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ANALYSIS OF OCCUPATIONAL EXPOSURE TO IONIZING RADIATION AT THE VAEC'S HOSPITAL No.103 IN 1994

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Analysis of Occupational Exposure to Ionizing Radiation at the VAEC' s Hospital No.103 in 1994

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This paper describes the analysis of doses to 32 medical workers at Hospital No.103 of Vietnam Atomic Energy Commission (VAEC) in 1994 for understanding the relation between the radiation protection system and the dose distribution in medical field. To assess the overall effectiveness of radiation protection system in hospital, the characteristics of monthly individual doses, monthly collective doses and annual doses have been analyzed by the conventional statistical method and the dose distribution method, separating the group of workers into subgroups by some factors. Monthly individual doses at the Hospital in 1994 were low and far below the monthly dose standard of 4.2mSv established by the VAEC based on the ICRP Publication 26. The monthly dose distribution showed the log-normality for all doses, being the same as the established finding of medical worker dose distribution. Most of doses below 0.3mSv, however, revealed the hybrid log-normality that reflects the effect of dose reduction efforts. The subgroup of monthly doses by medical doctor or technician, by X-ray diagnosis or radiotherapy, by each of workers and by each of months resulted in the same characteristics of dose distribution, that is, lognormal for all doses but hybrid lognormal for most of doses below about 0.3mSv. The annual dose distribution was also the same, that is, lognormal for all doses but hybrid lognormal for most of doses below 1mSv. It proved that the careful analysis of dose distribution could identify the effect of dose reduction efforts at hospital and could provide the overall assessment of effectiveness of radiation protection system.

Keywords: Medical Worker, Occupational Exposure, Monthly Individual Dose, Monthly Collective Dose, Annual Dose, Dose Distribution, Lognormal Model, Hybrid Lognormal Model, Radiation Protection.

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VAEC病院における1994年職業被ばくデータの解析

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(2000年11月30日受理)

本報告書は、医療分野における放射線防護体系と線量分布の関係を調べるため、ベトナム原子力委員会（VAEC）に付属した第103病院における医療放射線従事者32名の1994年職業被ばくデータを解析したものである。病院における放射線防護システムの全体的有効さを評価するため、いくつかの因子で作業者を小グループに分けて月ごとの個人線量と集団線量、さらに年個人線量の変動特性を通常の方法と線量分布解析法を用いて解析した。1994年における月個人線量は小さく、ICRP Publication26(1977)に準拠してVAECが制定した月線量基準4.2mSvよりも十分低くかった。月線量の分布は全線量について対数正規分布則性を示すが、これは医療作業者の線量分布としてよく知られた知見である。しかし、大半の線量がある0.3mSv以下では被ばく低減効果を反映した混成対数正規分布則性であることが確認された。医師または医療技師別、X線診断または放射線治療別、作業者別、月別に月線量を層別化しても分布則性の傾向は同じであった。年線量データについても全線量域で対数正規分布則性を示すが、大半の線量のある1mSv以下では同様に混成対数正規分布則性を示した。これより、病院における線量分布も注意深く分析すれば、実際の被ばく低減努力の効果が確認でき、防護の有効性評価が可能になることが知られた。

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1. INTRODUCTION

The ionizing radiation has been widely and extensively used in various sectors of society. The ionizing radiation exposure to a population may involve a risk, which should be fully assessed. The contribution of doses from ionizing radiation due to the overall effectiveness of the radiation protection system should be achieved for the controllable exposure due to all man-made sources as well as natural sources. The ICRP recommends that the assessment of the effectiveness should depend on the distribution of doses attained, as shown in the 1990 Recommendations [1].

Medical workers in hospitals, e.g., doctors, nurses, technicians and medical physicists are likely exposed to ionizing radiation emitted from the electronically producing machines and radiopharmaceutical sources for diagnosis and therapy. Radiation doses are usually reported to be rather lower for medical staff than for radiation workers in other industrial fields. The number of medical staff to be potentially exposed, however, is fairly large and hence may contribute a sufficient collective dose in the whole occupational exposure. The medical field occupies about a half of radiation workforce and contributes about one-fourth of collective doses to the workforce, for example, in the United States in 1980 [2], in Japan in 1990 [3] or in the world [4]. Thus, the knowledge of medical occupational exposure is substantially important, especially the statistical characteristics of individual doses attained in hospital to establish a suitable system of radiological protection.

This study describes the detail characteristics of ionizing radiation doses to thirty-two medical workers at Hospital No.103 of Vietnam Atomic Energy Commission (VAEC) in 1994. A small group of medical workers was selected to determine the detailed characteristics of the distribution of monthly doses among workers in each of twelve months, monthly collective doses to all of workers during twelve months and the distribution of annual doses among workers in the year by kind of workers and by type of sources. The characterization of variation of individual doses to each of workers among months in the year was also conducted. The multi-aspect of individual and collective doses could provide the interpretation of the relationship between exposure factors relating to medical jobs and the system of radiological protection, to review the effectiveness of the system in hospital. The methodology is the dose distribution analysis, including the conventional descriptive statistics. The results of the analysis are discussed according to the radiation standards established by the VAEC based on the ICRP Publication 26 (1977) [5]. In 1995 the VAEC adopted the radiation standards reflecting the ICRP Publication 60 (1990) [1] in its activities in Vietnam.

2. METHOD OF ANALYSIS

In order to assess the characteristics of radiation exposure and the overall effectiveness of radiation protection system at Hospital No.103 in 1994, first, the conventional statistical method is applied to evaluate the level and seasonal trend of doses to workers. Mean monthly doses and monthly collective doses in 1994 are calculated by division of X-ray diagnosis and radiotherapy (mainly γ rays), by type of workers between doctor and technician, or by whole workers. The dose distribution analysis method is then applied to assess the characteristics of monthly and annual dose distributions of 1994, enabling the evaluation of the overall effectiveness of the radiation protection system as recommended in the ICRP Publication 26 or 60.

The lognormal (LN) distribution has been popular for the dose distribution model since the ICRP Publication 26 and the UNSCEAR Report [6] were published in 1977. Explicitly defined, it is the distribution of X when Y= ln(X), which is normally distributed with mean μ and variance σ^2 [7]. Denoting the standard normal distribution by Z~N(0,1), the lognormal distribution is expressed by $\ln(X) \sim N(\mu,\sigma^2)$ because of normal variate $Z=\{\ln(X)-\mu\}/\sigma$. Then the median of X is given by $\exp(\mu)$.

The LN model generally provides a good fit to the variation of doses far below the dose limits, but not to the variation of higher doses approaching the dose limits [8-10]. The variation of higher doses submitting to exposure control is well fitted by the normal distribution [8]. Plotting such data as points (ln(x), z) or on log-probability paper gives a straight line in the range of low dose, but deviates from the straight line in the range of higher dose. The deviation appears a downward convex curve and the degree of the convex indicates the effect of dose reduction efforts. The effort becomes stronger for dose approaching the dose limits than for that far below the dose limits [8-11].

The unification of lognormal and normal distributions well fits the actual data of doses controlled by efforts of dose reduction, called the hybrid lognormal (HLN) distribution model [4, 9]. The HLN model, defined as the distribution of X when $Y= \ln(\rho X)+\rho X$ ($\rho>0$), is normally distributed with mean μ and variance σ^2. Defining the hybrid function $Y= \mathrm{hyb}(\rho X)=\ln(\rho X)+\rho X$ and its inverse function $\mathrm{cyb}(Y)=\rho X$, the median of X is $\mathrm{cyb}(\mu)/\rho$ because of the normal variate $Z=\{\mathrm{hyb}(\rho X)-\mu\}/\sigma$. The parameter ρ is the dose-reducing constraint factor per unit dose as feedback control by the radiation protection system. When ρ is small enough to give $\rho X<<1$, then $\mathrm{hyb}(\rho X)\approx\ln(\rho X)$. On the other hand, it shows $\mathrm{hyb}(\rho X) \approx\rho X$ when ρ is large enough to give $\rho X>>1$. Thus the hybrid function produces a hybrid scale of logarithmic and linear scales, analogous to the log-scale produced by the logarithmic function [11, 13]. The HLN model characterizes the variation of doses to be normally distributed in the hybrid scale reflecting the magnitude of controlled dose ρX. When doses approach the dose limits, the dose distribution is a downward convex curve as plotted in log-scale of X, but it is a straight line as plotted in the hybrid scale of ρX.

As mentioned above, in hybrid scale of probability paper, the HLN variation of observed doses is expressed as a straight line in a function of controlled dose ρX. Relatively larger values of ρ indicate the stronger effectiveness of dose reduction when the straight graph of dose distribution shifts toward the linear region of hybrid scale [$\mathrm{hyb}(\rho X)>0$], whereas relatively smaller values of ρ show the smaller effectiveness of dose reduction when the straight graph shifts toward the logarithmic region of hybrid scale [$\mathrm{hyb}(\rho X)<0$]. With no effective constraint factor ($\rho = 0$), the straight graph of dose distribution is completely located in the logarithmic region and the hybrid lognormal distribution becomes the lognormal distribution. The value of ρ reflects the exposure control mechanism depending on various factors such as jobs, radiation control processes, operational procedures, regulation and so on. Thus, by calculating values of ρ, the effectiveness of a radiation protection system will be assessed more easily and clearly. In addition, changing of ρ values on hybrid scale may judge whether a dose distribution is hybrid lognormal or not [4, 12, 13].

All three models of normal, lognormal and hybrid lognormal are applied to assess the occupational dose distribution of 32 medical workers at Hospital No.103 in 1994. The selection of the best model among these models is based on Akaike's Information Criterion

(AIC), minimizing AIC= n × ln [(sum of squared residual errors) / n] + 2 × (number of model parameters), where n is the number of data. The first term of AIC corresponds to −2 × (log-likelihood). It minimizes the total amount of residual errors and the number of parameters. In Canada these three models have been applied to the analysis of occupational exposure data, using maximum likelihood estimation [15-16]. This paper includes the additional term of minimizing the number of parameters.

3. PERSONNEL MONITORING AT VAEC'S HOSPITAL NO.103

In 1994, there were total 32 monitored persons (including 5 women) who worked at the X-ray diagnosis division and radiotherapy division of Hospital No.103. 18 persons of the X-ray diagnosis division were exposed to only X-ray, while 14 persons of the radiotherapy division were exposed to gamma rays and beta rays emitting from radioisotopes as Iron-59 (^{59}Fe), Chromium-51 (^{51}Cr), Cobalt-60 (^{60}Co), Iodine-131 (^{131}I), Phosphorus-32 (^{32}P) and other radiation equipment.

Occupational exposure to radiation at the hospital in 1994 was governed by the national regulation established in 1986 by the VAEC based on the Recommendations of the ICRP Publication 26. The annual dose limit was 50mSv as effective dose equivalent and the calculation of monthly dose standard was about 4.2mSv. The individual dose measurements were monthly conducted by the Nuclear Safety Technology Center of the VAEC from the first to the third day of month, by using film badge dosimeter. The value of dose was the whole body effective dose equivalent determined from a single dosimeter worn on the front left chest of the body at radiation work. The medical doctors put the lead apron that covered the dosimeter on chest when they controlled the machines of radioscopy to diagnose directly on the body of patients.

The minimum detectable dose was 0.01mSv as rounded (0.005-0.015mSv). Doses below the detection limit were recorded as 0 mSv. Increasing exposure comparing with the monthly dose standard, medical workers were always ordered to change their work and also repeatedly asked to call their attention to exposure reduction.

Radiation exposure was different among medical workers and its intensity changed day by day according to the number of patients or their task. In the X-ray diagnosis division, medical doctors did not work on the radiophotograph as frequently as technicians did, but they usually had to control the radioscopy and were likely to be directly exposed by X-ray for long time. In the radiotherapy division, where many radioisotopes and radiation equipment of diagnosing and treating patients were used, both medical doctors as technicians were similarly exposed. All these affected the characteristics of doses to medical workers and made many differences in individual doses in the hospital.

4. RESULTS

4.1 Dose data in 1994

The results of individual dose measurement obtained in 1994 at Hospital No.103 of the VAEC are presented in Table 1. About thirty-two medical workers was monitored at the hospital every month, leading to a total number of 378 monthly individual doses, excluding 6 cases due to lack of monitoring. Among them, the number of data below the measurable dose or detection limit of 0.01mSv is 61 (about 16% of all data). The fraction of measurable dose is a quite high percentage (about 84%), compared with other occupational exposure [4]. Most data (about 80% of all data), however, ranges from 0.01mSv to 0.3mSv and only two doses (0.53%) exceed 1mSv including a maximum of 1.31mSv. It is therefore clear that all medical workers received small monthly individual doses, far below the monthly dose standard of 4.2mSv.

The mean monthly dose and monthly collective dose of workers at the hospital in 1994 are given in Table 2, providing the separation by worker between doctor and technician and by source between gamma ray (mainly) and X-ray basis. The mean of monthly doses among all workers varies with month, from 0.04mSv (July and November) to 0.24mSv (March). The mean ranges from 0.03mSv (June, July and September) to 0.15mSv (March) among doctors and from 0.01mSv (December) to 0.32mSv (March) among technicians. Separated by type of source, the mean is from 0.04mSv (November) to 0.34mSv (March) for the X-ray group of workers, and from 0.01mSv (August) to 0.12mSv (March) for the gamma ray group. It is important to note that a maximum of the mean monthly dose is observed on March for all workers, doctors and technicians as well as for gamma ray and X-ray groups. Thus, the mean dose varies with month, kind of workers and type of sources.

The mean annual dose is reported at 0.96mSv among all workers, with remarked differences between doctors (0.85mSv) and technicians (1.06mSv) as well as between gamma rays (0.58mSv) and X-ray (1.25mSv).

Table 2 also shows the monthly and annual collective doses for all monitored workers, doctors and technicians, and two types of sources at the hospital in 1994. The monthly collective dose is the largest for March and the smallest for December as the same as the highest mean monthly dose for March and the lowest mean for December because of the similar number of workers per month shown in Table 1. The contribution of annual collective dose is larger for technicians (61%) than for doctors (39%) and also larger for the X-ray group (74%) than for the gamma ray group (26%).

4.2 Distribution of monthly individual doses to all workers

Figure 1 shows the distribution of 1994 monthly individual doses for all medical workers at Hospital No.103. Upper panel is the probability plot, having the vertical axis of normal variate z, which corresponds the probability not exceeding a given dose, and the horizontal axis of dose in linear scale. The graph is not linear for all observed doses. Therefore the dose distribution is not the normal distribution. Doses above 0.3mSv seem to be normally distributed because of linearity of their graph. Middle panel is the log-probability plot, where the horizontal axis of dose is in log scale. Plots of data show a linear graph and the dose distribution is lognormal, excepting doses above 0.8mSv where data deviate from the linear graph. Lower panel is the hybrid probability plot, having the horizontal axis of controlled dose ρx, where ρ is $0.63\mathrm{mSv}^{-1}$, in hybrid scale. The whole data form the best linearity of plots in hybrid scale among three kinds of the scales. The distribution of monthly doses to all workers in 1994 is likely hybrid lognormal.

The solid line in Figure 1 shows a lognormal fit to all data. It well fits data up to 0.8mSv but deviates from higher doses above this level (see upper or lower panel). The broken line represents a hybrid lognormal fit to all data. It fits the whole data better than the solid line. Using the AIC criterion, the hybrid lognormal model (AIC= -1458.7) is the best among the three models, noting that AIC=-462.2 for the normal AIC= -1411.9 for the lognormal. Table 3 shows statistic of monthly individual doses estimated by lognormal and hybrid lognormal models. The estimation of median dose is almost equal to the actual median for both models. The estimates by the hybrid lognormal model give a good approximation to the actual mean and standard deviation, but those by the lognormal model do not.

Investigating in detail, Figure 1 shows a considerable discrepancy of data from the fit curve from 0.15mSv to 0.35mSv. The distribution of doses below 0.3mSv, corresponding to about 95% of data, brings a hybrid lognormal fit shown by solid line on log-probability plot in Figure 2. Even if changing the dose range of fit between 0.1mSv and 0.3mSv, the characteristics of dose distribution is almost similar. Thus the hybrid lognormal fit of solid line in Figure 2 indicates the basic characteristics of distribution of lower monthly doses to most of workers. Monthly individual doses above 0.3mSv (5% of workers) explicitly deviate from the basic distribution of doses below the level. This might be due to the specific jobs needed by some workers and months. Consequently the effectiveness of controlling monthly individual doses can be clearly identified in the case of actual exposure control even if all doses are sufficiently low relative to the monthly dose standard of 4.2mSv. The constraint factor ρ of exposure is 4.57mSv^{-1} (Figure 2), while it is 0.63mSv^{-1} when the hybrid lognormal model fits all data (Figure 1).

4.3 Monthly dose distribution by type of workers and sources

The variation of monthly individual doses might be affected by kind of workers and by type of sources. Figure 3 shows the comparison of distributions of 1994 monthly doses pooled by kind of workers between doctor and technician, using three kinds of probability plots, the same as depicted in Figure 1. The shape of plotting data for technicians is almost the same as that for all workers showed in Figure 1 but the shape of plots for medical doctors is clearly different. The dose distribution range is narrower for doctor than for technician.

The linearity of the plots is identified only in higher doses on upper panel of linear scale and in lower doses on middle panel of log-scale for both doctor and technician. However, it is attained in the whole range of dose when data are plotted as a controlled dose of ρx in hybrid scale with ρ of 0.97mSv^{-1} for doctor and of 0.60 mSv^{-1} for technician. Thus, the hybrid lognormal model is applicable to determining the whole dose distribution and estimating the statistic.

The dose range of graph for doctor in hybrid scale of ρx shifts more strongly toward the linear scale more than that for technician. This means that doctors were affected stronger from radiation protection than technicians, although most of monthly doses are below 0.2mSv, for doctors and below 0.3mSv for technicians.

Figure 4 gives a similar comparison of distributions of 1994 monthly doses pooled by type of sources between gamma ray and X-ray groups. The distribution of doses for X-ray users is quite similar to that for whole data in Figure 1 as well as for technician's data in Figure 3. The dose distribution for gamma ray users is different from that for X-ray users. Middle panel shows roughly parallel straight arrays of plots on log scale for both gamma ray and X-ray. Plotting the data in hybrid scale gives a straight line in the deeply logarithmic region of hybrid scale for gamma ray, while for X-ray users a similar trend is observed in the region extending from logarithmic to linear feature of hybrid scale. The slope of graphs is very similar for both groups.

The dose distribution for gamma ray is almost lognormal because of linearity in log scale but that for X-ray is rather hybrid lognormal. The difference in dose distribution might be due to the characteristics of jobs and radiation protection between the two sources. The constraint factor ρ of exposure to gamma ray and X-ray is 0.004mSv^{-1} and 0.86mSv^{-1}, respectively. It suggests that the radiation control affected more strongly in exposure to X-ray users than to gamma ray users. As the mean dose of gamma ray users is about a half of that for X-ray users, it agrees with the principle of "the stronger control over the higher exposure."

Figures 3 and 4 show the characteristics of the whole distribution of monthly doses pooled by kind of workers and by type of sources. To understand the basic characteristics of dose distribution, we changed the dose range to fit the model to the data as well as possible. Figure 5 shows the best fit of the hybrid lognormal model to most of the data up to 0.2mSv for doctors and up to 0.3mSv for technicians. The higher doses above the level deviate largely from the fit for both kinds of workers. Figure 6 also shows the best fit of the model to most of the data up to 0.2mSv for gamma rays and up to 0.3mSv for X-ray. Similarly, the higher doses above the level deviate largely from the fit for both types of sources. These results indicate the consistent evidence of strong control of exposure so that monthly individual dose should range mainly from 0.01 to 0.3mSv. From Table 1, the fraction of measurable doses is only 16%, although many other cases are frequently about 50% or more [2]. In the mean time the fraction of doses above 0.3mSv is only 4.5%.

The constraint factor ρ of exposure for doctor and technician is $7.32 mSv^{-1}$ and $3.88 mSv^{-1}$ (Figure 5), respectively, while it is $0.97 mSv^{-1}$ for doctor and $0.06\ mSv^{-1}$ for technician (Figure 3) when the model fits each set of the data for all doctors and all technicians. The constraint factor ρ for gamma ray users and X-ray users is $7.10 mSv^{-1}$ and $6.25 mSv^{-1}$ (Figure 6), respectively, while it is $0.004 mSv^{-1}$ for gamma ray users and $0.86 mSv^{-1}$ for X-ray users in Figure 4. Thus, the hybrid lognormal analysis proved to extract the underlying effectiveness of radiation protection efforts.

4.4 Monthly dose distribution by each of workers

Each of workers generally has his role in job. The variation of distributions of monthly doses in a year by each of workers should be clarified, relating to the distribution of doses pooled by a certain group of workers. Figure 7 shows the log-probability plots of monthly doses to each of 32 workers over the year 1994, in comparison with the same plots for all workers with the hybrid lognormal fit to the data below 0.3mSv (the solid line). Thirty-two distributions of doses to each of workers range widely from the lognormal in the dose region below 0.1mSv to the hybrid lognormal or the normal in the region extending above 0.3mSv.

Figure 8 shows the same data in hybrid probability plot for each of workers and all workers with respect to the controlled dose ρx. The value of ρx was calculated by using the corresponding constraint factor for each of workers. Plots of doses to workers No.7 (□) and No.25 (♦) are roughly straight lines in the left margin of the hybrid scale and almost in the whole log scale. Their slope of graph parallels that of plots of data to workers ALL (□). Plots of doses to workers No.15 (∗) and No.18 (◇) are also roughly straight lines in the right margin of the hybrid scale and almost in the whole linear scale. Their slope of graph is similar to that for workers ALL (□). Thus, the hybrid probability plot presents a straight line of dose distributions ranging from log scale to linear scale via hybrid scale. Generally speaking, the straight line in the linear region reflects stronger control of dose reduction while the straight line in the log scale indicates week or homogenous control from the insignificant dose to the significant dose region.

The constraint factor of the dose distribution varies by each of workers considerably. The distribution of these 32 constraint factors is presented in the log-probability plot in Figure 9. The solid line is the hybrid lognormal fit to the data of constraint factors including two smallest data. The hybrid lognormal fit to the data is sufficiently satisfied. The median of constraint factors among 32 workers is estimated at 4.90mSv^{-1}. The constraint factor for the solid line shown in Figure 7 or 8, fitting to the data below 0.3mSv for all workers, is 4.57mSv^{-1}. Thus, the constraint factor of dose distribution for all workers is very close to the median of the constraint factors for each of workers.

The same relationship of constraint factors has been reported between the whole distribution of pooled data and the set of distributions by subgroup. One is daily dose distribution at JRR-3, whose constraint factors by each of workers are lognormally distributed with the median very close to the constraint factor for the distribution of daily doses pooled to all workers [17]. Another is annual dose distribution at light water reactors licensed by the U.S. Nuclear Regulatory Commission in 1998, whose constraint factors by each of reactor sites are lognormally distributed with the median similar to the constraint factor of the annual dose distribution of all sites [12].

In addition, the basic distribution of monthly doses at Hospital No.103 has the value of exposure constraint factor with the same order of magnitude for doctor (7.32mSv^{-1}) and technician (3.88mSv^{-1}) in Figure 5, or for gamma ray (7.10mSv^{-1}) and X-ray (6.25mSv^{-1}) in Figure 6.

4.5 Monthly dose distribution by each of months

In hospital radiation exposure strongly depends on the seasonal variation of medical activities. Tables 1 and 2 show that March is the largest in mean dose (0.24mSv) and collective dose (7.8 man mSv), while July or November is the smallest in mean dose (both 0.04mSv) and collective dose (1.14 or 1.17 man·mSv). The following is to analyze the effect of the seasonal variation of medical activities on the monthly dose distribution.

Upper and lower panels in Figure 10 show the variation of monthly doses among workers by each of months in 1994 with log-probability and hybrid probability plots, respectively. The overall variation of monthly dose distributions among 12 months is roughly similar but somehow smaller than that of monthly dose distributions by each of workers, shown in Figures 7 and 8, for both log-probability and hybrid probability plots (upper and lower panels, respectively).

March with the largest mean dose is the log-normality for the whole data but it is the hybrid log-normality for the data below 0.3mSv, where six workers exceed 0.3mSv and also exceed 0.6mSv. April with the second largest mean dose also shows the hybrid log-normality between 0.04mSv and 0.3mSv. Monthly doses above 0.4mSv in March and April contribute to most of higher doses deviating from the basic monthly dose distribution for all workers over the year 1994. The basic dose distribution is the solid curve in Figure 2, 7 or 8. Thus, it suggests the strong control of exposure at Hospital No.103 in 1994.

Monthly dose distributions in May, June, August and November are lognormal, while others are hybrid lognormal. Constraint factors of twelve months are hybrid lognormally distributed. The median of these constraint factors, however, is 1.66mSv^{-1} smaller than that (4.57mSv^{-1}) for those among 32 workers.

4.6 Annual dose distribution in 1994

The annual individual dose is the accumulation of monthly doses to a worker over the year. The distribution of 1994 annual doses among 32 workers at Hospital No.103 is lognormal as shown in Figure 11. All annual doses measured are far below the annual dose limit of 50mSv. However doses below 1mSv deviates from the lognormal fit and are fitted well by the hybrid lognormal model. This is attributed to the mixing of the basic dose distribution reflecting the effort of dose reduction with the occurrence of relatively higher exposure from the need of jobs or from the longer interval of monitoring by monthly basis. The annual dose of 1mSv corresponds to the mean monthly level of 0.083mSv. This is smaller than the level of monthly doses above which the higher monthly doses might be deviated from the basic dose distribution.

At Hospital No.103 radiation control is achieved by planning the intensity of radiation tasks so as to average exposure over workers, considering the recorded amount of previous monthly individual doses. This seems to bring the fewer fraction of less-than-measurable dose. Especially all of annual doses in 1994 are more than the measurable dose of 0.01mSv. However, the large variation of radiation jobs, especially due to the seasonal characteristics of patients, brings the lognormal types of annual dose distribution as a whole, while the basic distribution of dominant lower doses reflects the effect of reducing radiation doses.

5. DISCUSSION

The occupational exposure of 32 workers to ionizing radiation at Hospital No.103 in 1994 is sufficiently low, as mentioned above. To analyze such low doses is generally not useful for the practical purpose. Speaking frankly, we should analyze the significantly high doses in detail. The data presented here, however, give considerable findings about the characteristics of dose distribution and the effectiveness of radiation protection interpreted on the basis of the distribution of doses recorded.

The variation of occupational exposure is produced from many factors, including private reasons due to annual leaves and others from workers. So we need a simple model to understand the overall characteristics of the variation. The ICRP Publication 60 recommends investigating the overall effectiveness of dose distribution based on the distribution of doses attained. This report is one of efforts towards the application of dose distribution analysis in radiation protection.

There are many types of distributions to be analyzed by selecting the set of doses for the purpose of radiation protection. We should know the difference and the relationship among these distributions as well as their parameters. Especially the annual dose distribution is the final goal of evaluation but we should understand the distribution of doses, shorter or longer in an interval of time than one year, in each of different workers, by type of jobs or sources, and by other factors. Compiling this knowledge, the distribution of annual doses attained can be reasonably interpreted for the effectiveness of the system of radiological protection. This paper discussed some of them by using the small number of annual data with details of monthly individual doses.

The distribution of annual doses in the medical field is often reported to be lognormal. The annual dose distribution at Hospital No.103 in 1994 is apparently lognormal. However there are many evidences of dose reduction efforts by analyzing monthly dose distributions in various aspects, then the annual dose distribution at Hospital No.103 should not be considered simply to be lognormal. The distribution surely contains the evidence of the effectiveness of radiation protection as basic characteristics of dose distribution.

The annual individual doses are decomposed into monthly individual doses. The monthly individual doses are grouped into one distribution for all data, thirty-two distributions for each of workers and twelve distributions for each of months. These distribution data are analyzed by the hybrid lognormal model, the estimation of constraint factor ρ of the distribution for all data represents the median of the distribution of constraint factors corresponding to thirty-two distributions for each of workers or twelve distributions for each of months, at least in the same order of magnitude. This finding is useful for interpreting the overall distribution of all data, relating to a group of distributions decomposed by each of workers or by each of months. In this study the distribution of constraint factors among decomposed distributions showed the hybrid log-normality.

Next discussion is the characteristics of exposure at Hospital No.103, comparing with other medical occupational data. About 99.47% monthly doses are below 1mSv, and no data are over monthly dose standard of 4.2mSv. This result of the Hospital is better than that of 351 monthly doses in 1993 at 4 other hospitals in Vietnam, where 97% of monthly doses were less than 1mSv and 1.1% of them more than 4.2mSv [18]. From this paper the mean annual dose is about 0.96mSv and annual collective dose is 30.62 man mSv in 1994. About a quarter of annual doses and annual collective dose was attributed to March of busy month. The magnitude of mean annual dose is reported from 0.15mSv to 2.28mSv for medical occupational exposure from other countries [19-24]. The UNSCEAR Reports also show the mean annual effective dose of 0.5 mSv for medical radiation workers worldwide [4, 10]. Thus, the mean annual dose at Hospital No.103 in 1994 is within the common boundary shown in these reports.

The distributions of the actual data for all monthly and annual individual doses in 1994 at Hospital No. 103 are in logarithmic region of hybrid scale with small values of constraint factor (ρ = 0.63mSv^{-1} for monthly dose, and ρ = 0.037mSv^{-1} for annual dose). Thus, the actual dose distribution is similar to the lognormal distribution, which is suggested by ICRP 26 [5], and the exposure of many workers is well far below the level, required by the current radiation protection system and then not so close to the dose limits. The dose distribution of medical workers becomes lognormal because some medical workers incurred by higher doses attained at the jobs insufficiently controlled by the radiation protection system. As a result, the characteristics of distribution of all data apparently appear lognormal. Most of the actual doses at the Hospital are below 0.4mSv, except March when some doses are over this level. Analyzing the distribution of monthly doses below 0.4mSv, we find the hybrid lognormal characteristics of the distribution having ρ larger than few mSv^{-1}. It suggests that the major trend of monthly individual doses reflects a strong effect from the radiation protection at the Hospital. Thus the new dose standard in accordance to the Recommendations of ICRP Publication 60 (1990) [1] will affect the characteristics of dose distribution.

Exposure to radiation is very different among workers as shown in Figures 3 and 4. The level of dose received is not the same for each of workers; medical doctors were not exposed at high levels within a relatively narrow range of doses, but technicians exposure is ranging more widely in dose. In addition, the dose-reducing constraint factor calculated from the distribution of doses to each of workers varied widely, being hybrid log-normally distributed among all workers. Activity of many workers was still slightly free from the system of radiation protection. This suggests that there is a possibility of improving exposure control and the ALARA principle [25] should be addressed for actively individual monitoring shorter than a month. The variation of individual doses is necessary for the flexibility of work. It is important to find a reasonable variation of doses by radiation control. Therefore the hybrid lognormal model consists of the law of proportionate effect and the law of feedback mechanism.

Differences in dose and dose distribution by kind of workers, type of sources and each of month clearly demonstrate the characteristics of radiological working environment, operational procedures, radiation control processes and so on, including the positive and effective control efforts to suppress high exposure. Then the differences provide the informative suggestion on reasonably reducing dose by actions of radiation protection.

Data of radiation doses at Hospital No.103 in 1994 reveal the feature of variation by using three types of distribution models (normal, lognormal and hybrid lognormal). Data plotted on three types of scales (linear, log and hybrid) simply provide a clear comparison. Data are fitted well by the log or hybrid scale. The hybrid lognormal model fits data better when doses approach the dose limits or there is some dose control. Then the dose-reducing constraint factor becomes stronger. Based on this study, the hybrid lognormal analysis of dose distribution extracts a strong control effect of exposure in the range roughly between 0.1mSv and 0.3mSv, while the lognormal analysis does not show a similar trend due to some data of higher doses above 0.3mSv. This is not the case of doses approaching the dose limits but the case of some dose control.

6. CONCLUSION

The level of whole body doses each month and in the year of 1994 to radiation workers at Hospital No. 103 was sufficiently low, far below the national dose standard in Vietnam. The lognormal and hybrid lognormal analysis of the data showed the variation of monthly dose distributions by worker and by month. It also showed the difference of monthly dose distribution between medical doctors and technicians, as well as X-ray diagnosis and radiation therapy.

The distribution of monthly doses is lognormal for the whole range of dose. The hybrid lognormal analysis locates the distribution of monthly doses in the logarithmic region of hybrid scale for the whole range of dose. It, however, reveals the strong hybrid log-normality of the distribution of monthly doses below 0.3mSv that clearly reflects the overall effectiveness of radiation control except several data above 0.3mSv. The annual dose distribution showed similar characteristics that are lognormal for all data and hybrid lognormal for data below 1mSv. This proves the overall effectiveness of radiation control for most of workers annually exposed between 0.01mSv and 1mSv, reflecting the effort of averaging exposure over workers. The feedback of exposure records shorter than monthly monitoring will possibly bring the overall effectiveness for the whole dose range.

The results shown above suggest that the application of a limit on effective dose of 20mSv per year, averaged over 5years (100mSv in 5 years) recommended in the ICRP Publication 60 makes the exposure constraint factor larger due to reducing higher doses more but not lower doses.

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Table 1 Monthly individual dose at Hospital 103 in 1994

Month	No. of Workers	Monthly individual dose (mSv)							
		<MD*	MD-0.01	0.01-0.03	0.03-0.1	0.1-0.3	0.3-0.7	0.7-1	>1
1	32	0	6	6	15	5	0	0	0
2	32	0	10	9	8	5	0	0	0
3	32	0	1	1	16	8	2	2	2**
4	32	0	1	12	9	6	4	0	0
5	31	0	2	9	14	5	1	0	0
6	31	14	6	4	3	2	1	1	0
7	30	6	6	7	8	3	0	0	0
8	32	10	7	6	5	3	1	0	0
9	31	8	5	9	4	5	0	0	0
10	32	0	0	4	15	11	2	0	0
11	31	6	6	5	12	2	0	0	0
12	32	17	3	4	4	3	1	0	0
Total	378	61	53	76	113	58	12	3	2

*MD: Measurable dose ** Maximum dose is 1.31 mSv.

Table 2 Mean and collective doses for each month and year of 1994 at Hospital 103

Month	Mean dose (mSv)					Collective dose (man-mSv)				
	All workers	By worker*		By source**		All workers	By worker*		By source**	
		Doctor	Technician	γ ray	X-ray		Doctor	Technician	γ ray	X-ray
1	0.07	0.07	0.07	0.06	0.07	2.18	0.98	1.20	0.87	1.31
2	0.05	0.06	0.04	0.04	0.05	1.51	0.80	0.71	0.54	0.97
3	0.24	0.15	0.32	0.12	0.34	7.83	2.06	5.77	1.65	6.18
4	0.13	0.10	0.15	0.03	0.20	4.05	1.38	2.67	0.39	3.66
5	0.08	0.06	0.10	0.04	0.10	2.40	0.74	1.66	0.58	1.82
6	0.06	0.03	0.08	0.06	0.06	1.79	0.45	1.34	0.82	0.97
7	0.04	0.03	0.04	0.02	0.05	1.14	0.47	0.67	0.24	0.90
8	0.05	0.08	0.03	0.01	0.09	1.70	1.10	0.60	0.14	1.56
9	0.05	0.03	0.06	0.02	0.07	1.47	0.43	1.04	0.24	1.23
10	0.12	0.10	0.14	0.10	0.13	3.78	1.35	2.43	1.46	2.32
11	0.04	0.06	0.03	0.04	0.04	1.17	0.72	0.45	0.57	0.60
12	0.05	0.10	0.01	0.04	0.06	1.60	1.36	0.24	0.59	1.01
Total	0.96	0.96	1.06	0.58	1.25	30.62	11.84	18.78	8.09	22.53

* : 14 doctors and 18 technicians ** : 14 persons for γ ray and 18 persons for X-ray

Table 3 Comparison of statistic between data and model calculations

Statistic	Data	Lognormal	Hybrid lognormal
Mean	0.081	0.091	0.084
Standard deviation	0.14	0.23	0.15
Median	0.03	0.033	0.033

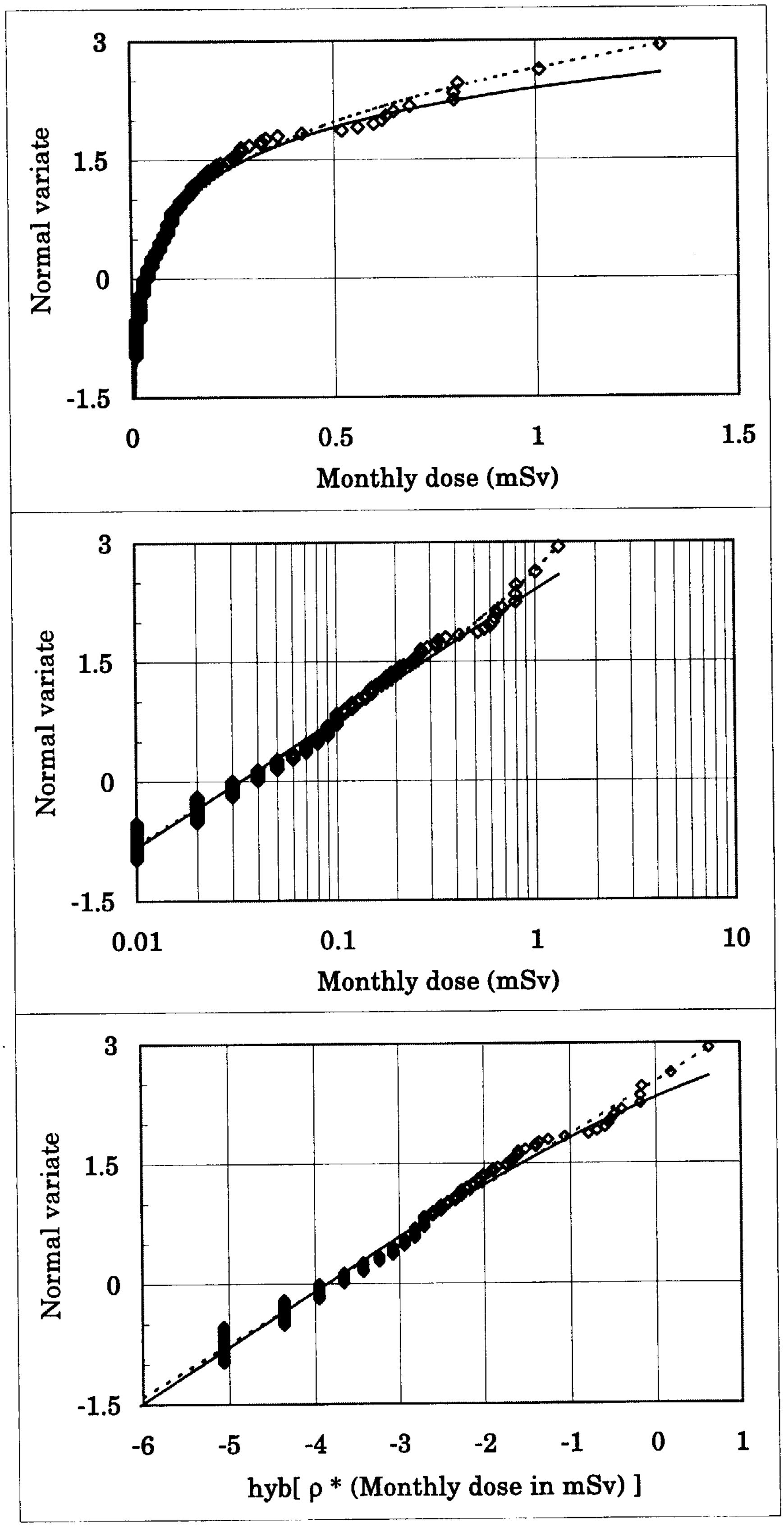

Figure 1 Probability plots of 1994 all monthly individual doses to 32 workers at Hospital No.103. Dose scales are linear (upper panel), log (middle) and hybrid (lower). Symbol shows data. Solid curve: lognormal fit; dotted: Hybrid lognormal fit to all data (ρ=0.63mSv^{-1}).

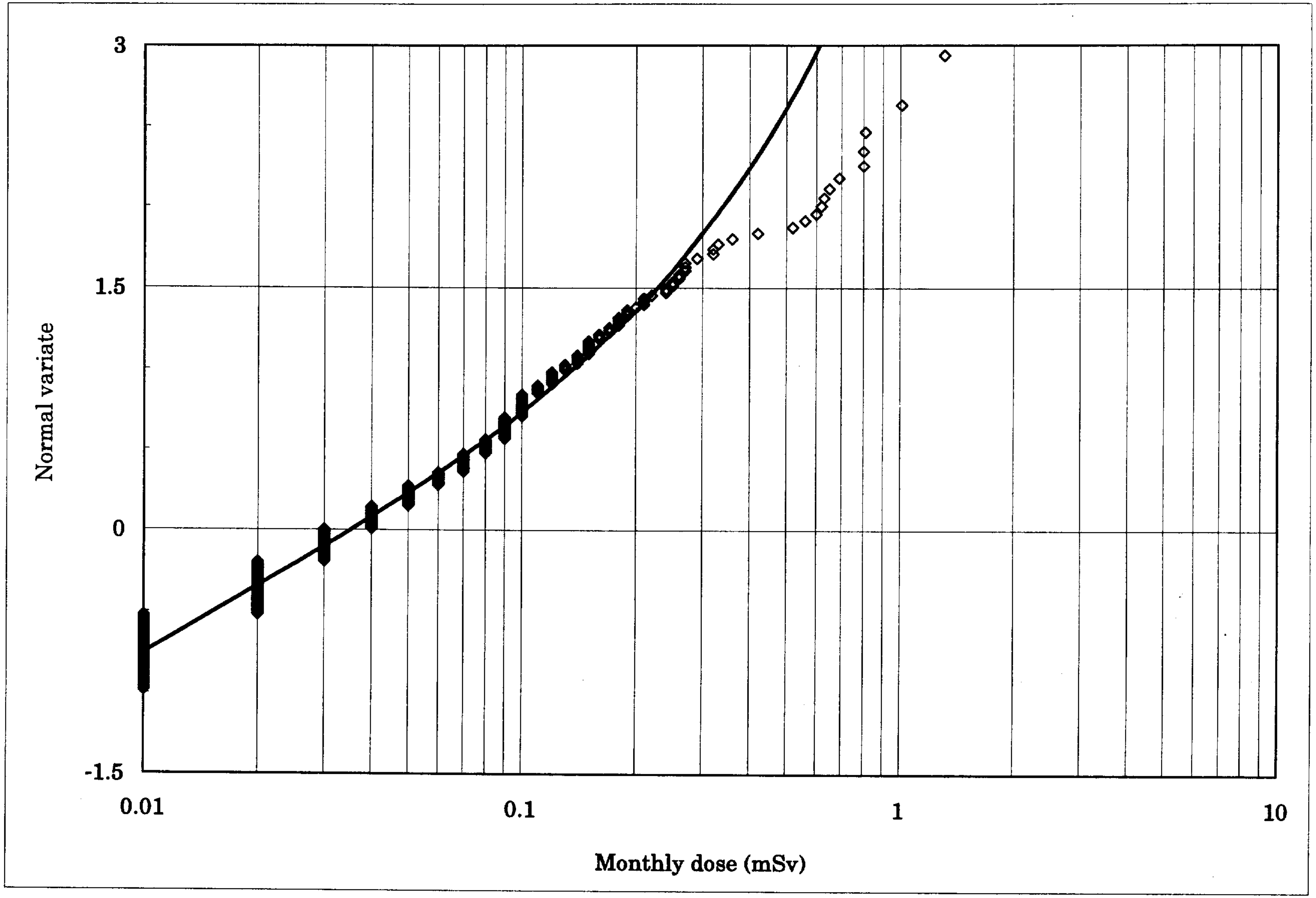

Figure 2 Log probability plot of the same data (diamond symbol) as Figure 1 with the hybrid lognormal fit (solid curve) to data below 0.3mSv, where ρ=4.57mSv^{-1}. Downward convex curve shows the effect of dose reduction efforts on most of data.

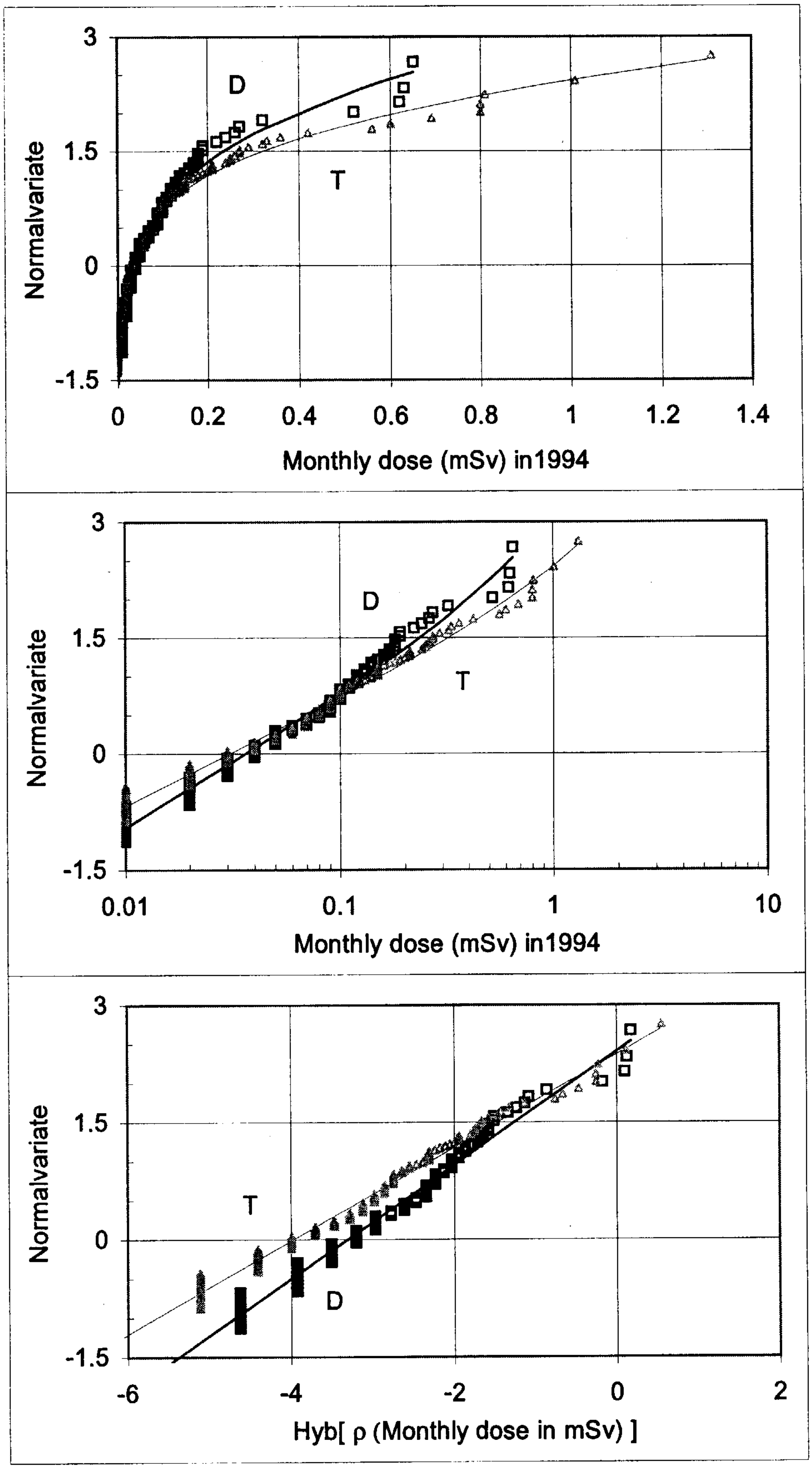

Figure 3 A comparison of probability plots of 1994 all monthly doses between doctor (D) and technician (T), the same presentation as Figure 1. Solid curves are HLN fits to each of data (D: ρ=0.97mSv^{-1}, mean= 0.07 mSv; T: ρ=0.60mSv^{-1}, mean=0.09mSv).

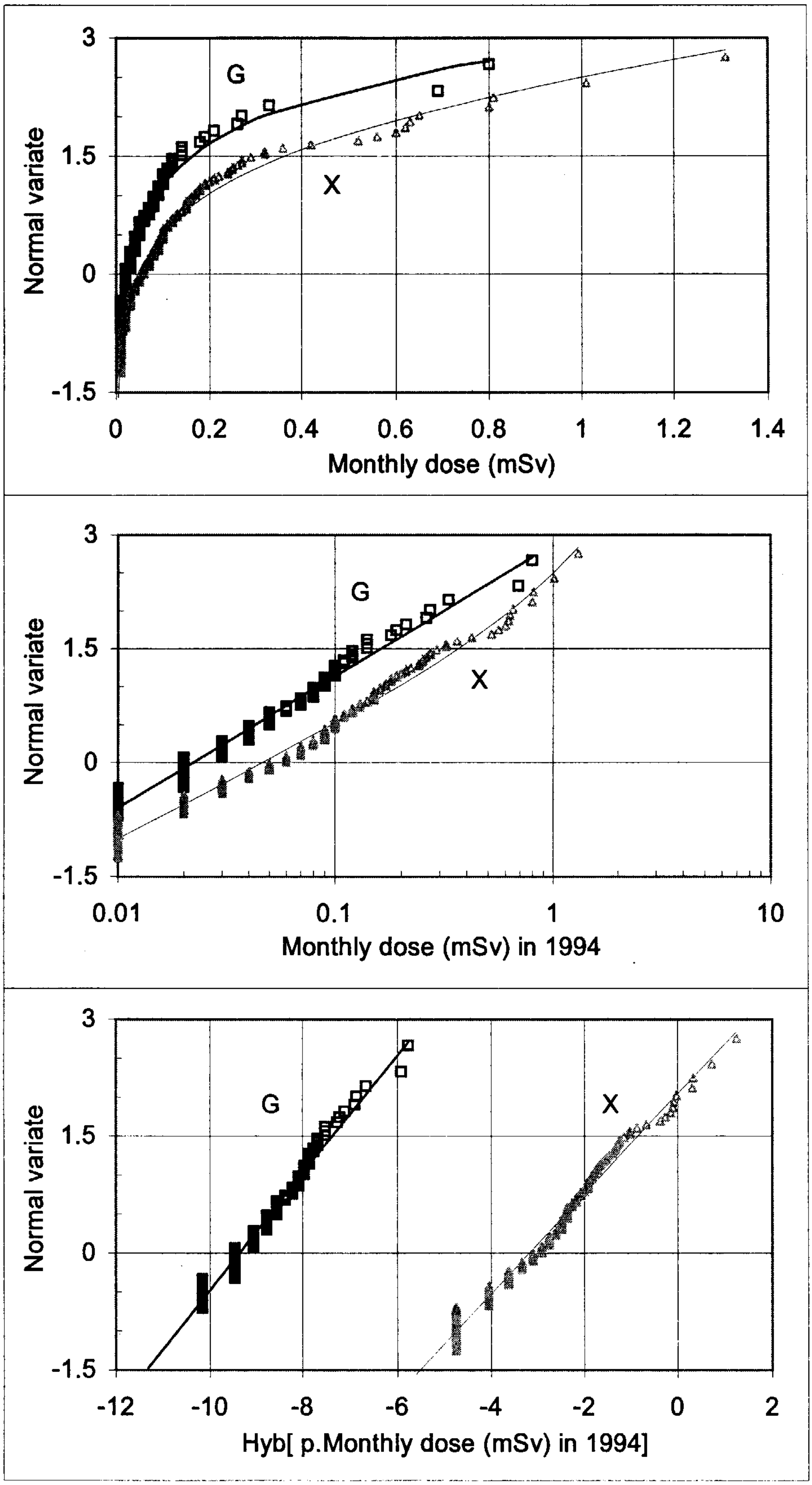

Figure 4 A comparison of probability plots of 1994 all monthly doses between gamma ray (G) and X-ray (X), the same as Figure 3. Solid curves are HLN fits to each of data (G: ρ=0.004mSv^{-1}, mean= 0.05 mSv; X: ρ=0.86mSv^{-1}, mean=0.11mSv).

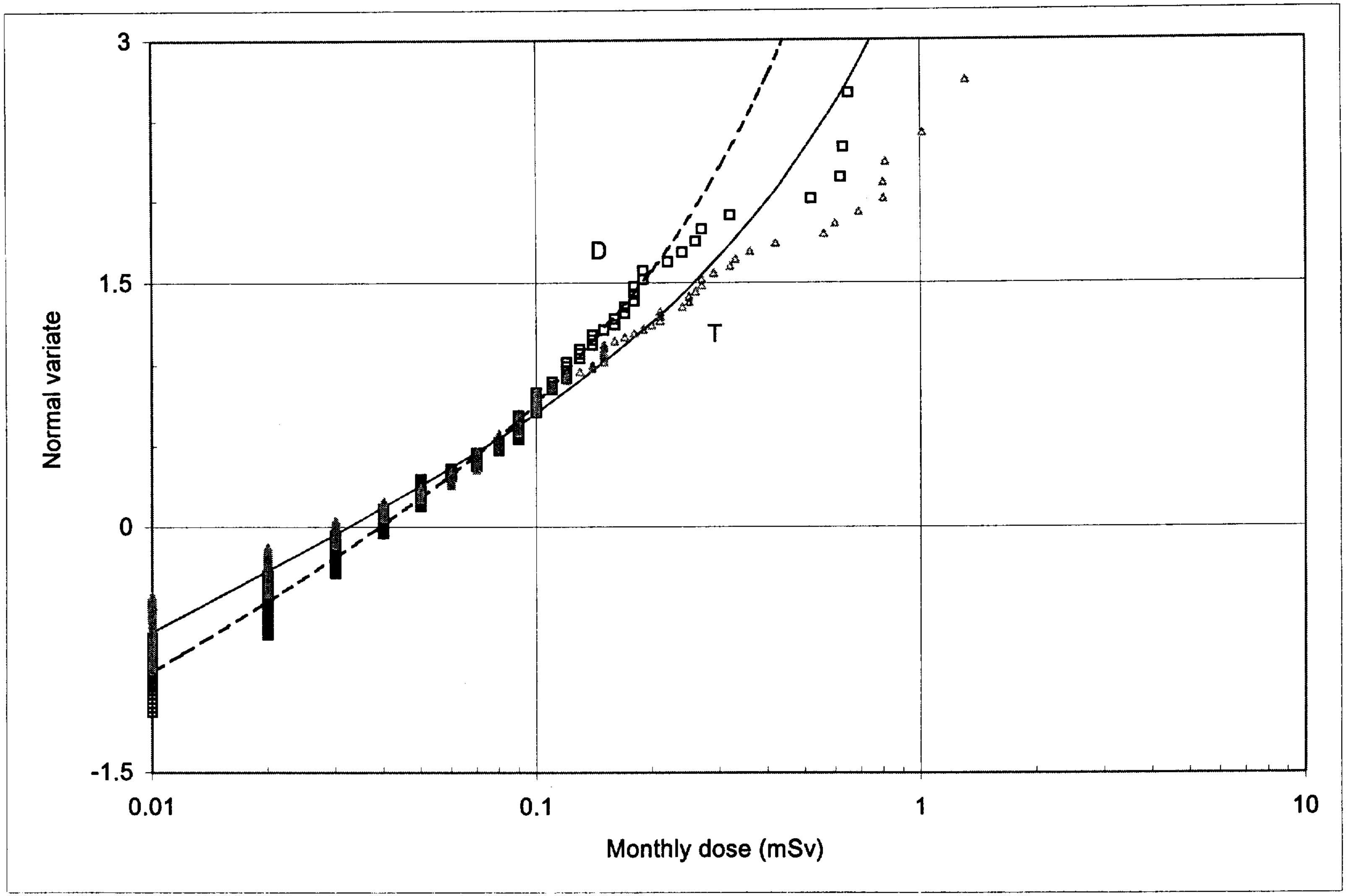

Figure 5 Hybrid lognormality of 1994 monthly doses below 0.2mSv for doctor (D) and below 0.3mSv for technician (T), which reflects the dose reduction efforts. Hybrid lognormal model fit (D: ρ=7.32mSv^{-1}, mean= 0.06 mSv; T: ρ=3.88mSv^{-1}, mean=0.07mSv).

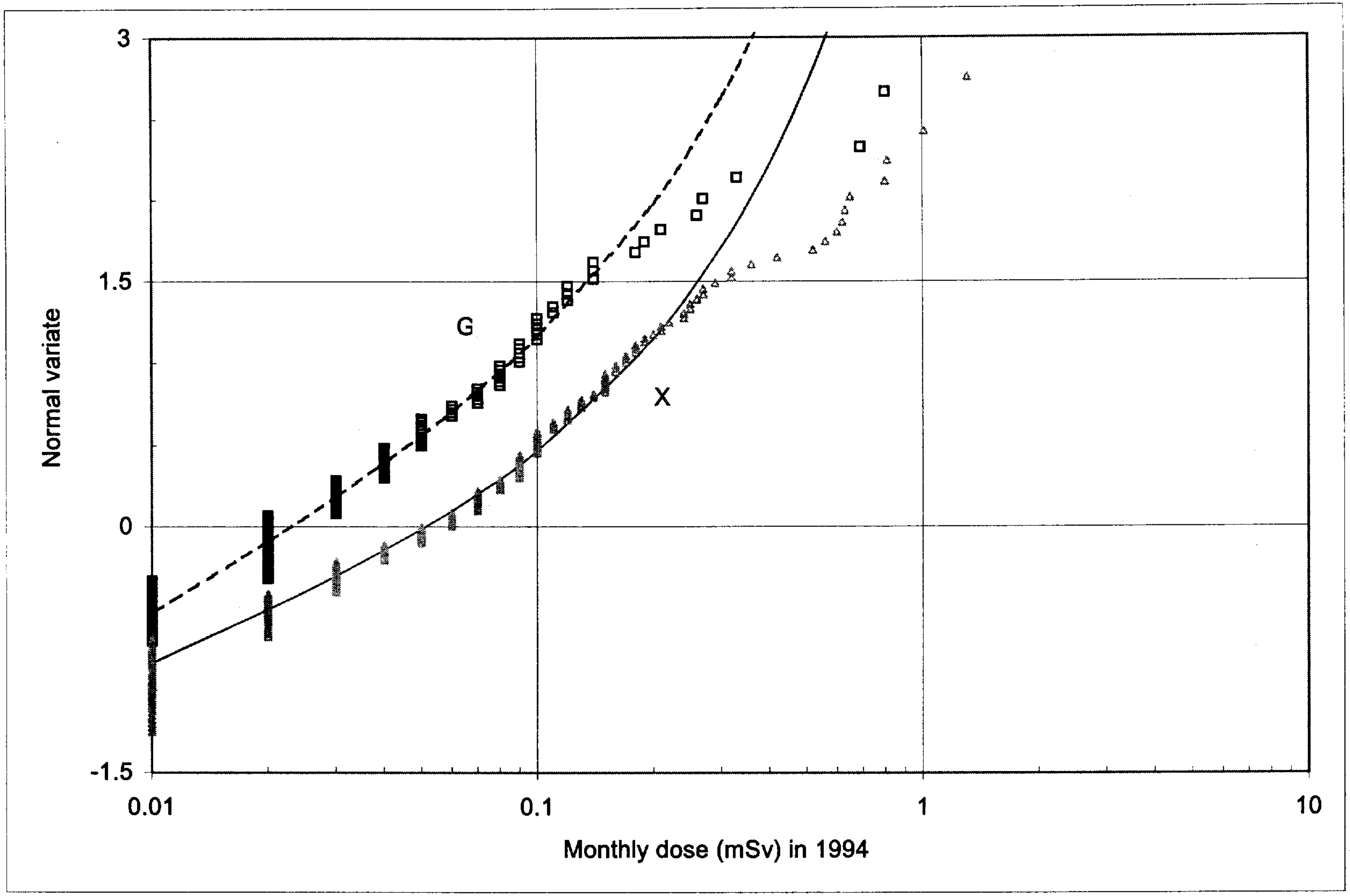

Figure 6 Hybrid lognormality of 1994 monthly doses below 0.2mSv for gamma ray (G) and below 0.3mSv for X-ray (X), which reflects the dose reduction efforts. Hybrid lognormal model fit (G: ρ=7.10mSv^{-1}, mean= 0.04 mSv; X: ρ=9.47mSv^{-1}, mean=0.09mSv).

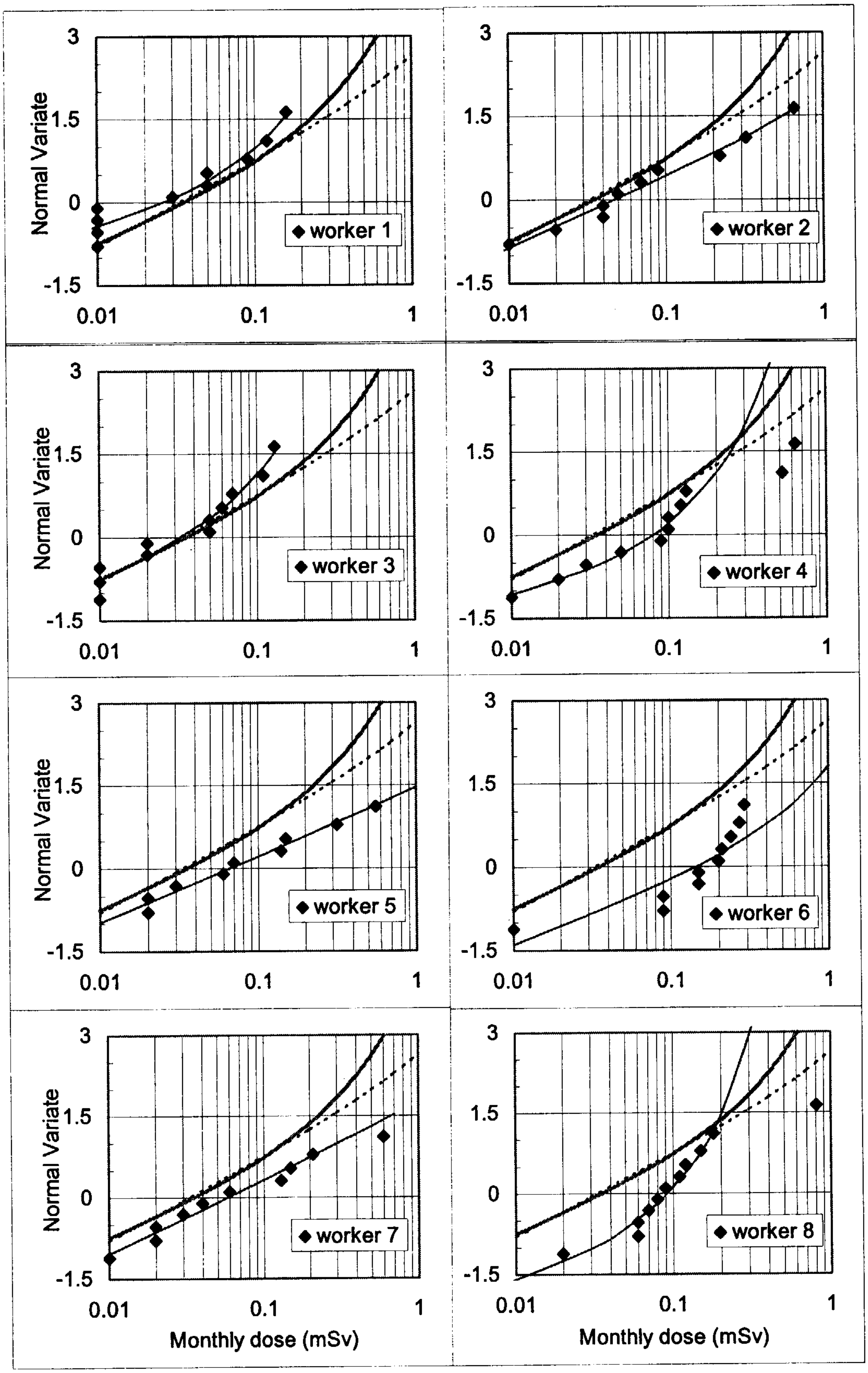

Figure 7a Log probability plots of 1994 monthly doses to workers (1-8) at Hospital.
Dashed curve: HLN fit to all data;Bold solid curve: HLN fit to data <0.3mSv;
Thin solid curve: HLN fit to data of each worker.

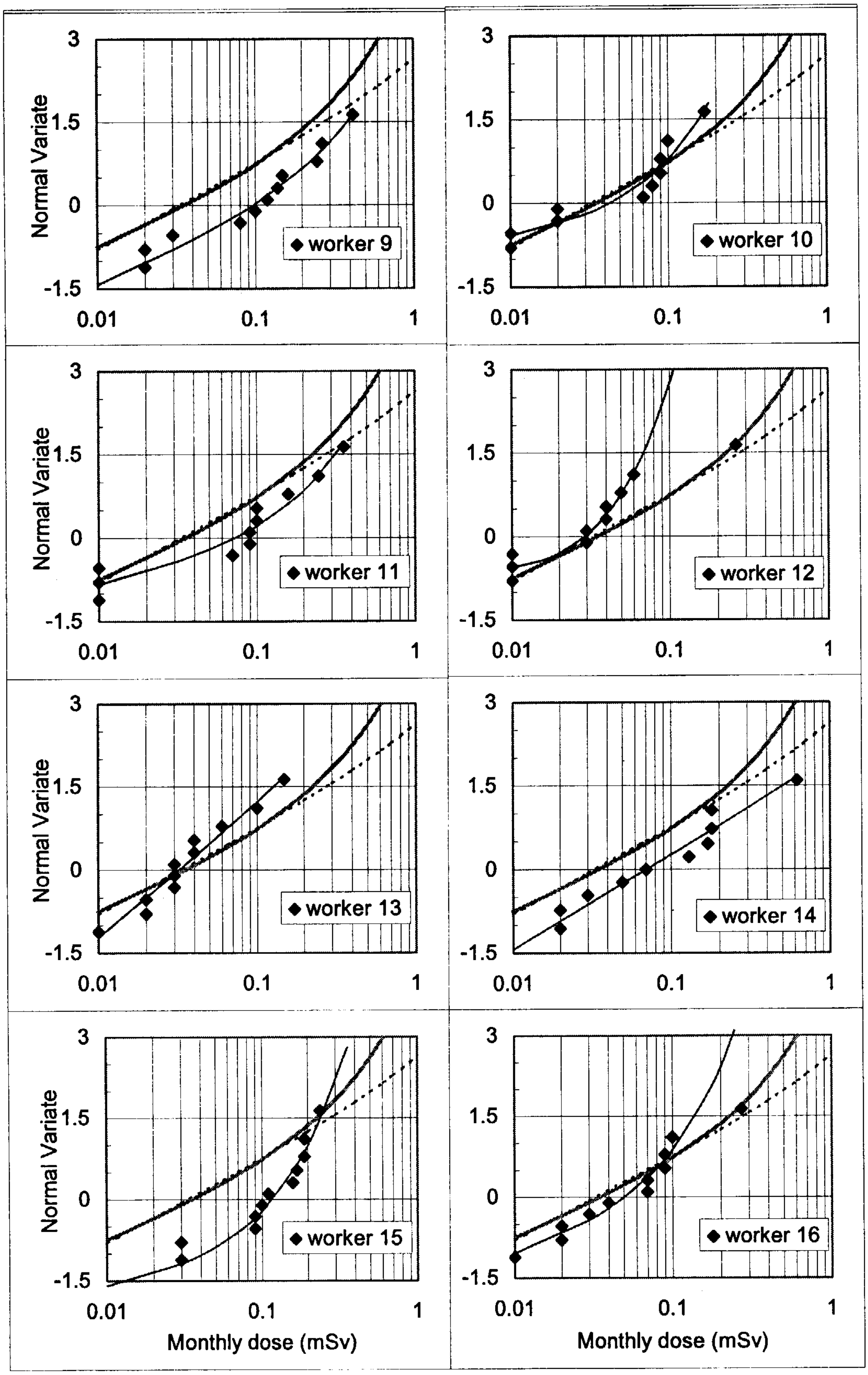

Figure 7b The same graphs as Figure 7a, 1994 monthly doses to workers (9-16).

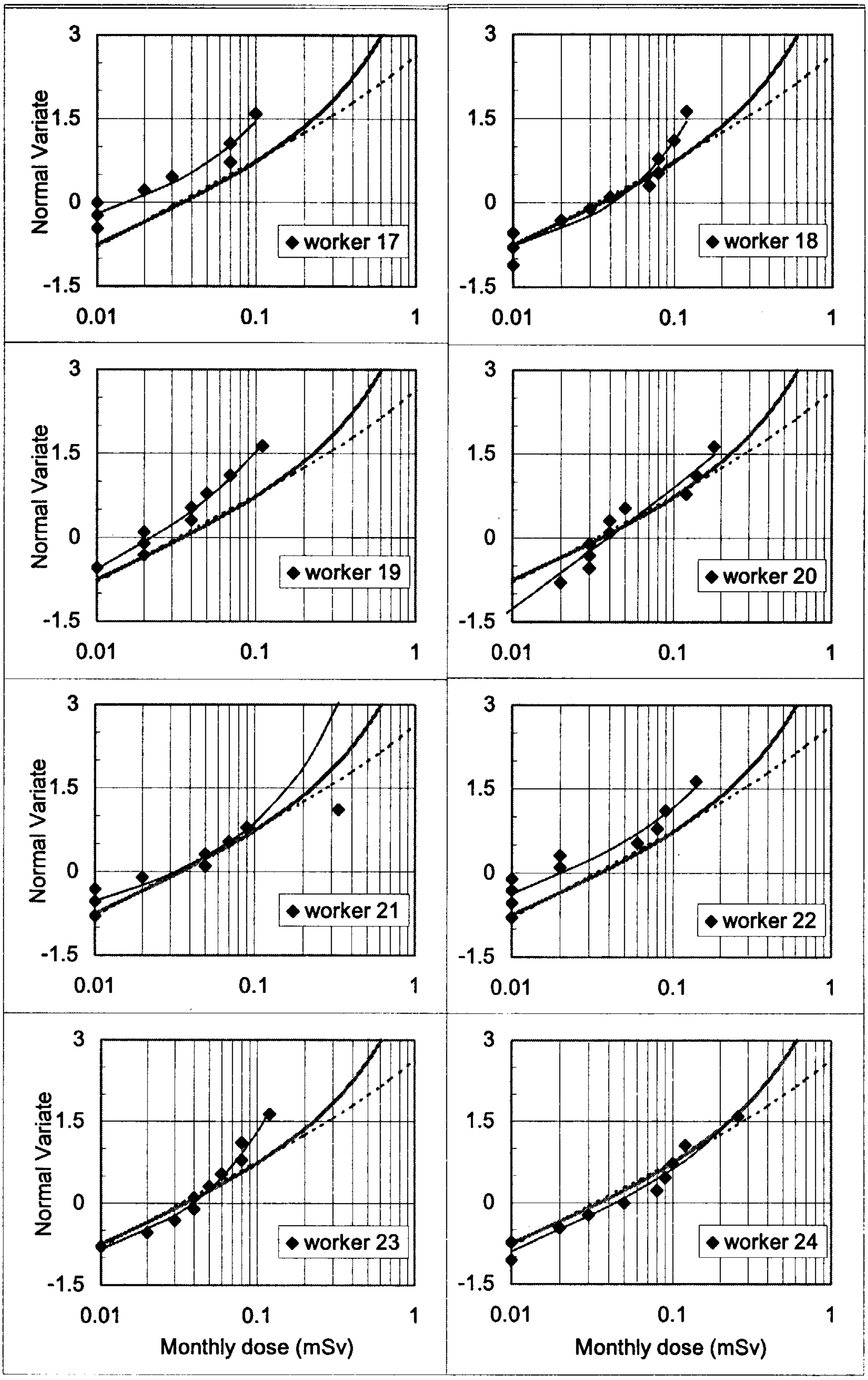

Figure 7c The same graphs as Figure 7a, 1994 monthly doses to workers (17-24).

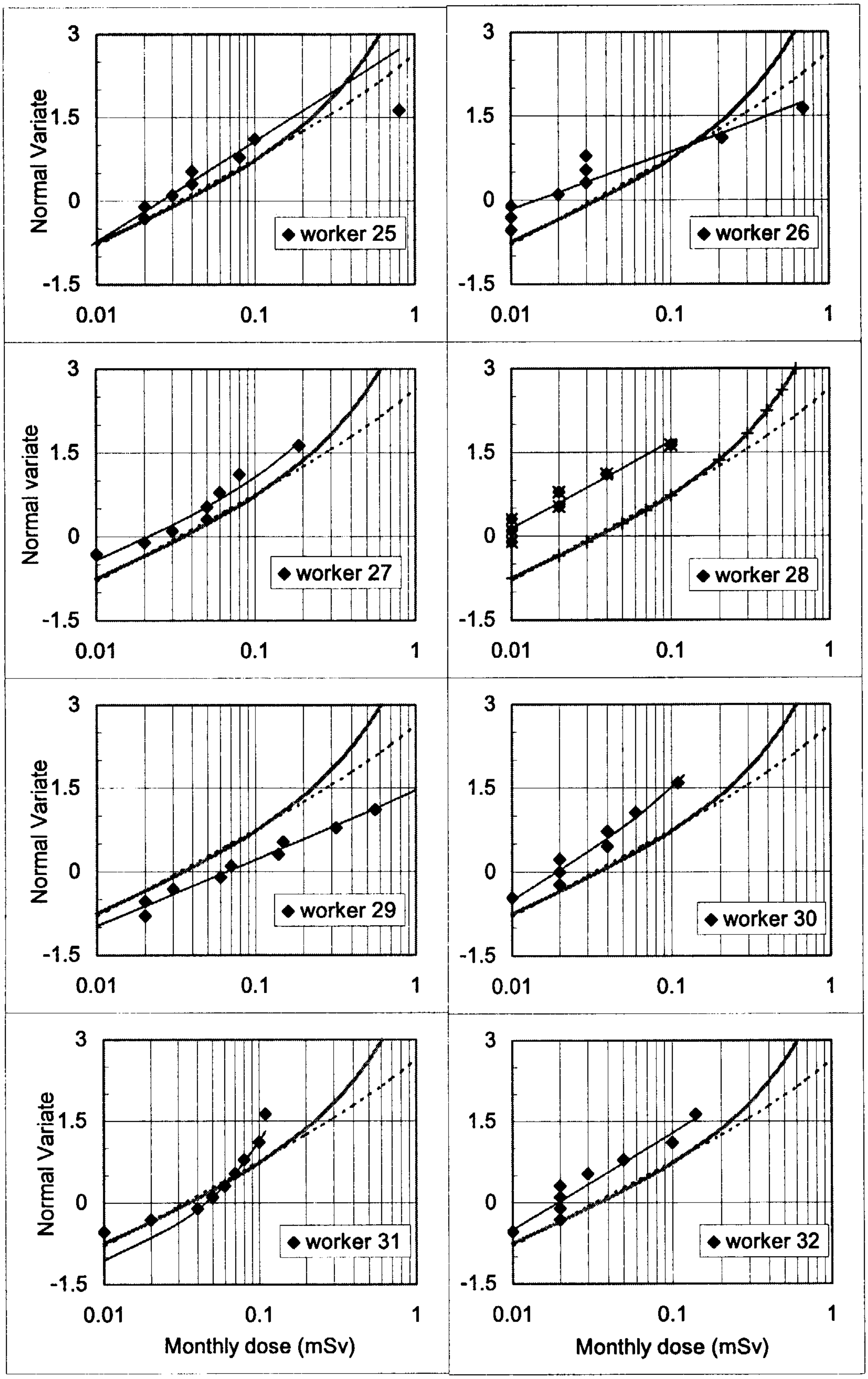

Figure 7d The same graphs as Figure 7a, 1994 monthly doses to workers (25-32).

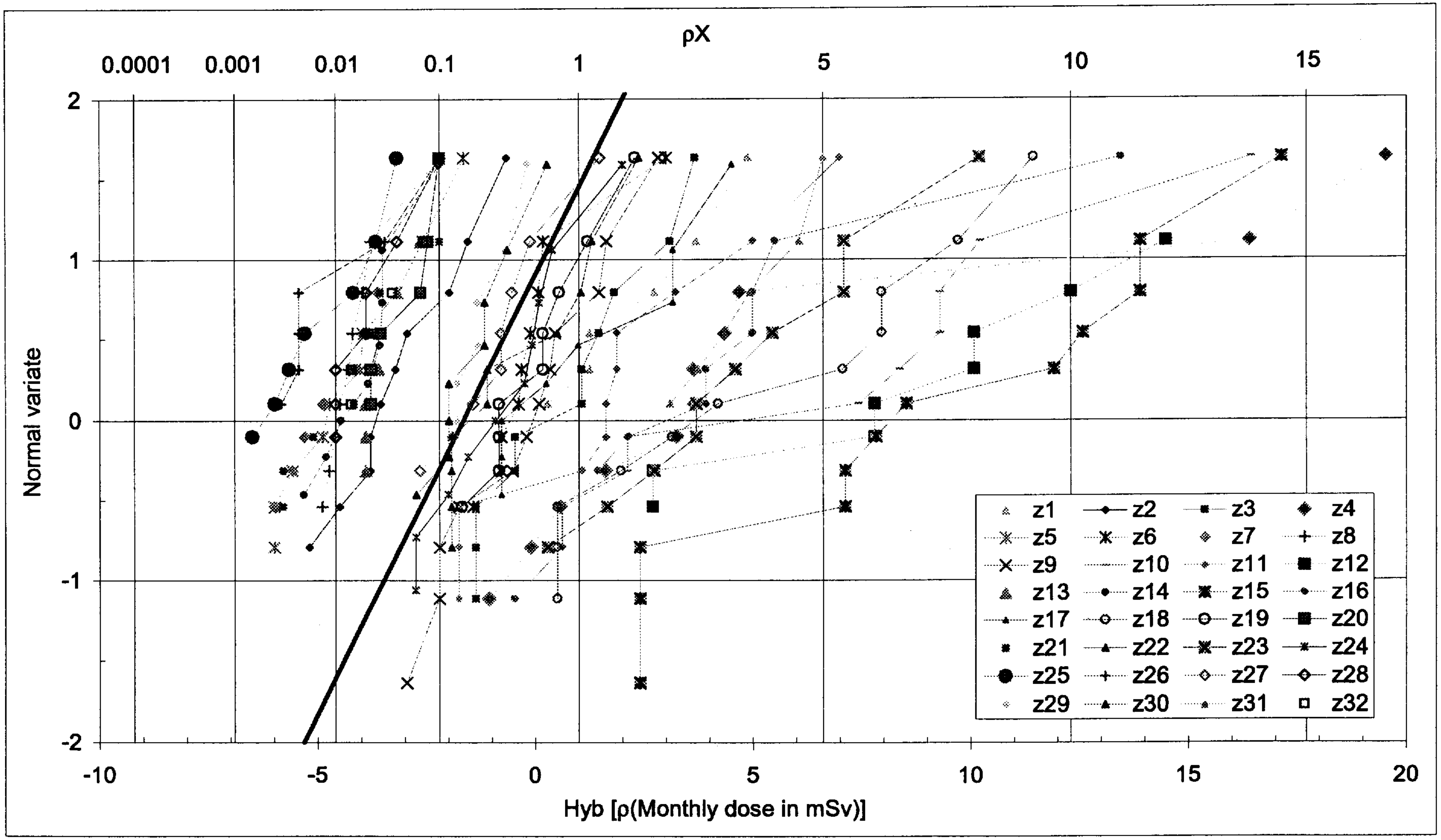

Figure 8 Hybrid probability plots of 1994 monthly doses to each of workers (z1 to z32). Solid line: HLN fit to all workers data <0.3mSv.

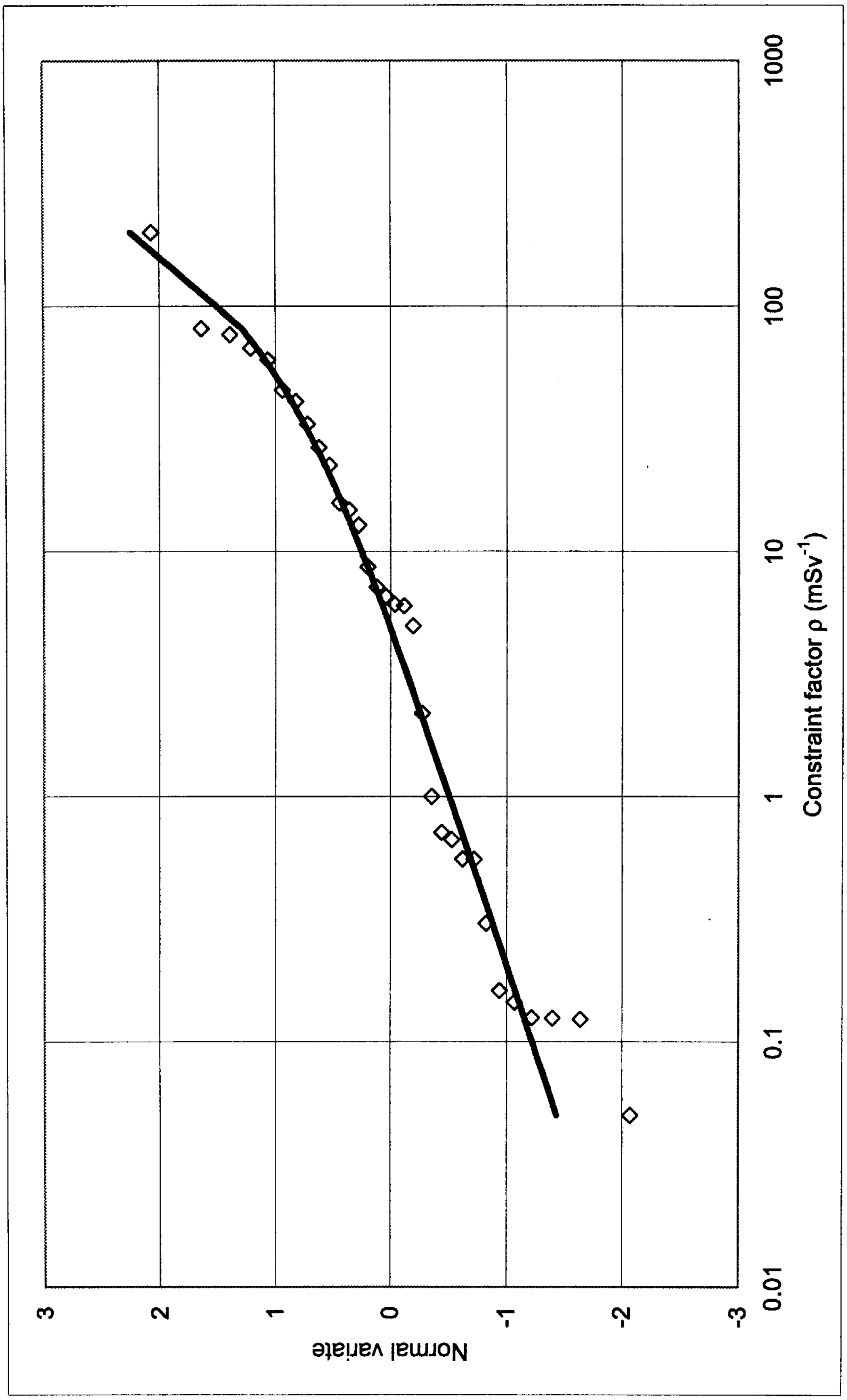

Figure 9 Log probability plot of exposure constraint factors of monthly dose ditribution among 32 workers at Hospital in 1994. Symbol represents data and solid curve shows the HLN fit to data except two smallest values of ρ.

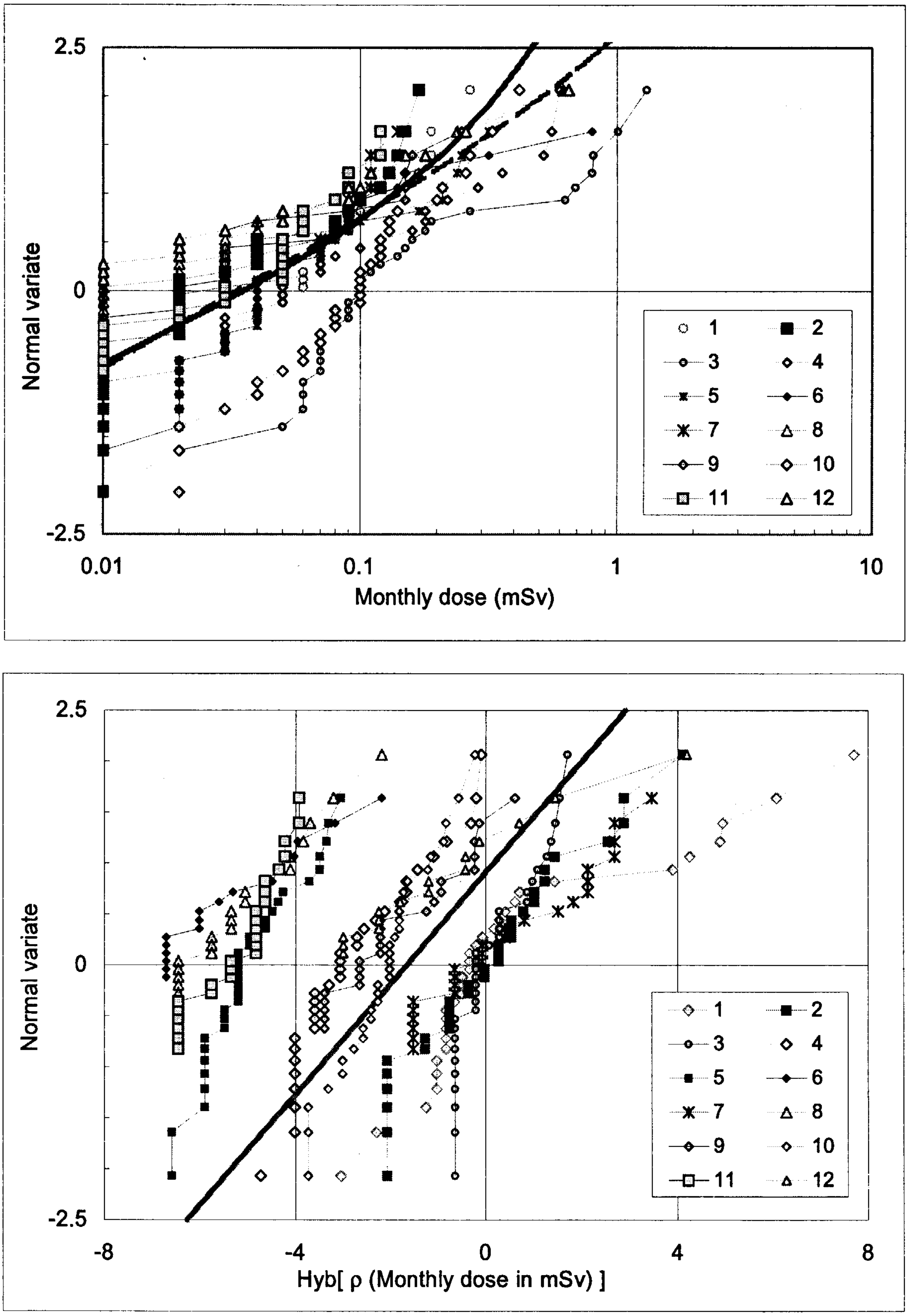

Figure 10 Log (upper panel) and hybrid (lower panel) probability plots of doses among workers by month in 1994. Bold solid line (both panel): HLN fit to all data below 0.3mSv (Figure 2); Broken line: HLN fit to all data (Figure 1).

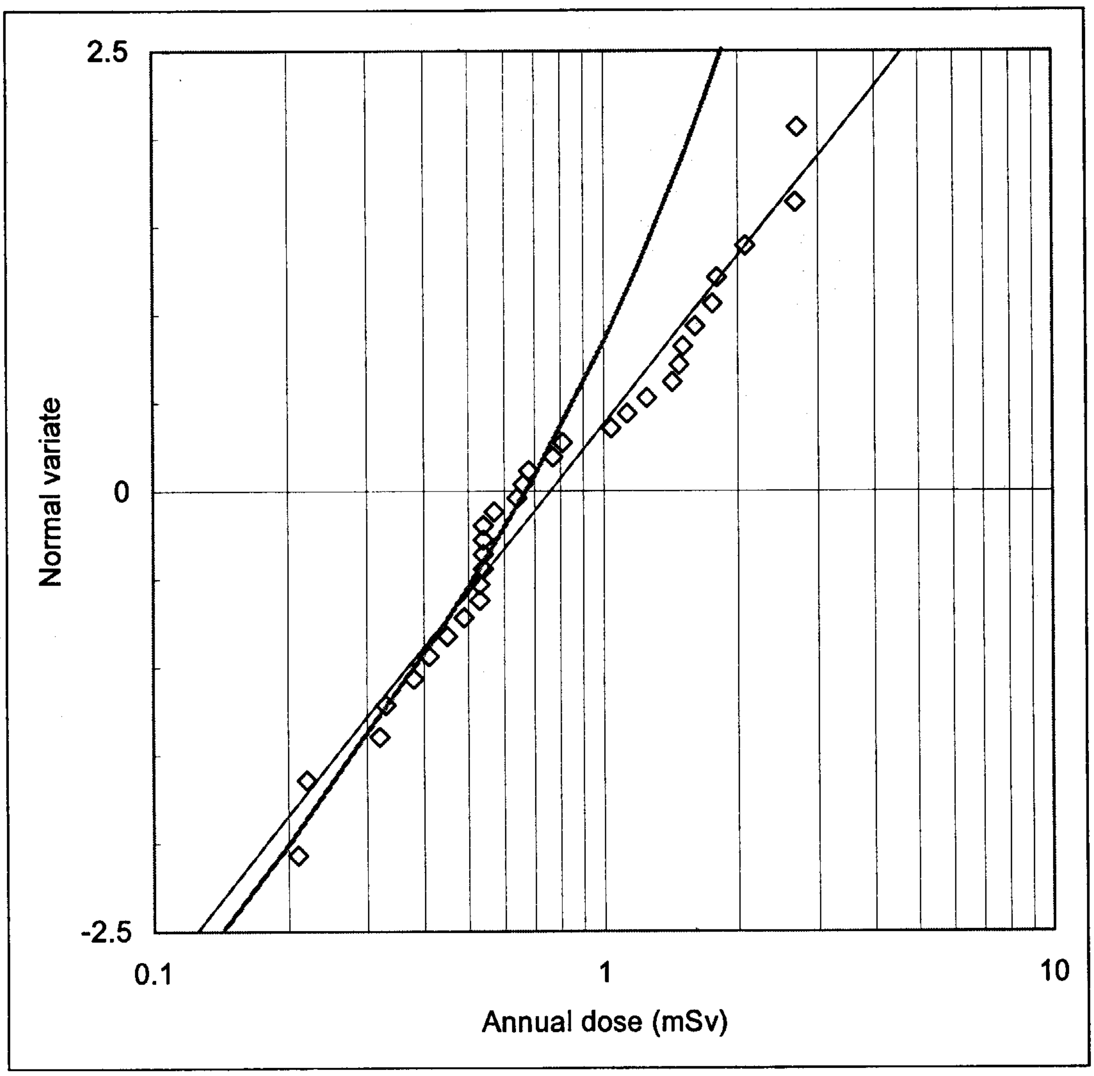

Figure 11 Log probability plot of 1994 annual doses to 32 workers at Hospital No.103. Symbol: data; Thin solid line: HLN fit to all data (ρ=0.037mSv^{-1}, the same as a LN fit); Bold solid line: HLN fit to data <1mSv where ρ=0.84mSv^{-1}.

国際単位系 (SI) と換算表

表1　SI基本単位および補助単位

量	名　称	記　号
長　さ	メートル	m
質　量	キログラム	kg
時　間	秒	s
電　流	アンペア	A
熱力学温度	ケルビン	K
物質量	モル	mol
光　度	カンデラ	cd
平面角	ラジアン	rad
立体角	ステラジアン	sr

表2　SIと併用される単位

名　称	記　号
分, 時, 日	min, h, d
度, 分, 秒	°, ′, ″
リットル	l, L
トン	t
電子ボルト	eV
原子質量単位	u

$1\ \mathrm{eV}=1.60218\times10^{-19}\mathrm{J}$

$1\ \mathrm{u}=1.66054\times10^{-27}\mathrm{kg}$

表5　SI接頭語

倍数	接頭語	記　号
10^{18}	エクサ	E
10^{15}	ペタ	P
10^{12}	テラ	T
10^{9}	ギガ	G
10^{6}	メガ	M
10^{3}	キロ	k
10^{2}	ヘクト	h
10^{1}	デカ	da
10^{-1}	デシ	d
10^{-2}	センチ	c
10^{-3}	ミリ	m
10^{-6}	マイクロ	μ
10^{-9}	ナノ	n
10^{-12}	ピコ	p
10^{-15}	フェムト	f
10^{-18}	アト	a

表3　固有の名称をもつSI組立単位

量	名　称	記号	他のSI単位による表現
周波数	ヘルツ	Hz	s^{-1}
力	ニュートン	N	$m\cdot kg/s^2$
圧力, 応力	パスカル	Pa	N/m^2
エネルギー,仕事,熱量	ジュール	J	N・m
工率, 放射束	ワット	W	J/s
電気量, 電荷	クーロン	C	A・s
電位, 電圧, 起電力	ボルト	V	W/A
静電容量	ファラド	F	C/V
電気抵抗	オーム	Ω	V/A
コンダクタンス	ジーメンス	S	A/V
磁束	ウェーバ	Wb	V・s
磁束密度	テスラ	T	Wb/m^2
インダクタンス	ヘンリー	H	Wb/A
セルシウス温度	セルシウス度	℃	
光束	ルーメン	lm	cd・sr
照度	ルクス	lx	lm/m^2
放射能	ベクレル	Bq	s^{-1}
吸収線量	グレイ	Gy	J/kg
線量等量	シーベルト	Sv	J/kg

表4　SIと共に暫定的に維持される単位

名　称	記　号
オングストローム	Å
バーン	b
バール	bar
ガル	Gal
キュリー	Ci
レントゲン	R
ラド	rad
レム	rem

$1\ \text{Å}=0.1\mathrm{nm}=10^{-10}\mathrm{m}$

$1\ \mathrm{b}=100\mathrm{fm}^2=10^{-28}\mathrm{m}^2$

$1\ \mathrm{bar}=0.1\mathrm{MPa}=10^5\mathrm{Pa}$

$1\ \mathrm{Gal}=1\mathrm{cm/s}^2=10^{-2}\mathrm{m/s}^2$

$1\ \mathrm{Ci}=3.7\times10^{10}\mathrm{Bq}$

$1\ \mathrm{R}=2.58\times10^{-4}\mathrm{C/kg}$

$1\ \mathrm{rad}=1\mathrm{cGy}=10^{-2}\mathrm{Gy}$

$1\ \mathrm{rem}=1\mathrm{cSv}=10^{-2}\mathrm{Sv}$

(注)

1. 表1－5は「国際単位系」第5版, 国際度量衡局 1985年刊行による。ただし, 1 eV および 1 u の値はCODATAの1986年推奨値によった。
2. 表4には海里, ノット, アール, ヘクタールも含まれているが日常の単位なのでここでは省略した。
3. bar は, JISでは流体の圧力を表わす場合に限り表2のカテゴリーに分類されている。
4. EC閣僚理事会指令では bar, barnおよび「血圧の単位」mmHgを表2のカテゴリーに入れている。

換　算　表

力	N($=10^5$dyn)	kgf	lbf
	1	0.101972	0.224809
	9.80665	1	2.20462
	4.44822	0.453592	1

粘　度　1 Pa・s(N・s/m²)=10 P(ポアズ)(g/(cm・s))

動粘度　$1\mathrm{m}^2/\mathrm{s}=10^4\mathrm{St}$(ストークス)($\mathrm{cm}^2/\mathrm{s}$)

圧力	MPa(=10bar)	kgf/cm²	atm	mmHg(Torr)	lbf/in²(psi)
	1	10.1972	9.86923	7.50062×10^3	145.038
	0.0980665	1	0.967841	735.559	14.2233
	0.101325	1.03323	1	760	14.6959
	1.33322×10^{-4}	1.35951×10^{-3}	1.31579×10^{-3}	1	1.93368×10^{-2}
	6.89476×10^{-3}	7.03070×10^{-2}	6.80460×10^{-2}	51.7149	1

エネルギー・仕事・熱量	J($=10^7$ erg)	kgf・m	kW・h	cal(計量法)	Btu	ft・lbf	eV
	1	0.101972	2.77778×10^{-7}	0.238889	9.47813×10^{-4}	0.737562	6.24150×10^{18}
	9.80665	1	2.72407×10^{-6}	2.34270	9.29487×10^{-3}	7.23301	6.12082×10^{19}
	3.6×10^6	3.67098×10^5	1	8.59999×10^5	3412.13	2.65522×10^6	2.24694×10^{25}
	4.18605	0.426858	1.16279×10^{-6}	1	3.96759×10^{-3}	3.08747	2.61272×10^{19}
	1055.06	107.586	2.93072×10^{-4}	252.042	1	778.172	6.58515×10^{21}
	1.35582	0.138255	3.76616×10^{-7}	0.323890	1.28506×10^{-3}	1	8.46233×10^{18}
	1.60218×10^{-19}	1.63377×10^{-20}	4.45050×10^{-26}	3.82743×10^{-20}	1.51857×10^{-22}	1.18171×10^{-19}	1

1 cal= 4.18605J (計量法)
　= 4.184J (熱化学)
　= 4.1855J (15℃)
　= 4.1868J (国際蒸気表)

仕事率　1 PS(仏馬力)
　= 75 kgf・m/s
　= 735.499W

放射能	Bq	Ci
	1	2.70270×10^{-11}
	3.7×10^{10}	1

吸収線量	Gy	rad
	1	100
	0.01	1

照射線量	C/kg	R
	1	3876
	2.58×10^{-4}	1

線量当量	Sv	rem
	1	100
	0.01	1

(86年12月26日現在)

Analysis of Occupational Exposure to Ionizing Radiation at the VAEC's Hospital No. 103 in 1994