Measurement of the Change in Noise-Effective Count Rate During PET Brain Studies With Additional Shielding

Christopher J. Thompson, *Member, IEEE,* and Jorge J. Moreno-Cantu

***Abstract*—We have recently installed removable shielding on a CTI HR$^+$ positron emission tomography (PET) scanner, and have evaluated its effect on the noise-effective count (NEC) rate during typical brain studies. This removable shielding system, known as the "NeuroShield," consists of a U-shaped lead plate attached to the removable headrest with a plastic coupling piece. The NEC was calculated from information obtained in the "head curves" collected during three different types of study: 1) from subjects undergoing 60-min 250-MBq ^{11}C-Raclopride studies in different bed positions with the NeuroShield in place; 2) from subjects undergoing bolus ^{15}O-water activation studies, with injected activities ranging from 170 to 750 MBq.; and 3) from subjects undergoing glucose utilization studies first without, then with the NeuroShield in place.**

During the Raclopride studies, the NeuroShield was slightly more effective when placed forward of the field of view (FOV). NEC improvements of up to 24% in the early frames were obtained with the NeuroShield in place. The NEC values during bolus water studies improved by up to 45% with additional shielding. The percentage of random counts diminished during the fluoro-deoxyglucose (FDG) studies from 17% to 12%/100 MBq of injected activity and the NEC value improved by 5% for a 100-MBq dose.

***Index Terms*—Noise effective count rate, noise reduction, positron emission tomography (PET), random counts, shielding.**

I. Introduction

A. Shielding PET Scanners From External Activity

POSITRON emission tomography (PET) scanners acquiring scans with their septa retracted are much more susceptible to excessive random count rates, scattered radiation, and dead time due to activity outside the field of view (FOV). Fig. 1 shows how activity in a patient's heart is not shielded from the scanner's detectors by the end-shields of whole-body PET scanners during brain studies. Several recent reports show the advantage of additional shielding to reduce these effects [1]–[5]. Grootoonk *et al.* [1] showed the advantage of a permanent "Neurological insert" in the CTI[1] HR$^+$ scanner, an option available with the instrument. Sossi [2] and Laforest [3] used lead shielding of the body regions axially beyond the FOV which were made for their situation. Hasegawa *et al.* [4] have shown that in designing the shielding for use during neurological PET studies, the area of the shielding is more important than the thickness. More recently, Thompson *et al.* [5] showed the benefits of the prototype NeuroShield®[2] in the reduction of random counts and dead time during bolus water activation studies. However, the noise-effective count (NEC) rates were not measured in that study.

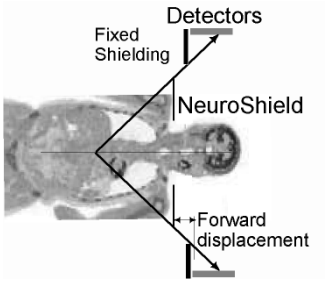

Fig. 1. Shielding geometry of the NeuroShield for the CTI ECAT HR+ fixed front collimators. The further forward the NeuroShield is with respect to detectors, the better the shielding. Without the NeuroShield in place the detectors are in the direct path of rays from the heart. (The fused PET-CT image was reproduced from the General Electric Medical Systems web-site.)

B. Studies to Measure the NEC Improvement

Three different types of brain PET studies were chosen in order to estimate the NEC improvement in protocols which are typically used in PET centers. The studies described here were not performed specifically to test the NeuroShield, but were modified slightly to allow this evaluation to be performed. Using the values obtained in each study for the true count rate T, the scattered count rate S, and the random count rate R, the NEC was calculated according (1) as proposed by Strother *et al.* [7]

$$\mathrm{NEC} = \frac{T}{1 + S/T + 2fR/T}. \tag{1}$$

The randoms FOV factor f was assumed to be 0.4, the randoms multiplication factor 2.0, and the scatter fraction S/T 45% unshielded and 43% shielded.

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C. J. Thompson is with the Research Computing Laboratory, Montreal Neurological Institute, Montreal, PQ H3A 2B4, Canada (e-mail: Chris@Med.McGill.Ca).

J. J. Moreno-Cantu is with the North-South Alliance Company, Toronto, ON M5N 2M2 Canada (e-mail: Kelcan_i@USA.net).

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[1]CTI Knoxville, TN, USA.

[2]Scanwell Systems, Montreal QC, Canada.

Fig. 2. The NeuroShield comprises a U-shaped lead plate mounted on the scanner's headrest which is then attached to the couch with Velcro. It is shown here on the couch of a GE Advance PET scanner with the bed extended and lowered.

C. Design of the NeuroShield

The "NeuroShield" is an easily removable lead shielding system for use during neurological studies on whole body PET scanners. The principal novelty is that the lead in the NeuroShield is attached to the headrest, not the gantry, and so moves with the couch. This allows the diameter of the hole through which the subject's head must pass to be made smaller than if the lead were fixed.

The headrest on all recent CTI PET scanners is made from rigid plastic and part of its strength comes from its complex curvature. In order to attach the lead plate, a thermoplastic piece was designed to fit closely the contour of the headrest in the region between the couch top and the head support. This piece has a plane vertical surface to which a cut lead plate is attached. Four ribs between these two surfaces provide structural support. The headrest is attached to the scanner's couch with VelcroR strips and so moves together with it as shown in Fig. 2.

II. Materials and Methods

A. Raclopride Studies

Since the NeuroShield is attached to the couch, the position of the lead shielding can vary from subject to subject. As can be seen in Fig. 1, the shielding effect should change depending on the position of the NeuroShield with respect to the permanent lead shielding. When the NeuroShield is used, subjects are normally positioned on the bed so that their shoulders are as close as comfortable to the lead plate. This implies the lead plate may be in a slightly different position depending on the length of the subject's neck. In order to see if there would be a preferred scanning position, we tested the NeuroShield in a study in which subjects were to have three scans on three different days. Four subjects were injected with approximately 1/3 of the maximum dose (370 MBq) of ^{11}C-Raclopride permitted by the Montreal Neurological Institute's Research Ethics Committee. In each case, the subjects played a video game. In the baseline study they were paid a $100, and in the activation case, the better they played, the more money they received. If the subjects had long necks, the bed, and the lead shield could be positioned differently for each scan. The positioning laser was used to ensure that the subject's head was placed in the same place for all scans.

All scans were done within a week, and the doses administered varied from 220 and 265 MBq. During that time, the NeuroShield was not removed from the couch, so the "bed position" is directly related to the forward displacement of the shield with respect to the FOV. From the scanner's "head-curve" files, the delayed and prompt counts were integrated from 120 to 240 s (in order to avoid the effects of injection rate), and the ratio of random to (prompt–delayed) counts calculated. This ratio was normalized to an injected dose of 250 MBq and plotted against bed position. The bed positions varied from 420 to 479 mm from the fully out position (the lower the bed position, the further the shield is from the FOV). The head curves were compared to those from Raclopride studies done with the same dose, on an identical scanner with no external shielding at the Brookhaven National Laboratory.

B. Water Bolus Studies

In a previously published paper [5], we examined the effect of the NeuroShield when using a 370-MBq injection of water during cerebral activation studies. It is well known that randoms rates increase when higher doses are administered. At the Montreal Neurological Institute (MNI), all cerebral activation studies are now performed with 370-MBq injections and data are acquired in the three–dimensional (3-D) mode with a span of 9 and a maximum ring difference of 22.

In that paper, we examined the effect of various shielding strategies for one injected activity (370 MBq) [5]. In order to assess the effectiveness of the NeuroShield at other injected activities, it would be necessary to study subjects with lower and higher doses, with and without the NeuroShield in place. These studies would be difficult to justify before the Institute's research ethics committee. Therefore, we re-examined data acquired just after the scanner was purchased. At that time, studies were performed on one subject with no additional shielding, using injections of 5, 10, 15, 20 mCi (175, 370, 545 and 740 MBq) [6]. Comparison of the random fraction and dead times encountered during the 370-MBq studies and recent unshielded studies acquired during transcranial magnetic stimulation, show that both the dead time and random fractions are similar. The scanner's dead time increases linearly with dose [6], and the random counts are proportional to the (live time) $\times$ (dose)^2. The ratio of the live time with and without the NeuroShield for 370-MBq injections is 1.02 and the ratio of the random counts is 0.69. The random fractions, count rates, and live times are known without shielding, for four doses, and they were estimated for the same doses, based on their known values at 370 MBq with the NeuroShield in place.

C. Glucose Metabolism Studies With FDG

The NEC was measured with and without the NeuroShield installed during the acquisition of glucose metabolism studies for routine 3-D brain scans of four patients of the Montreal Neurological Hospital. The FDG protocol consisted of a 1-min unshielded emission scan, a variable-length frame to allow the NeuroShield to be removed, followed by 10-min emission scan (with the NeuroShield present) 40–80 min after administration of 100–130 MBq ^{18}F-FDG. Since this procedure is different from the prescribed FDG study, the protocol was approval by

TABLE I
COUNT-RATES AND DEAD TIMES DURING BOLUS WATER ACTIVATION STUDIES

Injected dose mCi MBq		True counts Kcps		Scattered counts		Random counts		Dead time (%)		NEC Kcps		
NeuroShield ? No/Yes >>		No	Yes	No	Yes	No	Yes	No	Yes	No	Yes	Gain %
5	175	83	87	67	65	58	41	11	10	34.7	41.7	20
10	370	146	155	120	117	142	100	16	14	56.4	68.2	21
15	455	179	190	146	144	275	195	22	20	58.7	74.0	26
20	740	211	226	172	170	408	291	26	23	62.6	91.0	45

the researchethics committee, and all patients gave informed consent. The patients were asked to lie on the couch in the normal CTI scanner's headrest. Marks were made on their faces with a felt pen where the alignment laser shone to ensure accurate repositioning. A "rates file," or "head curve" was used to sample the prompt and delayed count rates and dead time every 10 s. During the variable-length frame, the couch was withdrawn, the patient asked to sit up, and the headrest was replaced with the one to which the NeuroShield is attached. A 10-min scan (which was read for diagnostic purposes) was then performed, followed by a transmission scan from which the attenuation was measured. The injected dose was corrected for the delay after injection, and the NEC was plotted against the delay-corrected dose.

III. RESULTS

A. Raclopride Studies

The NEC with no extra shielding was estimated assuming a scatter fraction of 45%, live time and random fractions of 95% and 145%, respectively, of that with the NeuroShield in place. These ratios were derived by comparing the live times and randoms fractions from studies performed at the Brookhaven National Laboratory. The NEC for eight studies was calculated after normalizing for injected dose, and plotted against the scanner's bed position. When the bed position is at 475 mm, the upper surface of the lead on the NeuroShield was aligned with the front of the scanner's FOV. The results are shown in Fig. 3. The average NEC would decrease from 35 to 28.2 kHz with the NeuroShield removed, suggesting that the benefit to the NEC during shielded studies is 24%. There appears to be a slight improvement in NEC as the shield is moved further forward but the variability of the data prevents this from being statistically significant.

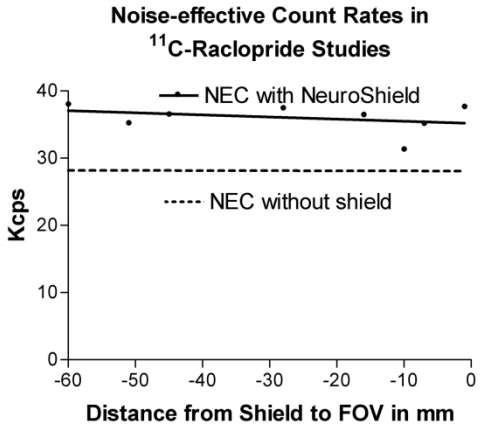

Fig. 3. NEC rates as a function of the distance which the NeuroShield is placed in front of the scanner's FOV, compared with the NEC rate without the NeuroShield.

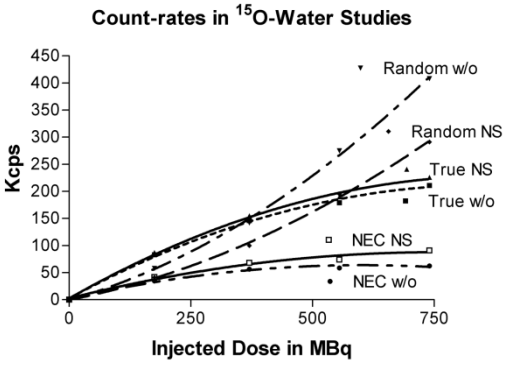

Fig. 4. Count rates during bolus water activation studies as a function of injected dose.

B. Water Bolus Studies

The NEC for water bolus studies at four different injected doses, performed before the NeuroShield was in use, was calculated assuming a scatter fraction of 45% and from the prompt and random rates measured in that study [6]. The NEC was then estimated as if the NeuroShield was in place. The results are summarized in Table I. Fig. 4 shows the count rates as dashed lines with no extra shielding, and as solid lines with the NeuroShield in place. Fig. 5 shows the NEC data only, in order to emphasize the difference. The peak NEC without the NeuroShield is at 500 MBq whereas it appears to be beyond 750 MBq with the NeuroShield in place.

C. Glucose Metabolism Studies With FDG

Of the six subjects who were enrolled in this protocol, two were rejected as examination of their scans showed that the head position had moved more then five slices after repositioning. The randoms count rates from the head curve from one of the subjects is shown in Fig. 6. There is an appreciable reduction

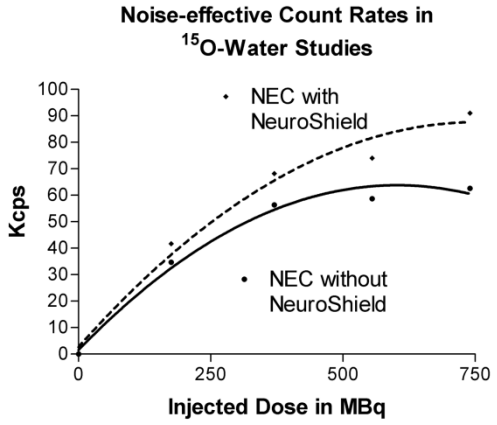

Fig. 5. NEC rates in bolus water studies with and without NeuroShield in place.

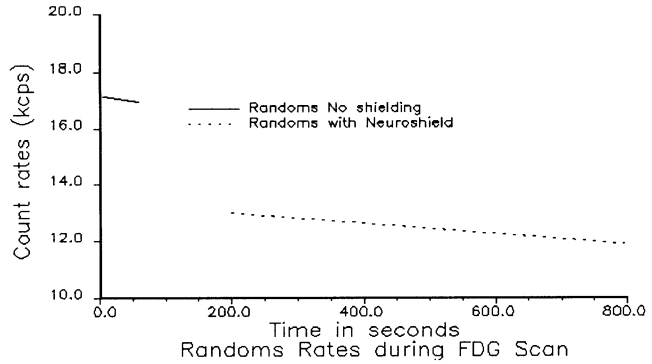

Fig. 6. Random count rate during the first minute of an FDG scan without NeuroShield, and for ten minutes with the NeuroShield in place.

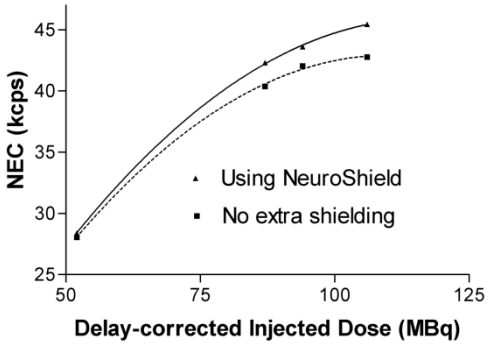

Fig. 7. NEC rates with and without the NeuroShield during FDG scans.

in the randoms rates in the later part of the study where the NeuroShield is in place. After correcting the random/true count rates for isotope decay, the randoms percentage was plotted against injected dose. The randoms fraction is reduced from 17%/100 MBq to 12%/100 MBq injected dose after the NeuroShield was installed. The NEC is plotted against delay-corrected injected dose for the four available subjects in Fig. 7. The NEC is improved by about 5% at the high end of the range of injected doses (106 Mbq or ∼3 mCi).

IV. Discussion

The NeuroShield is easy to install and well accepted by patients, staff, and researchers. The 22-cm-wide vertical cutout does not pose any problems when the subjects are viewing a large screen video monitor, nor in their access to the touch sensitive surface sometimes used to provide feedback during scanning.

The doses used at the MNI may be lower than those used in other centers. Most studies are done on normal volunteers. For this reason, the improvements in NEC obtained with the NeuroShield in these studies may be lower than at other centers where PET is used for diagnostic purposes, and higher doses are justified. The doses are limited by the radiation exposure to normal subjects. Many studies require multiple injections, which requires that the dose be fractionated further.

In the Raclopride studies, there did not seem to be any significant advantage in placing the bed forward in order for the shield to cast a larger shadow on the detectors. There appears to be a slight improvement, but its advantage would have to be weighted against patient comfort, and the possibility of movement if the shoulders are touching the lead shield. A substantial improvement in NEC was indicated when the NeuroShield is in place. The improvement is greater early in the study, where the frames in the dynamic study are shorter. The noise in early frames is due to the short counting times providing limited number of total counts, but also to increased dead time and random counts. The dose in single studies may be limited by the NEC at the start of the study. The use of additional shielding may extend the scanner's effective dynamic range in these cases.

It is likely that additional shielding will provide the greatest benefit during cerebral activation studies using ^{15}O-Water or ^{15}O-Oxygen. The data presented here for the bolus water studies was based on the way the dead time and random count rates changed in other studies. Since the NeuroShield is now always used at the MNI, it was not possible to obtain comparative data from the same subject with and without additional shielding. Other institutions which have purchased NeuroShields may soon be able to provide comparative data in a more rigorous way.

The headrest used in this scanner is the same one used in all recent CTI scanners, so the NeuroShield should work on any of these. The same NeuroShield also can be used on other whole body PET scanners like the GE Advance®.

V. Conclusion

The NeuroShield has now been tested in a wide variety of protocols. It is most effective in reducing random counts, so has its most important applications with short lived isotopes and at the start of dynamic studies. Since 3-D acquisitions expose the detectors to activity from outside the scanning field, additional shielding is most effective in this mode. It may be of greater benefit on the PET-CT scanners which have a larger patient port, and reduced shielding to activity outside the scanning field. Since the NeuroShield is easily removable it is especially useful where a mixture of "whole-body" PET scans and brain studies are performed. In the two years since it has been installed, it has been very well accepted by subjects, researchers, and technical staff.

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