PROGNOSIS MODELS OF HUMAN INJURY IN CHEMICAL DISASTERS

Valery V. IVANOV
Military Medical Academy
14 Ap., 54 Lensoveta St.,
St. Petersburg, 196143
Russia
Voice: 812-127-1158
Fax: 812-542-4707
E-mail (until 1 Sept. 1995): aihapeter@glas.apc.org

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ABSTRACT

Mathematical models are described for predicting the human injuries resulting from toxic chemical disasters.

In the case of chemical disasters it is very important to determine the resources (medical personal, medicines, equipment, transport) necessary for rendering of medical aid to casualties .

Advance forecasting of the number and structure of casualties helps to resolve this problem.

As a matter of fact, we may give a quantitative characteristic of damage to the health of persons and we may receive the opportunity of doing a prognosis of the appearance of a certain quantity of fatal outcomes and injuries (including the degree of severity of affect) during a disaster in a chemically dangerous object only if we are able to answer the question: what will happen with one person or with a group of persons who found themselves at a certain distance from the source of the accident and who were affected with the poison substance. It will be possible to answer this question if we are able to create models of injury to people who were situated in the area of dangerous effect of the toxic agents.

The analysis of this problem shows that the solution of this task is possible on the basis of consolidation of the law-governed nature of atmospheric diffusion of gases, the methodical approach of general theory of damage to the organism, the dependencies of the toxic action of substances, and consideration of the character of the accident and the peculiarity of toxic agent spreading in the atmosphere.

Our view is that the main position concerning this problem is utilization of the methodology of general theory of damage and, on this basis, the creation of a parametric law of toxic injury to persons.

Parametric laws (functions of injury) give the opportunity to describe the direct action of the injurious factor to persons and they show the dependence of probability of injury on the certain degree of severity from the parameters of the injurious factor.

Inhalation injury from gaseous poisonous substances is characterized by parameters determining the quantity of the approaching effect, and these parameters express the concentration of the substance in the environment and the time of its action. Let us see the dependence of toxic injury effect from the concentration of the substance and the time of exposure. Practical observations show us that if the concentration is higher and the time of its action is longer, the effect which they cause is higher also.

The relationship between the concentration of the poison, the time of its action and the effect in case of its inhalation was substantiated by the well-known German toxicologist F. Haber (1924) at the beginning of this century. This generalization is known as the rule of Haber:

$$W = C \cdot t = const \qquad (1)$$

The value W Haber named as "the quantity of the effect". The Soviet toxicologist N. Lazarev named $C \cdot t$ as "the toxic coefficient." Scientists today call it "the toxic load," but in Russian scientific literature the product $C \cdot t$ is called "toxodose".

J. Withers (1985) and other scientists assert that the relationship between concentration and time of exposure is described by the following formula:

$$W = C \cdot t^n, \text{ where usually } n<1 \qquad (2)$$

The use of the value $C \cdot t^n$ to appreciate the injurious effect of a substance is proposed by these authors in the theoretical plan and implies the use of a log-normal distribution:

$$F = \frac{1}{2\pi\sigma}\int_0^{\infty}\frac{1}{x}\exp\left[-\left(\lg x - m^*\right)^2 / 2\sigma^2\right]dx$$

where m^* is the parameter of the distribution (but, unfortunately , its value is not given).

We suggest using the toxic dose received by a person and the time during which this toxic dose was received, but not the concentration and the time of exposure, as the main parameters.

Let us consider the concept of toxic dose. We suggest using the concept of doses absorbed by the organism, which was formulated by F. Flury, but we don't use the above mentioned "pseudo-dose" - the product $C \cdot t$ and $C \cdot t^n$.

Flury suggested this formula:

$$D = V \cdot C \cdot t \qquad (3)$$

where D - the absorbed toxic dose; V - the volume of the pulmonary ventilation; C - the concentration of the substance; t - the time of exposure.

Thus, we may come to a level other than the level of concentration and conditional doses. In this case we may use the arsenal of biometrical approaches which is accumulated in radiobiology to appreciate the effect of the dose.

Unfortunately, the accessible literature doesn't give us information about the dependence of absorbed toxic dose from the time of exposure. To describe this dependence let us see the formula 2:

$$W = C \cdot t^n = const$$

Concretizing, we may write:

$$C_1 \cdot t_1^n = C_2 \cdot t_2^n$$

Let us multiply two parts of this equation on the value of the volume of pulmonary ventilation, then we present t^n as $t \cdot t^{n-1}$ and we have:

$$V \cdot C_1 \cdot t_1 \cdot t_1^{n-1} = V \cdot C_2 \cdot t_2 \cdot t_2^{n-1}$$

Let us designate the product $V \cdot C \cdot t$ as toxic dose D, so we see:

$D_1 \cdot t_1^{n-1} = D_2 \cdot t_2^{n-1}$, consequently,

$$D_1 = D_2 (t_2 / t_1)^{n-1} \quad (4)$$

Generalizing equation 4, we may assert that having determined the toxic dose once (let us call it D_0) which characterizes the effect of interest, we may find the effective toxic dose D_{eff} (which is very interesting for us and which causes this effect) for any time of exposure t:

$$D_{eff} = D_0 (t_0 / t)^{n-1} \quad (5)$$

As D_0 we may use the value of the toxic dose, which can be calculated on the basis of lethal concentration LC_{50} (let us call it "$C_{letha(0)}$, $C_{lth(0)}$"), which we can find in the literature, and the corresponding value of the time of exposition (let us call it "$t_{lth(0)}$"):

$$D_{lth(0)} = V \cdot C_{lth(0)} \cdot t_{lth(0)} \quad (6)$$

Now we have found the equation for calculating the lethal toxic dose, i.e. that index which characterizes the death of persons. Effective lethal toxic doses which were calculated with the help of real data are, for example, for chlorine - 180 mg, for ammonia - 3000 mg.

But, besides dead persons, during chemical disasters we have a great amount of victims who need medical aid.

At present we use a classification of human injury according to the degree of severity: the first group - injuries of light degree; the second group - injuries of medium degree; the third - severe injuries.

To calculate the toxic dose characterizing injury of light degree we may use the formula 3 and the data of the injurious concentration - IC_{50} (I - incapacitating) and the corresponding values of exposure:

$$D_{ligh(0)} = V \cdot C_{i(0)} \cdot t_{i(0)} \quad (7)$$

where C - the injurious concentration; t - the time of exposure.

This approach is legitimate, because we understand the injurious concentration (IC_{50}) as the value of the concentration which doesn't cause the symptoms of injury in 50% of persons, but which causes injury of light degree in the other 50% of persons who were in the contaminated area with the given concentration of toxic agent.

Then we need to determine the threshold values of toxic doses for injuries of medium and severe degrees. For this case it is necessary to get experimental data and then to use probit analysis.

But we have another way of determining the threshold values of toxic doses for these injuries, even if we have no experimental data. The construction of mathematical models of injury to the population is connected with the necessity of the formalization of ideas concerning the structure of the human organism.

Let us use models of injury to persons which are based on the formal ideas considering the organism of a man as a total combination of functional systems and considering the mechanism of damaging of these systems. These models were substantiated in research in radiobiology.

In coordination with the essence of these models the acceptable approximation of the parametric law of injury is Weibull's distribution:

$$F(z(x,y)) = 1 - exp\left[-(\beta_\gamma \cdot U_i)^\gamma\right] \quad (8)$$

where β_γ, γ - the parameters of distribution of Weibull, characterizing certain effect (level of injury); U_i - the complex fixed parameter of injury.

The parameter of injury U_i (for i - the severity of injury: light, medium, severe, death) is determined as the ratio of the value of the dose of the really acting factor of the injury to the predefined effective value of the dose of the injurious factor which characterizes this effect (level) of the injury.

The value of parameters of the distribution of Weibull for the different degrees of severity of the injury, according to the data of G. Maximov (1983), are shown in Table 1.

According to the above-mentioned analogy we suggest using the distribution of Weibull to describe the levels of injury during the inhalation influence of a poisonous substance on the population during a chemical disaster. We think that this approach is justified, because it's based on the hypotheses of the determination of injury, which tells that a certain degree of severity of injury occurs when a certain number of "systems" of an organism are injured.

So we may use values β_γ and γ , which we see in Table 1. Now we are going to determine the essence of the parameter U_i . In our case the parameter U_i is the ratio of the toxic dose received (absorbed) in this concrete case D_{abs} , to the predefined toxic dose which causes a certain effect of injury $D_{eff(i)}$:

$$U_i = \frac{D_{abs}}{D_{ef(i)}} \qquad (9)$$

Now we are faced with the necessity of determining the toxic doses characterizing the medium and severe degrees of injury. We may determine the threshold values of the toxic doses, based on the hypothesis of the determination of injuries and on the consideration of the interval between the injurious and the lethal toxic doses, because these intervals may differ substantially if the toxic substances are different, according to this formula:

$$D_{ef(i)} = D_{light(0)} + \left(D_{lth(0)} - D_{light(0)}\right) \cdot r_i \qquad (10)$$

where $D_{ef(i)}$ - threshold values of the toxic dose for given outcome; $D_{light(0)}$ - toxic dose characterizing injury of light degree and which is determined according to formula 7; $D_{lth(0)}$ - lethal toxic dose, which is determined by formula 6; r_i - the injury coefficient.

We suggest using the following values of r_i — light degree of injury - $r = 0$; medium degree - $r = 0{,}3$; severe degree - $r = 0{,}6$; lethal dose - $r = 1{,}0$.

Thus, all the characteristics of the threshold values (fixed levels) of toxic injury during the action of poisonous substance are determined.

At last we have :

$$U_i = \frac{D_{abs}}{D_{ef(i)} \cdot (t_0 / t)^{n-1}} \qquad (11)$$

where t - time of exposure of the toxic substance.

The analysis of the given dependence for determining the complex fixed parameter of injury shows the necessity of more detailed study of the value D_{abs}. That's why the mechanism of determining this value according to dependence 3 suggested above (in general terms) must be concretized and then developed for receiving the possibility to calculate D_{abs} practically in reference to the zone of a chemical accident.

For this case we suggest using the following scheme of population injury ("absorption of toxic substance") to accidents involving hazardous substances, based on the data of a number of scientists.

As a result of destroying a tank a primary gas cloud is formed, and a big quantity of the toxic substance from the tank may go with this cloud. Simultaneously, the evaporation of spilled agent begins, and a secondary cloud is formed. Investigations show that the primary cloud as a rule has the higher concentration of the substance, but its influence on a "spot" object is limited in time (no more than 15-20 minutes).

The concentration in the secondary cloud is lower, but the time of its action may last from some hours to 24 hours and even more, depending on the substance and its quantity.

Thus, we may look at the following scheme of the toxic substance affecting the population during chemical disasters.

Conventionally we may divide the zone of toxic injury of the population into three areas. The primary and secondary clouds influence persons in the area S_1 . In the area S_2 only the secondary cloud influences the population, and only the primary cloud influences persons in the area S_3.

We have two variants of toxic injury objects in every area: the first has an area which is much less than the area of the injury zone (we shall call it a "spot" object) and the second has an area comparable to the area of the injury zone (we shall call it an "area" object).

Now we are going to determine the probability of toxic injury for a "spot" object. For this case we take the point M with the coordinates x and y as the prototype of the "spot" object. We are looking at the process of toxic injury at the point $M(x,y)$ accordingly in the areas S_1 , S_2 and S_3 .

During an elementary time interval dt at the point $M(x,y)$ a person will receive the following toxic dose:

$$dD = V \cdot q(t,x,y,O)dt$$

where V - the volume of pulmonary ventilation; $q(t,x,y,O)$ - the concentration at point $M(x,y)$ at the moment T.

The general absorbed toxic dose during the passing of the primary cloud over the point $M(x,y)$ is:

$$D_3 = V \cdot \int_{t_1}^{t_2} q(t,x,y,O)dt \qquad (12)$$

where t_1 -the time when the front edge of the cloud reaches the point $M(x,y)$; t_2 -the time when the back edge of the cloud reaches the point $M(x,y)$.

Now we determine the complex fixed parameter of toxic injury and the probability of injury to the population, based on dependencies 8 and 11 :

$$U_3 = \frac{D_3}{D_{ef(i)} \cdot \left(\frac{t_0}{t_2 - t_1}\right)^{n-1}}$$

$$F(U_{3i}) = 1 - exp\left[-(b_i \cdot U_{3i})^{\gamma_i}\right] \qquad (13)$$

So, considering the process of evaporation as a stationary process, the toxic dose at the point $M(x,y)$ from the influence of the secondary cloud in the area S_2 is:

$$D_2 = V \cdot q(x,y,O,) \cdot t \qquad (14)$$

where t - the time of evaporation of the poisonous substance or the time of staying of persons in the injury zone.

Correspondingly, the complex parameter of toxic injury and the probability of the injury are:

$$U_2 = \frac{D_2}{D_{ef(i)} \cdot \left(\frac{t_0}{t}\right)^{n-1}}$$

$$F(U_{2i}) = 1 - exp\left[-(b_i \cdot U_{2i})^{\gamma_i}\right] \qquad (15)$$

For calculation of the complex parameter of injury in the area S_1 we must take into consideration the imposition of injury action by both clouds, primary and secondary. It is suggested that ejection of the toxic substance at the moment of destruction of a tank (primary cloud generation) and its further spreading at the expense of the spilled agent (the secondary cloud) take place practically simultaneously. The probability of toxic injury from the primary and secondary clouds is described by the above-mentioned dependencies 13 and 15.

Looking at these dependencies, we may come to the conclusion that the second term in the right part of these equalities determines the probability of non-injury of the population. Thus, the probability that the population will not be injured during passing of the primary and secondary clouds is determined as:

$$P = \exp\left[-(b_i \cdot U_{1i})^{\gamma_i}\right] \cdot \exp\left[-(b_i \cdot U_{2i})^{\gamma_i}\right]$$
$$= \exp\left[-(b_i \cdot U_{1i})^{\gamma_i} - (b_i \cdot U_{2i})^{\gamma_i}\right]$$

Consequently, the probability of injury during the action of both clouds is determined as the dependence:

$$F(U_{1i}, U_{2i}) = 1 - exp\left[-(b_i \cdot U_{1i})^{\gamma_i} - (b_i \cdot U_{2i})^{\gamma_i}\right]$$

Now we will look at methodical approaches for determining the losses in population if the region of allocation of the people is commensurable with the area of the injury or if the region is larger than the injury area, i.e. if we speak about the "area" object.

Let us define an elementary area with dimensions $\Delta x \Delta y$ in the injury zone. The losses in this area are:

$$\Delta N_n = \rho dx dy - \rho \, exp\left[-(b_i \cdot U_i)^{\gamma_i}\right] dx dy$$

where ρ - the density of the population.

If we are going to add up all the losses in all the elementary areas inside the injury zone, increasing the number of the areas up to infinity and under the condition that their dimensions try to attain zero, a variable characterizing the general losses is expressed by the integral:

$$\Delta N_n = \rho \iint_S dx dy - \rho \iint_S exp\left[-(b_i \cdot U_i)^{\gamma_i}\right] dx dy$$

Taking into consideration that:

$$U_i(x,y) = \frac{D(x,y)}{D_{ef(i)} \cdot \left(\frac{t_0}{t}\right)^{n-1}}; \quad \rho \iint_S dx dy = N$$

We have :

$$N_n = N - \rho \iint_S exp\left\{-\left[b_i \cdot \frac{D(x,y)}{D_{ef(i)} \cdot \left(\frac{t_0}{t}\right)^{n-1}}\right]^{\gamma_i}\right\} dx dy$$

where N - the number of persons in the injury zone.

To calculate the integral we are going to use the theorem about the integral calculus mean value. Thus, the losses may be determined according to the dependence:

$$N_n = N - \rho S \exp\left\{-\left[b_i \cdot \frac{\overline{D_S}}{D_{ef(i)} \cdot \left(\frac{t_0}{t}\right)^{n-1}}\right]^{\gamma_i}\right\}$$

where $\overline{D_S}$ - the mean integral toxic dose in the area S.

The mean integral toxic dose in the area S may be determined by integration, using the dependencies:

a) for the primary cloud:

$$\overline{D_S} = \frac{1}{S}\iint_S D(x,y)\mathrm{d}x\mathrm{d}y$$

where $D(x,y)$ - the toxic dose at the point $M(x,y)$, which is determined according to dependence 12;

b) for the secondary cloud:

$$\overline{D_S} = \frac{V \cdot t}{S}\iint_S q(x, y, O)\, \mathrm{d}x\mathrm{d}y$$

Table 1. The value of the parameters of distribution of Weibull

Parameters	Injury severity degree			
	light	medium	severe	death
γ	2.5	3.8	4.4	5.3
β_γ	0.889	0.904	0.912	0.92

In order to determine the effective dose in the case of the primary cloud we must first determine the mean integral time of exposure.

Now we may use the dependence:

$$\overline{t}_S = \frac{1}{S}\iint_S t(x,y)\mathrm{d}x\mathrm{d}y$$

Thus, to determine losses in the area, we use the same dependencies as for the "spot" object, but we substitute values of the mean integral toxic dose $\overline{D_S}$ and the mean integral time of exposure $\overline{t}_S$ (for the primary cloud) instead of the toxic dose and the time of exposure at the point $M(x,y)$.

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