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PARAMETERS OF THE MOVEMENT OF HUMAN FLOWS CONSISTING OF PREGNANT PATIENTS OF MATERNITY HOSPITALS

The problem of ensuring safety during the fire evacuation of pregnant patients of maternity hospitals is considered. Quantitative data are obtained on the process of their evacuation. The handling of the experimental video material was carried out. The obtained empirical data are processed using the methods of mathematical statistics and the theory of human flows. The parameters describing the relationships between the emotional state, pace and density of the human flow are calculated. It is concluded that the obtained data array will reduce the risk of death of pregnant women in case of a fire situation due to an increase in the accuracy of educated estimates associated with the ensuring of their safety.

Keywords: evacuation process; pregnant women; human flow parameters; people with limited mobility; maternity hospitals.

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Introduction

Reducing the risk of maternal and infant death, including in a fire situation, is one of the strategic objectives of the state policy.

According to the Ministry of Health of the Russian Federation, about 240 institutions in our country are engaged in the organization of medical and preventive measures aimed at protecting women's health during pregnancy, childbirth and the postpartum period [1, 2].

Buildings of maternity hospitals belong to the functional fire hazard class F1.1. Orphan asylums and rest homes belong to the same class of buildings. The studies [3–7] have shown that evacuation processes for children, elderly people, people with disabilities are significantly different from each other. Common requirements for evacuation routes and exits [8] for this entire group do not allow ensuring the safety of people in the event of a fire situation.

Currently, four mobility groups have been identified [9], but pregnant women have not been assigned to any of them [9] and the parameters of their movement have not been determined. No specific features of their evacuation process during a fire situation have been identified.

Based on experimental studies conducted in municipal hospitals [10], a classification of people with disabilities was developed depending on the characteristics of their movement, and the parameters of the movement of each of these groups are mathematically described. The number of patients belonging to different mobility groups in hospital departments has been determined. In particular, patients with no mobility amounted to 10 % in the Department of Gynecology (including the Labor Department), and the ones with restricted mobility amounted to 7 %.

The article of the team of foreign scientists [11], dealing with evacuation issues, analyzed a number of works published since the middle of the twentieth century. Due to the analysis of studies conducted in different countries, the following factors have been shown to influence the pace of human flows: the age of the evacuees, their physical dimensions (overweight and obesity), disability [12–14].

The authors believe that the current norms based on studies of homogeneous human flows conducted more than 50 years ago cannot fully ensure the safety of people belonging to groups with different mobility level. The reason for the loss of confidence in the data is that every year the proportion of people with different health restrictions increases.

It is established [15] that pregnancy, especially in the second half of the term, has a significant effect on the motion activity of a woman. The child begins to grow rapidly, therefore, the body weight increases, as it is normally should not increase by more than 10–12 kg (but it can increase much more considerable). At the same time, the area of the horizontal projection also grows. The female body needs to compensate for its rapidly changing biomechanical parameters. For example, a pregnant woman has an increasing axial load on the joints of the limbs because of the weight redistribution. It is noted in the work [16] that almost all women are diagnosed with complaints of impaired functions of the supporting-motor apparatus during pregnancy. More than 80 % of women complain of pain in the legs, mainly in the area of the feet. These features can influence the movement of patients in maternity hospital when they are evacuated in the event of a fire situation. Thus, it is necessary to determine the quantitative measure of such influence on the organism of a pregnant patient, and the studies were conducted in various maternity hospitals in the period from 2015 to 2018 for achieving this purpose.

In order to achieve this goal, the following tasks were set:

- conducting research in perinatal centers and maternity homes of the country in two stages: 1) field observations to determine the paces of free movement of pregnant women in different parts of the route; 2) experimental studies aimed to determine the dependence of the pace of movement of pregnant women on the density of the human flow in different route sections;
- processing of the obtained empirical data using the methods of mathematical statistics and the theory of human flows in order to determine the dependence of the pace of pregnant women on the density of the human flow and on their emotional state when moving along different type of routes.

Experiment

Method for obtaining empirical data for determining the pace of free movement

Throughout 2015–2016, field observations were conducted aimed to determine the pace of free movement of patients in maternity hospitals in one of the largest perinatal centers in Moscow. A total of about 700 measurements were made for the group of women in question, along the horizontal type of the route, downstairs, up the stairs. Observations were conducted in the morning (from 8:00 to 11:00 a. m.) and in the evening (from 4:00 to 7:00 p. m.). It was during these periods that the patients either went to see a doctor, or returned home in the greatest hurry. It was possible to measure the pace of movement of about 40 women for 3 hours of observation. Women for evaluation were selected in the third trimester (the 7th–9th months) of pregnancy (Figure 1).

The measurement of pace of free movement was carried out as follows:

- the sections of the route convenient for observation were previously selected and their length and width were measured;
- the observer took a place at the end of the observed section along the route;

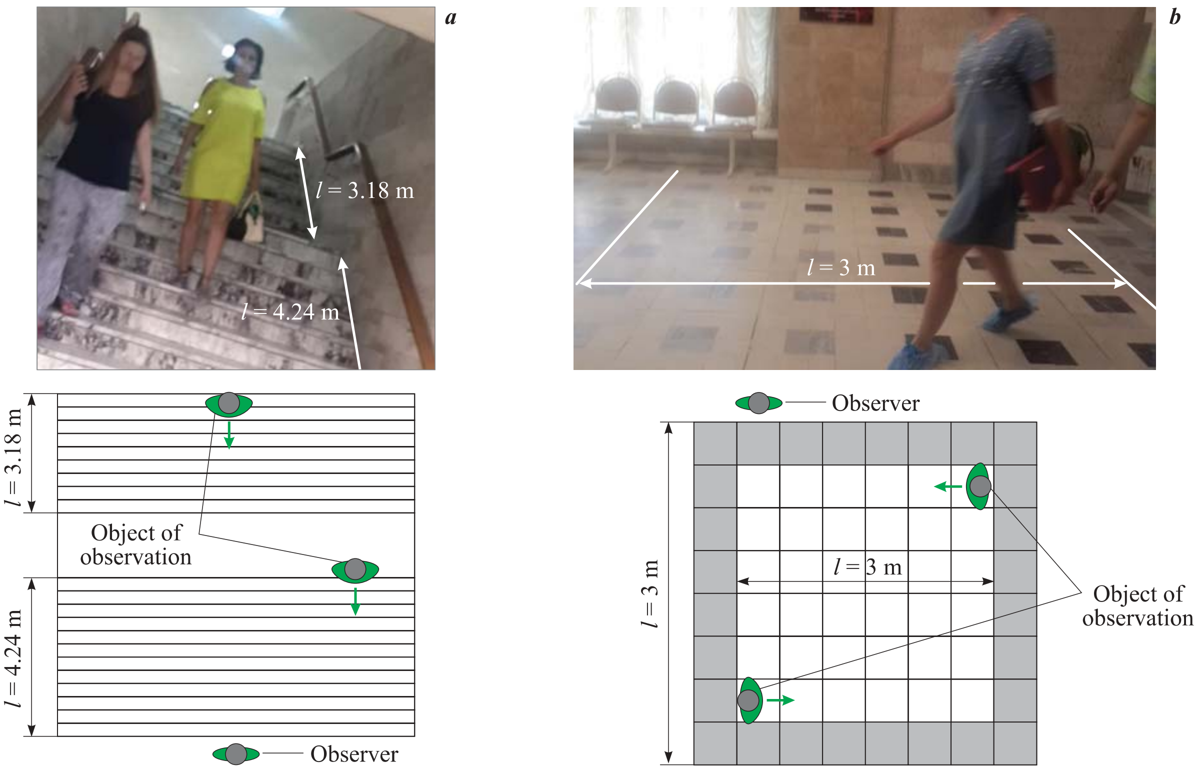

Fig. 1. The routes with the length *l* the record of movement paces of patients of the perinatal center down the stairs (*a*) and along the horizontal section of the route (*b*)

- the elapsed time needed for covering the selected distance was measured with the help of a stopwatch and then the pace of movement was calculated.

The method of obtaining empirical data for determining the paces of movement of patients in different density ranges

The main functional contingent of maternity hospital can be differentiated as follows:

- medical staff;
- service staff;
- visitors;
- patients and newborns.

If we consider the possibility to evacuate patients in an institution in case of a fire situation, it turned out that the following groups of patients would not be able to leave the building without the help of the medical staff:

- women in the antenatal period who have medical contraindications;
- women in the second and third stages of labor; puerperas after Caesarean operation, as well as after normal delivery (before the expiration of a certain period of time for the restoration of forces — the cessation of the action of medications).

In Figure 2, one can see the ways to move patients of institutions with mobility restrictions.

At the same time, women in the antenatal period, who do not have medical contraindications, maternity patients in the first stage of labor, puerperas after Caesarean operation (after 6–12 hours) and after normal delivery (after 2–6 hours) are able to leave the building on their own (Figure 3).

Fig. 2. The ways of moving patients of maternity hospitals with mobility restrictions: *a* — on a gurney; *b* — in a wheelchair

Experimental studies of the movement of human flows consisting of patients from maternity hospitals were conducted for the subsequent determination of the parameters of their movement in the departments of pathology and gynecology.

Carrying out evacuation without warning of medical personnel, as well as under condition, when patients are not prepared for it, is extremely problematic (and it is virtually impossible) due to the vulnerable psycho-physiological state of the patients during this process in the maternity hospitals. That is why all the staff and patients of the hospital were warned in advance and prepared for the forthcoming experiment.

The experimental studies were carried out in the following sequence:

1) the departments, where the evacuation was about to be organized, were chosen in advance, the medical staff were talked on the issue;

2) the video recording devices were placed with a viewing angle of at least 120° on the sections (corridor, doorway, staircase) of the movement of the human flow;

3) a scale grid (with a cell size of 1×1 m) was installed with the help of which the geometrical dimensions of the route section were recorded.

At the end of the preparatory activities, video recording equipment (DVRs) was activated. Then the process of simultaneous evacuation began of those pregnant patients who had no medical contraindications.

The next stage of the study was the analysis of video materials. Screen Marker was used to apply the contours of the scale grid to the computer screen from the captured control frame. At the next stage, a frame-by-frame preview of the video was conducted (see Figures 2 and 3).

After the patient enters the cell area of the scale grid Δl = 1 m, the number of frames was recorded until she

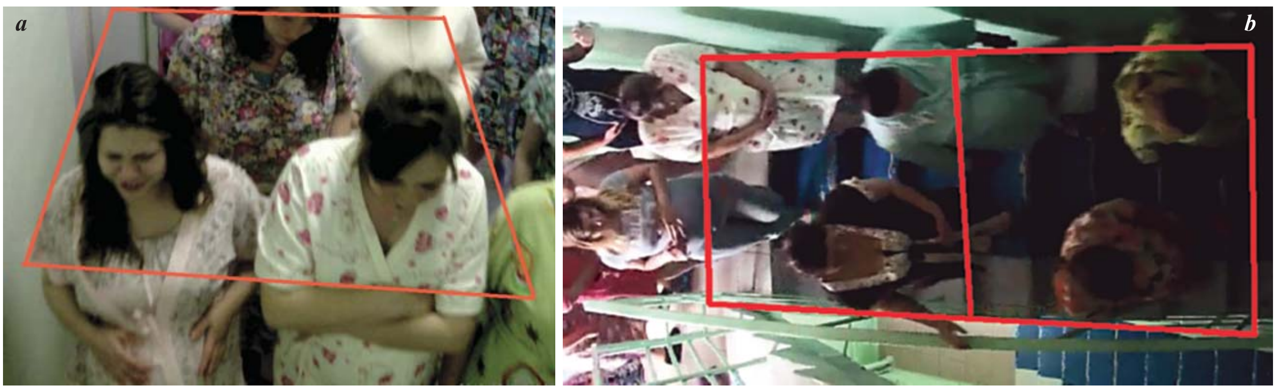

Fig. 3. The process of movement of patients of maternity hospitals, who are capable to evacuate independently: *a* — along the horizontal type of the route; *b* — down the stairs

left the observed route section. The flow density was determined at the route section D (persons/m^2).

With this mode set, 1 second of shooting consisted of 30 changeable frames, which made it possible to set the time with greater accuracy Δt (minutes) of passing by the patient of the cell zone of the scale grid — the stepping into the observed route section, as well as its leaving.

Then the pace was calculated V_{mov} (m/min) and human flow intensity q_D (persons/(m · min)):

$$V_D = \Delta l / \Delta t; \quad (1)$$

$$q_D = V_D D. \quad (2)$$

Statistical processing of empirical data

The data obtained during the experiments were subject to statistical processing, which was carried out using Microsoft Excel and SPSS Software, Statistical Package for the Social Sciences.

The testing of the empirical sample for compliance with the normal distribution is the most important stage of scientific research. The choice of the method of statistical data analysis directly depends [17–19] on the results of the hypothesis testing for normality of a sample population distribution.

In the course of experimental studies, depending on the number of patients in the department and their medical records, there was formed a human flow in the corridor, which consisted maximum of 16 patients and had a density of no more than 4 persons/m^2. Thus, small samples were formed in each density range. In order to carry out the hypothesis testing for normality of the statistical law, the Shapiro–Wilk criterion was applied in this case (W), as the number of observations was less than 50 (for a larger number of observations the criterion becomes excessively rough).

When carrying out the field observations, more than 50 samples could be formed to determine the paces of free movement of patients, which made it possible to apply the Kolmogorov–Smirnov test to carry out the hypothesis testing for normality of sample populations distribution.

At the next stage, independent samples were compared from different series of experiments with respect to homogeneity using the parametric criterion — Student's t-distribution. The possibility of its erroneous application is excluded by taking into account the presence or absence of homogeneity of the variances in the studied samples using F-test:

$$F = S_1^2 / S_2^2, \quad (3)$$

where S_1^2 – the variance of a smaller sample;
S_2^2 — the variance of a larger sample.

Table 1. The values of F and t tests for comparing independent samples from different series of experiments on homogeneity for their unification when moving along the horizontal type of the route

Sample number	Density D, persons/m^2			
	1–2		2–3	
	F	t	F	t
1, 2	1.002	2.2	1.139	1.3

In case of different number of observations and variance values, Student's t-distribution is calculated as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{S_1^2/n_1} + \sqrt{S_2^2/n_2}}, \quad (4)$$

where $\bar{X}_1$, $\bar{X}_2$ — mean values of compared samples;
n_1, n_2 — the number of compared samples.

The totality of statistical data was formed from the samples, which homogeneity was confirmed, in order to construct a dependence between the main parameters of the movement.

For the two samples studied, the following values were obtained F-test and Student's t-distribution (Table 1).

The sufficient number of pace values was determined so that they reflect the main characteristics of the general population with the least probability of error (3–5 %), as a small number of these pace values in the samples could cause erroneous results. To determine

Table 2. The pace of movement of pregnant women in maternity hospitals along horizontal routes and stairs

Density range D, persons/m^2	Number of observations n	Mathematical expectation of pace $m(V)$, m/min	Standard deviation $\sigma(V)$, m/min	95 % confidence range, m/min	
				Lower limit	Upper limit
Horizontal route					
0–1	380	55.2	10.2	54.2	56.2
1–2	55	46.3	6.9	44.4	48.2
2–3	38	37.0	4.9	35.4	38.6
3–4	10	26.6	1.5	25.6	27.7
Down the stairs					
0–1	156	34.5	6.9	33.4	35.6
1–2	44	32.7	3.4	31.7	33.8
2–3	29	27.0	2.2	26.2	27.9
3–4	4	20.5	0.4	19.8	21.1
Up the stairs					
0–1	155	31.3	5.6	30.4	32.1
1–2	29	29.6	2.5	28.7	30.6
2–3	61	22.7	2.3	22.1	23.3
3–4	17	18.8	1.5	18.0	19.6

the necessary number of experimental data, a calculation was made according to a formula

$$n = (xv)^2/\varepsilon^2, \qquad (5)$$

where x — confidence coefficient $P(0.96)$; $x = 2.06$;

v — variability value, %; $v = (\sigma/\bar{X}) \cdot 100$ %;

ε — accuracy of research; $\varepsilon = 3 \div 5$ %.

For example, the required number of paces of free movement for the horizontal type of route was calculated as follows:

$$n = (2.06 \cdot 18.48)^2/4^2 = 90.58 \approx 91;$$

$$v = (10.2/55.2) \cdot 100 = 18.48 \text{ \%}.$$

Based on the results of calculations, the necessary number of measurements is established, which was compared with the actual one.

The obtained paces of movement of pregnant patients of maternity hospitals in various density ranges for various types of the routes are shown in Table 2.

Determination of dependence of pace of free movement of pregnant patients on their emotional state

The next stage of the study was the scaling of emotional states to determine the movement categories, as well as the corresponding paces [20]. For this purpose, a technique was used developed in the 80s of the last century (and repeatedly tested at a later stage) by prof. V. V. Kholshchevnikov [21], which is based on the theory of distribution of the extreme members of the sample on the basis of the double exponential distribution.

Sampling of maximum values V_n in each of the sample populations in the density range $D = 0 \div 1$ persons/m^2 was carried out under the condition $V_n > \bar{V} + 2\sigma(V)$ (where $\bar{V}$ — mathematical expectation of paces in the sample, m/min; $\sigma(V)$ — standard deviation, m/min).

It was further determined (Table 3):

- empirical probability of extreme members of the sample $P(V_n)$:

$$P(V_n) = \frac{n}{\sum n + 1}; \qquad (6)$$

- probability of the extreme members of a sample based on the double exponential distribution:

$$P(V_n) = e^{-e^{-x_n}}; \qquad (7)$$

- normalized deviation from the mode of the distribution density curve X_n with allowance for empirical values $P(V_n)$:

$$X_n = -\ln[-\lg P(V_n)] - 0.83405. \qquad (8)$$

In the sequel, a graph of the empirical distribution of the maximum values of the paces of people' movement and the probabilities corresponding thereto was constructed (Figure 4), which was approximated by a linear dependence of the type

Table 3. Data for determining the probabilities of the maximum paces of movement of pregnant women along different types of routes

n	V_n	$P(V_n)$	X_n
Horizontal type of the route			
1	76.60	0.125	–0.73212
2	76.60	0.25	–0.32665
3	77.59	0.375	0.019339
4	80.72	0.5	0.366495
5	80.72	0.625	0.754997
6	82.19	0.75	1.245882
7	95.74	0.875	2.013401
Up the stairs			
1	50.88	0.25	–0.32665
2	51.02	0.5	0.366495
3	60.19	0.75	1.245882
Down the stairs			
1	44.68384	0.25	–0.32665
2	46.99507	0.5	0.366495
3	49.55844	0.75	1.245882

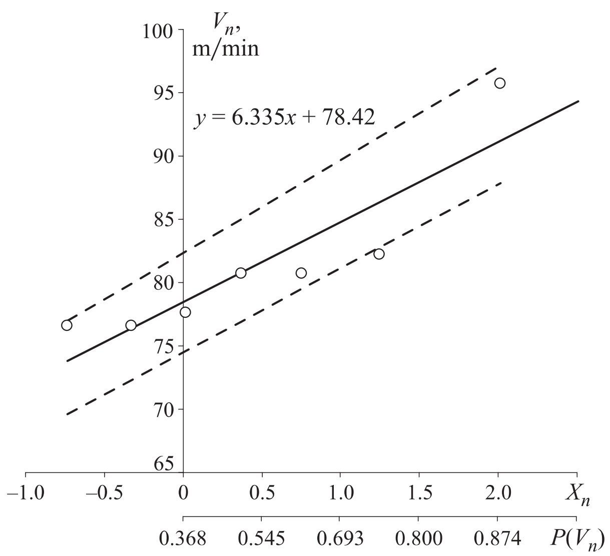

Fig. 4. The building of a theoretical model for the distribution of the maximum values of the paces of movement of pregnant women in maternity hospitals along the horizontal route section: ○ — the values of the maximum members of the sample; – – – — area boundaries at 5 % significance level

$$V_n = \alpha X_n + g, \qquad (9)$$

where α, g — approximation coefficients.

Then we obtain:

- for horizontal route:

$$V_n = 6.335X_n + 78.42; \qquad (10)$$

- for down the stairs:

$$V_n = 6.118X_n + 51.40; \qquad (11)$$

- for up the stairs:

$$V_n = 3.091X_n + 45.75. \quad (12)$$

Taking into account the fact that the normalized deviation from the mode of the distribution density curve X_n with allowance for empirical values $P(V_n)$ is determined by the formula

$$X_n = -\ln[-\lg P(V_n)] - 0.83405, \quad (13)$$

formula (9) takes the form:

$$V_n = a(-\ln[-\lg P(V_n)] - 0.83405) + g. \quad (14)$$

Then, when moving along the considered types of routes, we obtain the formula:

- for horizontal route:

$$V_n = 6.335(-\ln[-\lg P(V_n)] - 0.83405) + 78.42; \quad (15)$$

- down the stairs:

$$V_n = 6.118(-\ln[-\lg P(V_n)] - 0.83405) + 51.40; \quad (16)$$

- up the stairs:

$$V_n = 3.091(-\ln[-\lg P(V_n)] - 0.83405) + 45.75. \quad (17)$$

The law on the impossibility of exceeding the maximum sample member of its doubled mean value allows to jump from the maximum values to the average ones:

$$V_0^e = 0.5(g - a \cdot 0.83405) - 0.5a\ln[-\lg P(V_n)]. \quad (18)$$

where V_0^e — pace of free movement of a person depending on the emotional state, m/min.

Then we obtain:

- for horizontal route:

$$V_0^e = 0.5(78.42 - 6.335 \cdot 0{,}83405) - 0.5 \cdot 6.335\ln[-\lg P(V_n)]; \quad (19)$$

- for down the stairs:

$$V_0^e = 0.5(51.40 - 6.118 \cdot 0.83405) - 0.5 \cdot 6.118\ln[-\lg P(V_n)]; \quad (20)$$

- for up the stairs:

$$V_0^e = 0.5(45.75 - 3.091 \cdot 0.83405) - 0.5 \cdot 3.091\ln[-\lg P(V_n)]. \quad (21)$$

Based on the generated array of values V_n, dependences were obtained relating the paces of free movement V_0 (m/min) for different types of routes and the emotional state of pregnant women E [20]:

- for horizontal route:

$$V_0^e = 36.57 - 3.17\ln[-\lg(0.1 + 1.284E)]; \quad (22)$$

- down the stairs:

$$V_0^e = 23.15 - 3.06\ln[-\lg(0.1 + 1.284E)]; \quad (23)$$

- up the stairs:

$$V_0^e = 21.59 - 1.55\ln[-\lg(0.1 - 1.284E)]. \quad (24)$$

Analysis of the dependence shows that its character changes markedly as the E value, taking into account the degree of psychological tension of the situation, increases. In this regard, it is necessary to solve the problem of the reasoned justification of the E values for the correlation of the paces of movement with its categories [22]. For this purpose, each of the dependencies for different route sections (22)–(24) was divided into segments, each of which was described by a linear, then quadratic and then by an exponential relationship (Figure 5). The natural criterion for selecting points at which the function changes its characteristics and, consequently, the movement category changes), is the minimization of the deviation of the selected approximation from the studied curve. In other words, the sought-for points are the points at which the correlation coefficient is below 0.99 for the given problem. Solving the problem in this way, we determined the numerical characteristics of the pace of free movement for various movement categories of patients of the perinatal center along different route sections (Table 4).

A further objective of the study was to determine the dependence of the pace of movement of the human flow consisting of pregnant patients on its density range.

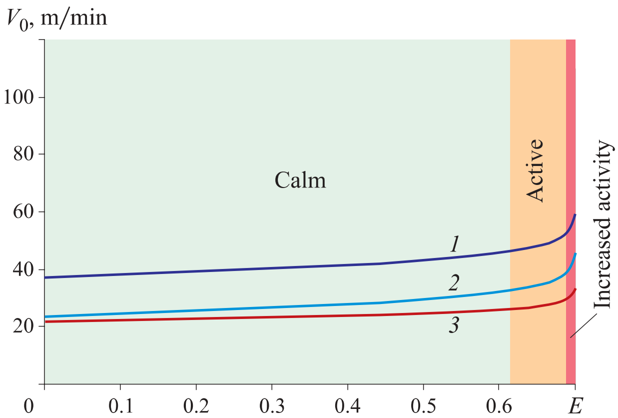

Fig. 5. Dependence of the pace of free movement of patients in maternity hospitals on the degree of psychological tension of the situation when moving along different types of route: *1* — along the horizontal route; *2* — down the stairs; *3* — up the stairs

Table 4. The paces of free movement of pregnant women in maternity hospitals along different types of route in appropriate movement categories

Movement category	Pace of free movement V_0, m/min, along the horizontal		
	route	down the stairs	up the stairs
Comfortable	Less than 36.6	Less than 23.1	Less than 21.6
Calm	36.6–45.5	23.1–31.7	21.6–25.9
Active	45.5–52.6	31.7–38.7	25.9–29.4
Increased activity	52.6–60.2	38.7–46.0	29.4–33.1

The problem of determining the relationship between the parameters of human flows was studied by many scientists, both in Russia and abroad. There were some observations made in the United States, Germany, Japan in which the dependence of the pace on the density range of the human flow was determined [23—27], but the authors of these studies did not provide a theoretical approximation of the empirical data. Prof. V. V. Kholshchevnikov established in work [21] a regression dependence that relates the pace of the human flow V and its density rage D based on extensive experimental material, and this study was recognized as an international scientific discovery in the field of social psychology [28].

When the density value threshold is exceeded D_0 the pace of free movement V_0 begins to decrease in each density range by an amount $\Delta V = V_0 - V_{Dj}$. Then the relative decrease in pace R_{exp} amouts to:

$$R_{exp} = V_0 - V_{Dj}/V_0, \quad (25)$$

where V_{Dj} — the pace in the density range for which the degree of influence of the external factor on the human sensory system is determined, m/min.

The dependence build on the basis of empirical data is approximated by the theoretical function (Fig. 6):

$$R_{Dj} = a \ln (D_j/D_0), \quad (26)$$

where a — coefficient determining the influence degree of the flow density along the j type of route on the pace of movement;

D_j — the density of the human flow in which the value is determined R_{Dj}.

Thus, the form of the general dependence [21] was confirmed on the basis of theoretical generalization of the experimental data and the characteristics reflecting the influence of density on the pace of the human flow, consisting of pregnant patients in maternity hospitals (Fig. 7), were determined.

The human flows forming at the doorway were studied as follows. The pace of movement V_D of human flow with the established density D (persons/m^2), approaching to the border of the doorway, was determined:

$$V_D = l/t. \quad (27)$$

Then the intensity of movement was calculated (Table 5):

$$q_D = V_D D. \quad (28)$$

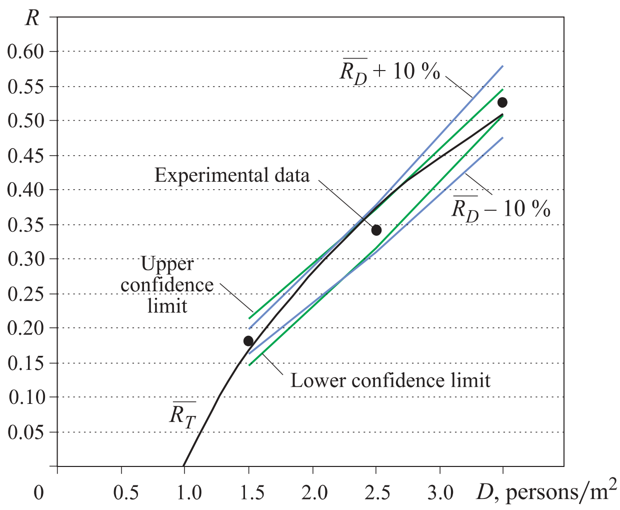

Fig. 6. Approximation of dependence $R = f(D)$ for human flow consisting of pregnant patients in maternity hospitals when moving along the horizontal route

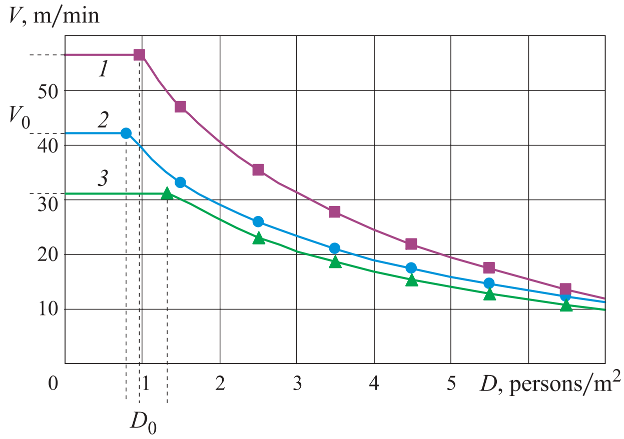

Fig. 7. Dependence of the pace of movement of pregnant women in maternity hospitals on the density of different types of route: *1* — horizontal route; *2* — down the stairs; *3* — up the stairs

Table 5. The mean values of the intensity of movement of pregnant patients through the doorway in maternity institutions

Density range D, persons/m^2	Number of observations n	Intencity q, persons/(m·min)
1–2	36	84
2–3	23	90
3–4	9	96

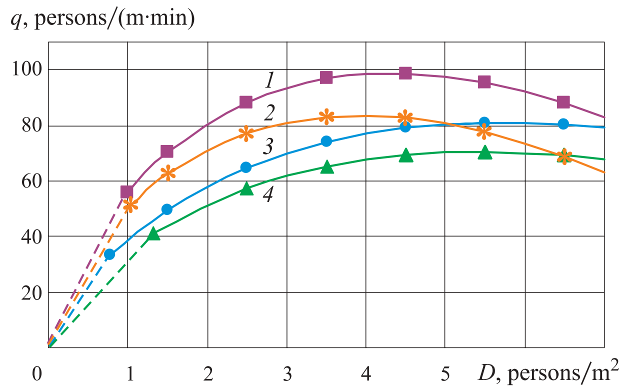

Fig. 8. Dependence of the intensity of movement of pregnant women in maternity hospitals on the density of different types of route: *1* — horizontal route; *2* — doorway; *3* — down the stairs; *4* — up the stairs

It is characteristic that as the human flow density increases, the intensity of movement increases and then decreases after reaching its maximum value (Fig. 8).

Conclusions

According to the existing norms, the main functional contingent of maternity hospitals refers to the groups of population with restricted mobility. However, pregnant women were not assigned to any of the existing groups. The parameters of their movement were not established, that made it impossible to ensure safety of pregnant women in maternity hospitals in case of a fire situation.

Some field observations and experimental studies of the movement of human flows consisting of pregnant women were carried out in the maternity homes and perinatal centers of the country. Within the framework of these studies, the paces of movement of pregnant women were measured in different density ranges along different routes (horizontal route, doorway, down the stairs, up the stairs).

As a result of statistical processing and theoretical generalization of the experimental data, the paces of free movement of pregnant women at various levels of psychological tension of the situation were determined, as well as the dependence of the paces of the human flow on its density.

The obtained data array will reduce the risk of death of pregnant women in case of fire situation due to an increase in the accuracy of educated estimates associated with the ensuring of their safety.

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