nuclear radiation dose applied on the pediatric patients and the quality of the diagnostic results, and to select or determine an optimal or minimized effective dose and critical organs to reduce the risk of nuclear radiations [3]. Effective dose provides an approximate indicator of potential detriment from nuclear radiation and should be used as one parameter in evaluating the appropriateness of examinations involving nuclear radiation. In addition, the organ receiving the highest dose is referred to as the critical organ. In fact, effective dose is a calculated quantity and cannot be measured. Multiplying the average organ equivalent dose by the ICRP tissue-weighting factor and summing the results over the whole body yields the effective dose [4]. Although effective dose is an average evaluation value, it is still an important parameter in estimation of average potential risks of nuclear radiation on patients.

Because of the popular applications of nuclear medicines on pediatric diagnostics andtreatments, remarkable increase in the use of nuclear medical procedures have been shown in the US in recent years [5]. Different techniques and models have been reported and developed to optimize the nuclear radiation dose to reduce the risk of nuclear radiations on patients in last decades [6-

15]. One of the most important reasons for these developments is to reduce the potential risk of cancers that results from the nuclear radiations exposed from the usage of the nuclear medicine procedures [16-32].

Roberto Accorsi and Joel S. Karp et al. provided a method to improve the dose regimen in pediatric PET [9]. Some other research organizations reported different radiation sources used in nuclear medicines in recent years [10,11]. Fazel R, Krumholz HM, Wang Y, et al. developed a procedure to use low-dose ionizing radiation in medical image process [13]. Frederic H. Fahey, S. Ted Treves, and S. James Adelstein provided a survey to review most recent developments in using minimized dose to reduce the risk of inducing cancer [16]. Loevinger R and Budinger TF reported a method to calculate the absorbed dose to limit the effects of radiations [17]. Stabin MG and Siegel JA discussed some popular physical models and dose factors for use in internal dose assessment [18]. Ward VL, Stauss KJ, Barnewolt CE, et al. developed a method to reduce the effective dose for the pediatric radiation exposure [22]. Preston RJ reported an on linear non-threshold dose-response model and implications for diagnostic radiology procedures [23]. Gelfand MJ developed a method to reduce the dose applied in pediatric hybrid and planar imaging process [25]. Hsaio E, Cao X, Zukotynski K, et al. reported a technique to reduce the radiation dose in MAG3 renography by enhanced planar processing [27]. Other researchers reported different techniques and methods to reduce radiation exposures in nuclear medicine and medicine image processing [28,29,30,31,32].

However, most of these technologies and developments either utilized simple shapes to present the organs or used more realistic models to estimate the nuclear dose applied on pediatric patients. The former are too simple to provide accurate estimation results, and the latter are too complicated to intensively involve complex calculations. Also, these estimations are averages over a wide range of patients at each age and they are not related to individual differences in anatomy and physiology from the standard models. Application of these pediatric models is problematic because children can vary greatly in body size and habitus. A good model should deal with both the children's age and the body-size to determine the optimal effective dose.

The advantage of using our model as discussed in this paper is that the physicians can easily and quickly calculate and select the optimal or minimized effective dose based on the given age and body-size of the pediatric patient to significantly reduce the effects of nuclear radiations on patients. This kind of model will be more suitable and appropriate for pediatric examination and diagnoses.

2. Materials and Methods

We used the fuzzy inference system (FIS) to build a dynamic model to set a mapping relationship between each age, weight and the desired optimal effective dose and critical organs for pediatric patients' groups. All related data and operational parameters used for this model are based on data provided by [16]. The estimates of critical organ and effective dose for common pediatric nuclear medicine procedures developed by [16] are shown in Table 1. This table shows estimated relationships between the pediatric patients' ages, weights and effective doses as well as critical organs for ^{99m}Tc-ECD.

Table 1. Estimates of Critical Organ and Effective Dose for Common Pediatric Nuclear Medicine Procedures

	Max admin act (MBq)	1-y-old	5-y-old	10-y-old	15-y-old	Adult
Mass (kg)		9.7	19.8	33.2	56.8	70
^{99m}Tc-MDP*	740					
Bone surface (mGy)		54.5	46.0	45.6	49.2	46.6
Effective dose (mSv)		2.8	2.9	3.9	4.2	4.2
^{99m}Tc-ECD†	740					
Bladder wall (mGy)		13.4	23.0	30.5	37.2	37.0
Effective dose (mSv)		4.1	4.6	5.3	5.9	5.7
^{99m}Tc-sestamibi*	740					
Gallbladder (mGy)		32.9	20.9	20.4	27.0	28.9
Effective dose (mSv)		5.4	5.9	6.3	7.2	6.7
^{99m}Tc-MAG3*	370					
Bladder wall (mGy)		17.2	19.8	31.3	44.1	42.7
Effective dose (mSv)		1.2	1.3	2.2	2.8	2.7
^{123}I-MIBG*	370					
Liver (mGy)		16.6	18.5	22.4	25.6	24.8
Effective dose (mSv)		3.4	3.8	4.5	5.0	4.8
^{18}F-FDG†	370					
Bladder wall (mGy)		25.6	35.9	44.4	48.8	50.5
Effective dose (mSv)		5.2	5.9	6.6	7.3	7.4

* Based on ICRP 80 (25), † Based on ICRP 106 (26).

Max admin act = maximum administered activity is that administered to adult or large child (70 kg) (administered activities for smaller children are scaled by body weight); ECD = ethyl cysteinate dimer; MIBG = meta iodo benzyl guanidine.

It can be seen from Table 1 that this table only provided limited information between certain children ages with selected weights and the minimized nuclear effective dose and critical organs. In other words, the relationship or mapping between the children ages, weights and the optimal effective dose and critical organs is incomplete or discrete because it does not provide all optimal effective doses and critical organs for any given children age and weight group.

To improve that incomplete and discrete model, in this study, we will use a fuzzy inference system (FIS) to build a complete and continuous model to provide all related

optimal effective doses and critical organs for different given children ages and weights groups in a simple and easy way. In fact, we will use the FIS to interpolate the optimal effective dose and critical organs based on the specified age and weight of each child group to simplify the calculation and estimation process for the effective dose and the critical organ.

To make our study simple, we only use the bladder wall with ^{99m}Tc-ECD as an example to illustrate how to use FIS to simplify this effective dose calculation and critical organ estimation process. This study can be easily extended to cover all other organs and methods shown in Table 1. A graphic mapping between effective dose and given age and weight of each group children with the bladder wall in Table 1 is shown in Figure 1.

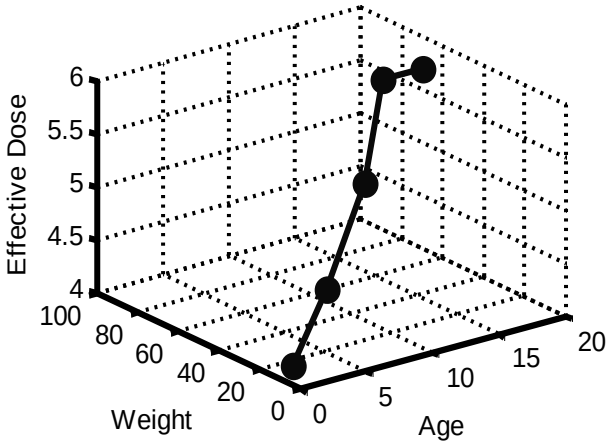


Figure 1. Graphic representation of Table 1 – Bladder Wall

The basic idea behind this model development is based on the fact, that the optimal effective dose and critical organs are not continuous functions for all different given ages and weights located between known ages and weights. Also the relationship between the minimized effective dose, critical organs and different age-weight is ambiguous, or at least it is not a linear function as shown in Figure 1. Therefore we need to use the fuzzy inference algorithm to derive those optimal effective doses and critical organs for all those 'missed' age-weight pairs. In fact, we use fuzzy inference method to interpolate those optimal effective doses and critical organs for any specified age-weight pair.

2.1. Fuzzy Inference System

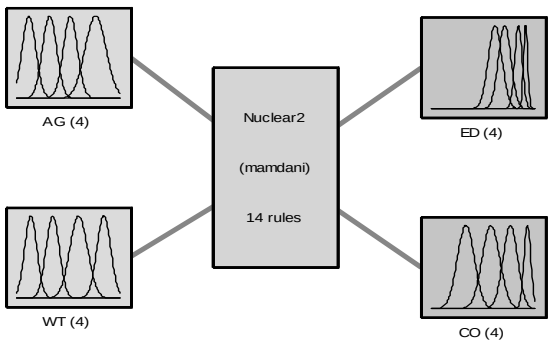


Figure 2. The block diagram of the fuzzy inference system (FIS)

We use given age and weight of the pediatric patient as inputs, and the optimal effective doses and critical organs as outputs for a fuzzy inference system. Therefore this is a multi-input and multi-output system. Both inputs and output are connected and controlled by the fuzzy system control rules. Figure 2 shows the block diagram of this fuzzy inference system.

As for the membership functions for two inputs, pediatric patient Age and Weight, we utilized *gaussform* as the shape for both of them. Similarly, this shape is also used for two outputs, the optimal effective dose and the critical organ.

The membership functions for both inputs (patient's age - AG and weight - WT) are shown in Figure 3. The membership functions for two outputs (effective dose - ED and critical organ - CO) are shown in Figure 4, respectively. Those membership functions are derived based on the data provided by [16] for common pediatric nuclear medicine procedures.

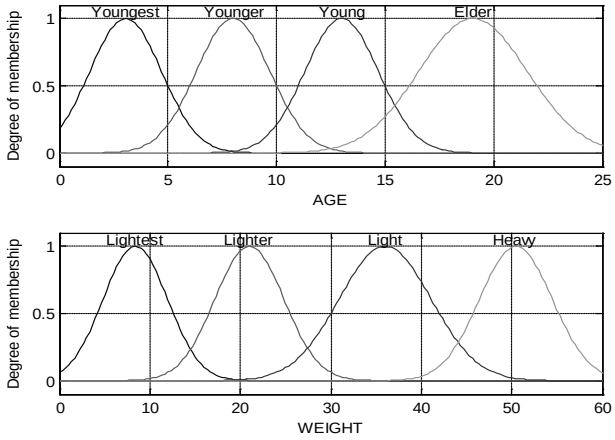


Figure 3. Membership functions for two inputs - patient age (AG) and weight (WT)

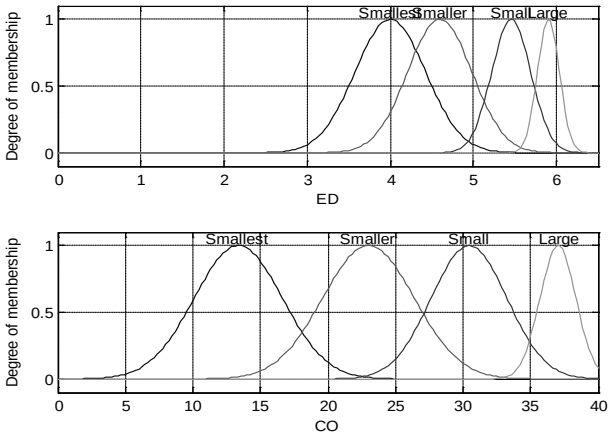


Figure 4. Membership functions for two outputs - effective dose (ED) and critical organ (CO)

The definitions for the membership functions of the pediatric patient's age and weight are shown in Table 2 and Table 3, and the membership functions for effective dose and critical organs are shown in Table 4 and Table 5.

Table 2. MF for the pediatric patient's age

AG (years old)	0 ~ 7	4 ~ 12	9 ~ 17	13 ~ 25
MF	Youngest	Younger	Young	Elder

Table 3. MF for the pediatric patient's weight

WT (kg)	0 ~ 17	12 ~ 30	24 ~ 48	40 ~ 60
MF	Lightest	Lighter	Light	Heavy

Table 4. MF for the effective dose

ED (mSv)	3.0 ~ 5.0	3.7 ~ 5.5	4.9 ~ 6.0	5.6 ~ 6.2
MF	Smallest	Smaller	Small	Large

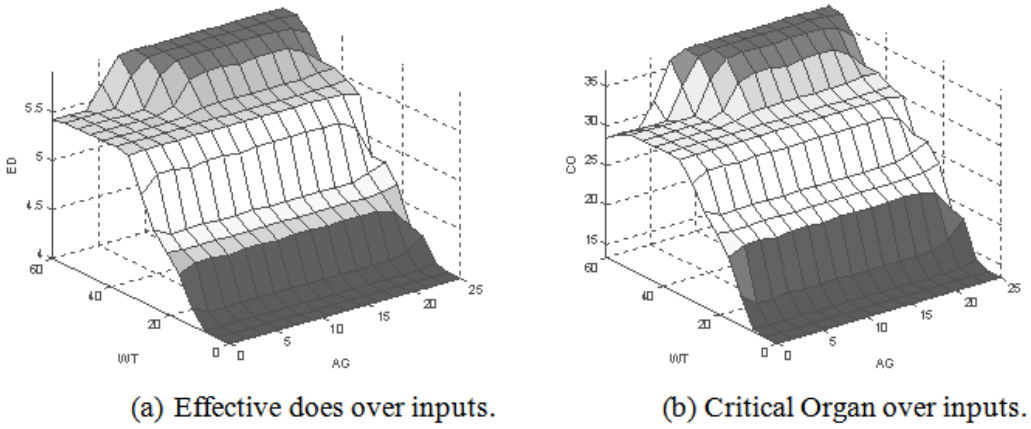
Table 5. MF for the critical organ

CO (mGy)	5.6 ~ 21.0	15.0 ~ 31.0	23.8 ~ 37.0	33.9 ~ 40.0
MF	Smallest	Smaller	Small	Large

For this implementation, fourteen control rules are developed based on the input-output member functions. These fourteen control rules are shown in Table 6. The surface relationship between the output effective dose (ED) and the inputs, age (AG) and weight (WT), is shown in Figure 5a, and the surface of the critical organ (CO) over the age (AG) and the weight (WT) is shown in Figure 5b.

Table 6. Fourteen fuzzy control rules

1. If (AG is Youngest) & (WT is Lightest) then (ED is Smallest) & (CO is Smallest) (1)
2. If (AG is Youngest) & (WT is Lighter) then (ED is Smaller) & (CO is Smaller) (1)
3. If (AG is Youngest) & (WT is Light) then (ED is Small) & (CO is Small) (1)
4. If (AG is Younger) & (WT is Lightest) then (ED is Smallest) & (CO is Smallest) (1)
5. If (AG is Younger) & (WT is Lighter) then (ED is Smaller) & (CO is Smaller) (1)
6. If (AG is Younger) & (WT is Light) then (ED is Small) & (CO is Small) (1)
7. If (AG is Young) & (WT is Lightest) then (ED is Smallest) & (CO is Smallest) (1)
8. If (AG is Young) & (WT is Lighter) then (ED is Smaller) & (CO is Smaller) (1)
9. If (AG is Young) & (WT is Light) then (ED is Small) & (CO is Small) (1)
10. If (AG is Young) & (WT is Heavy) then (ED is Large) & (CO is Large) (1)
11. If (AG is Elder) & (WT is Lightest) then (ED is Smallest) & (CO is Smallest) (1)
12. If (AG is Elder) & (WT is Lighter) then (ED is Smaller) & (CO is Smaller) (1)
13. If (AG is Elder) & (WT is Light) then (ED is Small) & (CO is Small) (1)
14. If (AG is Elder) & (WT is Heavy) then (ED is Large) & (CO is Large) (1)



(a) Effective does over inputs. (b) Critical Organ over inputs.

Figure 5. The surfaces between inputs and outputs

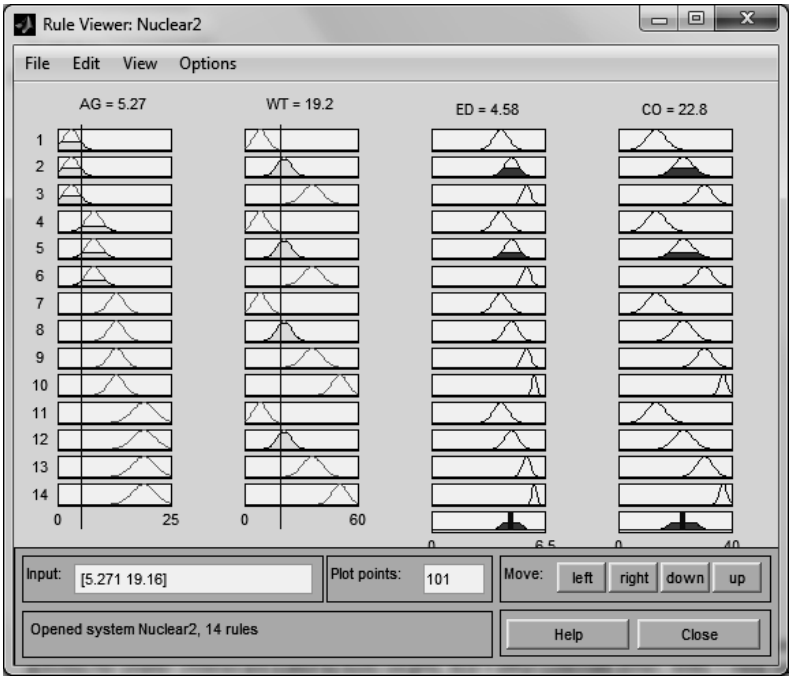


Figure 6. The fuzzy rule mapping relationship between the inputs and the outputs

3. Results

3.1. The Optimal Effective Dose and the Critical Organ

Based on the membership functions of two inputs, patient's age and weight, and the membership functions of two outputs, effective dose and critical organ, the desired optimal effective dose and the estimated critical organ for the given patient's age and weight can be easily determined and obtained directly from the fuzzy rule relationship. Figure 6 shows this kind of model for the calculation of optimal effective dose and critical organs used in pediatric bladder wall inspection using the nuclear medicine procedures.

In Figure 6, a typical pediatric patient age (5.27 years old) and weight (19.2 kg) are selected. The related optimal effective dose (4.58 mSv) and the critical organ (22.8 mGy) are determined directly from this fuzzy rule relationship.

During the implementation process, the vertical bars on both inputs, patient's age and weight, can be moved by the pediatric physician to either left or right to select the specified age and weight group of pediatric patients, and the desired optimal effective dose and critical organ can be easily determined directly from this fuzzy input-output rules relationship map. This model provides great flexibility and simplicity to determine the optimal effective dose and critical organs for common pediatric nuclear medicine procedures.

We can also easily build a similar FIS model by using the data provided by [16] to determine the related optimal effective doses and the desired critical organ for all other kinds of pediatric organs' nuclear medicine procedures.

4. Conclusion and Discussion

A flexible and simple model used to set a fuzzy mapping relationship between the pediatric patients' age-weight and the optimal effective dose and critical organs is developed in this study to enable pediatric physicians to easily and directly determine the optimal effective doses and critical organs for the common pediatric nuclear medicine procedures. The advantage of using this model is that the pediatric physicians can easily and directly obtain the desired minimized effective dose and the critical organs from the fuzzy rule relationship based on the given group of pediatric patients' data, such as ages and weights.

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