D.A. Samoshin, R.N. Istratov. "The parameters of pedestrian flows in hospital during fire evacuation". Proceedings of 13th International Conference "Interflam 2013". Royal Holloway College, University of London. UK, 2013, pp. 1003-1012

THE PARAMETERS OF PEDESTRIAN FLOWS IN HOSPITAL DURING FIRE EVACUATION

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ABSTRACT

In case of fire emergence hospital occupants will move on the same route during the same time to available exits creating a flow. These flows consists of people with various diseases and consequently with various mobile characteristics. A wide range of experiments were undertaken during 2011-2012 in Moscow city hospitals and it became possible to develop a classification of disabled people and mathematically describe the parameters of each of these groups movement. Based on analysis of videotapes some individual features of disabled people movement is described. An analytical relations to calculate transportation time for patients on the stretchers is also discussed.

THE PROBLEMS OF HOSPITAL FIRE EVACUATION

Hospitals have to be considered as places of mass stay of people with malfunctions of different systems in their bodies limiting their abilities not only in normal (safe) conditions, but also in case of a threat to their lives and health, e.g. in the event of fire. First attempts to regulate fire safety in Russian hospitals were made in the 30th of the last century [1, 2]. Issues of safe evacuation of people with physical limitations from hospitals and other facilities is being considered closely since the 80th [3, 4] and especially since the 90th of the last century [5 - 7]. However, authors of these works have usually considered only certain aspects of evacuation specifics: analysis of fires in hospitals [4], methods and speeds of carrying immobile patients by the personnel [3, 8], different characteristics of individual pedestrian movement of the disabled [6, 7, 9], specifics of evacuation via stairs and ramps [10 - 12], specifics of practicing the evacuation plan in hospitals [13] and even individual aspects of movement of mixed human flows [14].

When examining the hospital fire regulations it is worth noting that the main fire safety requirements are about dividing a building into fire compartments and sections, setting standards for sizes of evacuation paths and exits, availability of smoke removal and fire extinguishing systems, fire lines and other systems in a building. But to assess a possibility for people to evacuate from such buildings (built according to regulations and protected with the whole complex of systems), one should at least know the characteristics of patients from the point of view of their mobility and abilities of the personnel to evacuate them.

There is a medical classification of patients in hospitals into the following groups in Russia: ambulatory, transportable while sitting, transportable while laying and non-transportable, which does not allow assessing neither the specifics of pedestrian movement of patients, nor their speed and other aspects of their evacuation.

The most completely worked out classification given in [15] and is currently used in practice of the architectural and building design and in fire safety industry in Russia, Table 1

Table 1
Existing classification* of disabled people [15]

Mobility groups	General characteristics of people in mobility groups
M1	People without mobility limitations, including people with ear malfunctions
M2	Ailing people with limited mobility due to ageing (disabled due to the age); disabled with artificial limbs; disabled with vision malfunctions who use a white walking stick; people with mental deviations
M3	Disabled who use additional supports while moving (crutches, sticks)
M4	Disabled who move in manually-driven wheelchairs

* The results of recent experiments have shown a necessity to correct significant the given classification, see for example [16].

Having this classification as the basis, the authors have conducted a survey among attending physicians in 13 clinical hospitals of Moscow to identify mobility groups of patients in different departments. About 3,500 medical reports have been analyzed. Classification results are given in table 2, and we should note the necessity of using two additional mobility groups, non-mobile and non-transportable, specified in the notes below the table.

Table 2.
Number of patients belonging to different mobility groups in the departments of hospitals

Departments of hospitals	Number of patients belonging to different mobility groups, %					
	M1	M2	M3	M4	Non-mobile*	Non-transportable**
Therapeutic	27	55	11	6	1	-
Neurological	15	50	9	7	17	2
Oncological	41	37	10	7	4	1
Cardiological	24	61	6	5	3	1
Chemotherapeutical	40	40	10	6	3	1
Surgical	42	41	6	5	4	2
Pulmonological	58	32	5	5	-	-
Urological	41	43	7	6	3	-
Neurosurgical	42	12	30	9	5	2
Gynaecological (including maternity department)	83	3	4	-	10	-

*Non-mobile people (patients) – people who can't move by themselves due to heath issues; they are evacuated by means of stretchers or gurneys.
** Non-transportable people (patients) - people who can't move by themselves due to heath issues and can't be evacuated by means of standard stretchers or gurneys (surgery patients, connected to hospital equipment, people with spine damages, etc.).

It should be noted, that the occupancy of the hospital wards varies. In winter, as a rule, 100 % of the beds available at hospital departments are occupied; in spring and autumn the number of patients may be reduced by 5 - 10 %; in summer - by 50 %. Evacuation is more complicated at night due to small number of employees present at the hospital. When the number of patients in the department is 60 (average from clinical hospitals of Moscow), the evacuation during the day is likely to be successful (10 - 12 employees in the department - department administration, physicians, interns, nurses, laboratory technicians), but at night, when there are 2 - 3 employees, it may cause serious problems. For example, an average capacity of the neurological department is 60 people - 10 people are to be evacuated on stretchers, 2 patients cannot be moved because they non-transportable, 4 people are to be evacuated in wheelchairs, and in addition it is necessary to organize the evacuation of another 44 people, some of whom use additional support.

Despite the fact, that classification given in Table 2 should be reevaluated, it gives us an understanding of mobile characteristics of patients from the particular hospital department. Considering the number of patients with reduced mobility, the neurological and surgical departments occupants were asked to take part in the flow research experiments.

EXPERIMENTAL SETUP FOR HOSPITAL PATIENTS FLOW MOVEMENT RESEARCH

In order to determine the dependences between the parameters of the movement of the flows of people in hospitals, experiments of patient's movement through various sections of the path using video equipment were conducted. Before the video record was performed, a scale grid with 1x1m cells had been built and installed at the test site in order to record the parameters of the movement of people through sections of communication paths (horizontal section, stairs down and up). Then a test frame that records the geometric dimensions of the section and a size grid with regard to the perspective distortions was constructed. After that the grid was removed. It should be noted that modern digital cameras "Spy" were used for the first time during the field observations, in contrast to the ones previously conducted. Their compact size (including small weight) and the possibility of placement virtually anywhere in the room ease the organization of observations, do not attract attention of the people observed or distort their behavior.

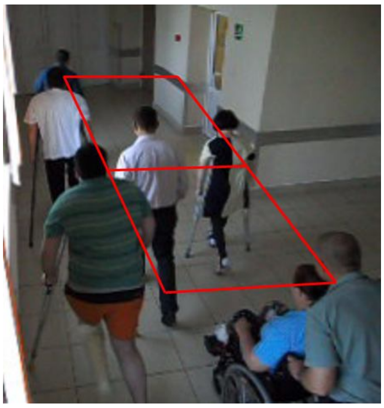
The analysis of video tapes and the creation of a statistical aggregate of received data were made after the experiment. After the video showed a frame with a size grid, the video was stopped and outlines of the grid were drawn on the computer display with a marker pen, Fig. 1. Viewing of the footage continued with a scale grid on the display.

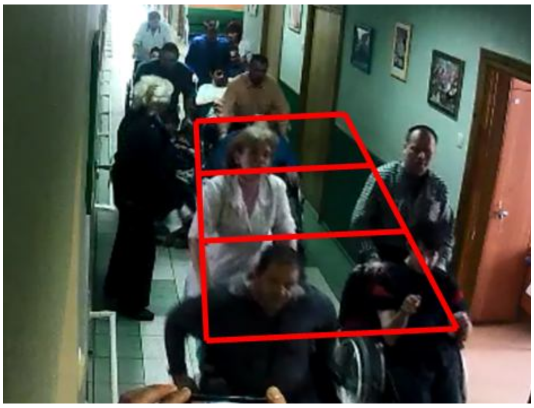
Once a person gets to the boundary of the first square of the grid, the number of people in the cell in front of him is counted, and thus the density of the flow D_i, expressed in persons/m^2, is calculated, Fig.1. With this density the observed person travels a distance of Δl in a certain period of time Δt. This time is calculated as a relation between measured number of frames per second (*fps*) and number of frames per second which is a video tape property (*fps'*). Thus travel speed V_D is calculated:

$$V_D = \Delta l / \Delta t, \text{ m/min, where } \Delta t = \frac{fps'}{fps} \times 60 \text{ , min} \qquad [1]$$

This process is continued until the observed person leaves the observation zone. Likewise, the movement of following people selected for observation is traced.

Figure 1
Fragments of experiment video record processing (overlay of the scale grid of 1x1m). The scale grid is overlaid on the video to determine the density of the flow of people





This is a general method of determining the values of movement speed of people in the flow through the linear sections of the communication path. The movement speed through the doorway is impossible to measure in the same way since the length of the path section in the doorway is close to 0. Therefore, while moving through the doorway, the number of people N passing through it over a certain time interval Δt was counted. The Δt value was determined by the duration of existence of the flow of certain density D_i in front of the doorway.
If we have N values, we calculate the movement intensity (q_D) through the doorway of *b* (m) wide at flow density D_i that is observed in front of it over the time interval Δt:

$$q_D = N/b\,\Delta t \text{, persons/ (m} \bullet \text{min)} \qquad [2]$$

and then the speed V_D of crossing the doorway at the density D_i:

$$V_D = q_D / D_i \text{, m/min} \qquad [3]$$

Thus, a total of about 2,000 measurements were received by measuring the speed of the flows of people depending on its density for the flows of people.

THE PARAMETERS OF FLOW CONSISTING OF HOSPITAL OCCUPANTS

Primary statistical analysis permitted to reveal a relation between travel speed and flow density and empirical curves were plotted. However, it is known that the mathematical formula that we fit to approximate empirical data only then gets a real value when it is adequate to the inner relations of the phenomena. These inner relations were found in 80th of last century [17, 18] and are being used for more than 30 years in Russian Building Codes. Theoretical relations were constructed based on the empirical data in the form of the following law:

$$V_D = V_0(1\text{-a} \ln D \,/ D_0) \;\; if \;\; D \geq D_0 \qquad [4]$$

In this formula: V_D is a speed of flow movement; V_0 is the random variable of speed of free movement of people in the flow that depends on physical and psychological state of people; D_0 is the threshold value of the density i.e. density does not affect the speed of movement of people; **a** is the coefficient of people's adaptation to changes in the flow density while; D is the value of density of the flow of people.
It has been mentioned previously that there is basically an unlimited list of diseases that result in travel speed and other parameters of movement decline. Mathematical analysis revealed, that all this variety

of movement disabilities and consequently travel speed variability are fit well in 4 groups based on their movement aids (it should be noted, that the same classification were applied for elderly people [16]): 1) without movement support aids; 2) with 1 movement support ais (i.e. stick); 3) with 2 movement support aids (i.e. crutches); 4) wheel chair users. However, it is practically impossible to predict precise number and location of the representatives of these groups in the hospital, that is why a category "mixed flow" based on reasonably worth case scenario were introduced, Table 3. The obtained parameters are illustrated on Fig. 2.

Table 3
Parameters of hospital patients flow movement

Mobility group	Parameters	The value of the parameters by type of path (*j*)			
		Horizontal	Door	Stairs down	Stairs up
Without movement support aids	$V_{0,j}$, m/min. $D_{0,j}$, people/m^2 a_j	62,05 0,4 0,4	56,53 0,74 0,5172	42,12 0,64 0,2112	31,84 1,12 0,587
With 1 movement support aid	$V_{0,j}$, m/min. $D_{0,j}$, people/m^2 a_j	44,03 0,77 0,4135	37,67 0,017 0,1467	24,09 0,96 0,522	13,69 1,24 0,4634
With 2 movement support aids (i.e. crutches)*	$V_{0,j}$, m/min $D_{0,j}$, people/m^2 a_j.	55,34 1,3 0,3014	22,45 0,38 0,3425	12,86 - -	10,00 - -
Wheel-chair users	$V_{0,j}$, m/min $D_{0,j}$, people/m^2 a_j.	60 0,399 0,14	**	- - -	- - -
Mixed flow	$V_{0,j}$, m/min. $D_{0,j}$, people/m^2 a_j	58,01 0,95 0,4426	47,5 0,81 0,4356	42,12 0,92 0,4635	29,02 1,0 0,5255

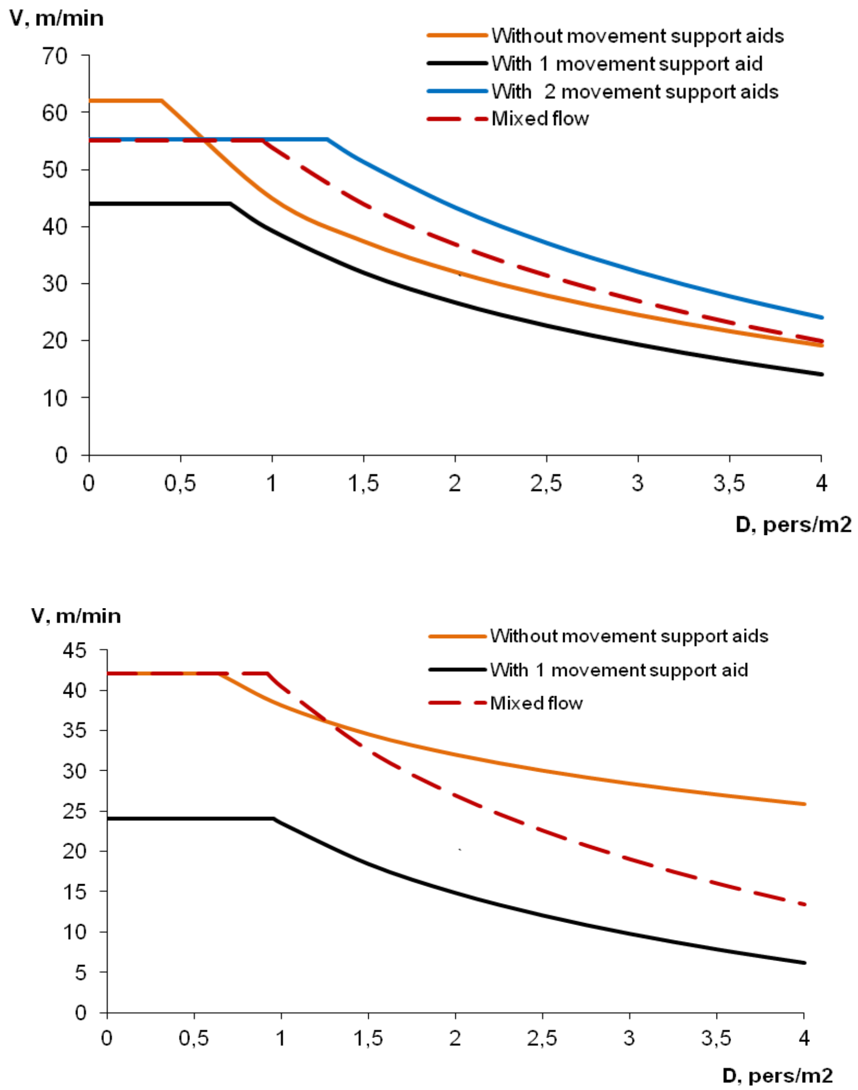
* disabled patient movement in a situation where $D \geq D_0$ (see formula [6]) were not investigated due to safety circumstances

** density doesn't have direct impact on movement parameters of wheel-chair users (*wchu*) through door. For door width less then 1.6m flow is about 35 *wchu*/min, in case of crowded conditions (i.e. there are several wheel-chair users in front of door and they try to overcome it in the same time) flow is 20 *wchu*/min.

Flow of people consists of individuals with their inherent set of mental and physical attributes, stipulating their behavior during movement in a flow. An analysis of empirical data based on non-formal indicators revealed that their movement is different compare to healthy ones. It has been found that maneuvering (an overtake) is almost twice less likely and was performed only by 15.1% of total people with limited mobility. A number of active pedestrians (moving with the speed higher than average flow speed) is the same, but number of passive pedestrians (moving with the speed lower than average flow speed) is 3 times higher compared to the mobile ones. Apparently, this is due to the dominance of physical deterioration over the usual features of movement, Fig.3.

Figure 2

The relation between travel speed and flow density for flow of people comprising hospital patients



a)

b)

Fig.2 The relation between travel speed and density for flow of people comprising hospital patients: a) horisonatl plane; b) stairs down

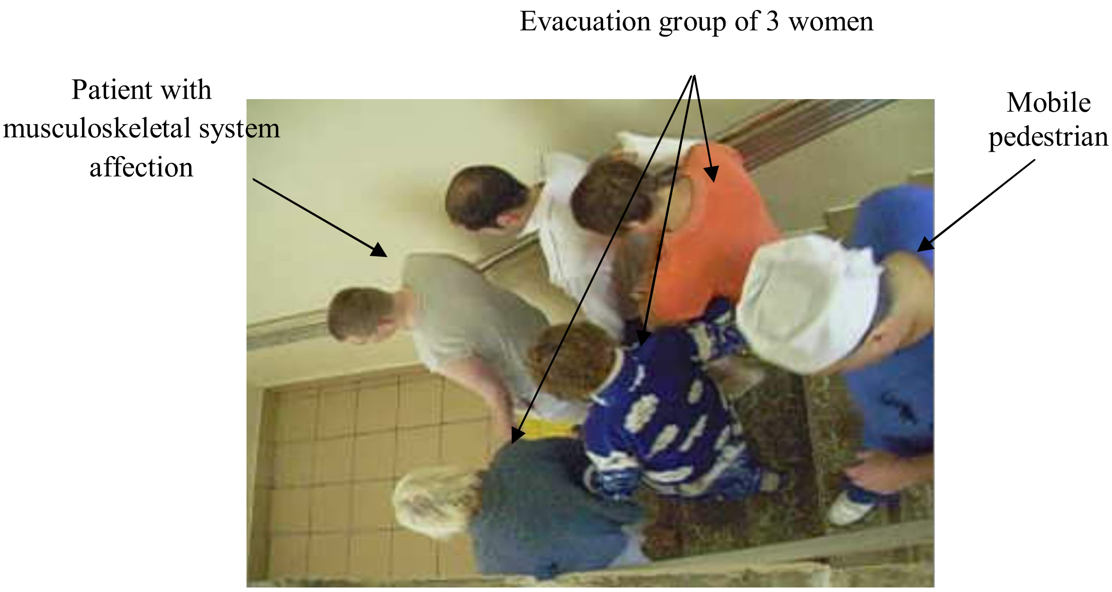
These diagrams indicate that severe disability (i.e. using movement support aids) results in low density impact on travel speed. This might be explained by the fact that movement by itself is very complicated task and human sensor system irritant (surrounding people) considered as not valuable. Another interesting issue is that people moving with two movement support aids are considered by the rest evacuation participants as dangerous for them due to external dimensions of clutches. This permits people with crutches move relatively fast. Table 3 indicates also that movement along stair in upward directions in general is faster which is explained by the fact that risk to fall down is higher in case of moving in downward directions.

The authors should note here that due to ongoing research these variables might be a subject of minor amendments.

Figure 3
Peculiarities of maneuvering of pedestrians with impaired body functions: obvious reluctance to maneuver (outrun) when moving up (a) and down (b) the stairs. A woman in a gray jacket (marked with a triangle) does not outrun a very slow elderly woman and adjusts to her speed while going up ($V_{avg.up}$ = 21 m/min) and down ($V_{avg.down}$ = 38 m/min) the stairs.

The second important factor that contributes to the overall low speed of the flow is the evacuation in groups, which is typical for 55% of pedestrians, Fig. 4.

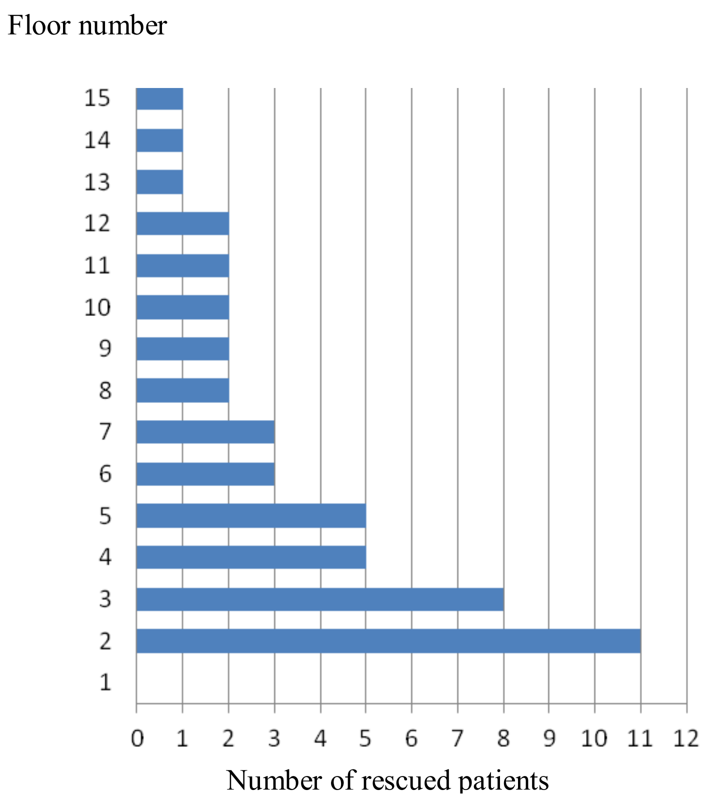
Figure 4
Creation of a typical cluster: a patient with musculoskeletal system affection (without additional support) hinders the movement of 3 women walking in a group and holding hands. A formed group makes it impossible for faster pedestrian to outrun them. Total speed of the group was 18m/min.



Further analysis showed that, 38,2 % of hospital patients use handrails, and for some of them this support is compulsory condition for movement. However moving in this manner evacuees facilitates for general traffic capacity decline of evacuation route. For instance, in case of stair width 1.35m - 36 % decline and for stair with width 1.2m - 42 % decline.

While considering the problems of evacuation of hospital complexes we can not ignore the issues of evacuation of immobile people. As noted above, at night only 2 employees are very likely to stay in a hospital treatment department. Figure 5 gives the results of assessment of physical capacity of 2 people to evacuate immobile patients. Moreover, when analyzing the data in the diagram, it should be taken into consideration that, apparently, we are talking about the most favorable forecast, because the evacuation was carried out by physically fit young men and the weight of the evacuated was 60 kg, which is not typical for hospital treatment departments (patients usually weight more).

Figure 5.
Evacuation of a patient (60 kg) on a stretcher by two rescuers from different floors (number of rescued patients from the first floor might be over 20).



In the absence of source data necessary to assess the speed of carrying the stretchers by employees (which is directly depends on weight of the patient and physical ability of staff), data from Table 5, that were received after a set of experiments under various conditions, might be useful.

Table 4
Speed of employees when carrying a stretcher, m/min

Type of path	Travel speed, m/min	
	With a carried person	Without a carried person
Horizontal path	70	100
Stairs down	30	80
Stairs up	20	60

Time of saving the people incapable of independent movement from a particular floor of a building can be determined by the formula [5]:

$$t = (t_1 + t_2 + \frac{L_1}{V_1^p} + \frac{L_2}{V_2^p} + \frac{L_1}{V_1} + \frac{L_2}{V_2}) \cdot \frac{N_{NM}}{0,5 \cdot N_{STAFF}} - (\frac{L_1}{V_1} + \frac{L_2}{V_2}) \quad [5]$$

t_1 - time of placing a person incapable of independent movement on a stretcher, min;
t_2 - time of moving a person incapable of independent movement from a stretcher in a place safe from dangerous fire factors, min;
N_{NM} - number of non-mobile people;
N_{STAFF} - number of medical personnel;
L_1 - length of the rescue path, horizontal, m;
L_2 - length of the rescue path, stairs, m;
V_1 - movement speed of medical personnel with a stretcher, horizontally without a patient, m / min;
V_1^p - movement speed of medical personnel, horizontally with a patient on a stretcher, m / min;
V_2 - movement speed of medical personnel up the stairs, with a stretcher without a patient, m / min;
V_2^p - movement speed of medical personnel, down the stairs with a patient on a stretcher, m / min.

Time of placing a non-mobile person incapable of independent movement on a stretcher, carried out by one pair of rescuers from the employees, is 0.35 min; the time of moving a patient from a stretcher to a prepared flat surface in a place safe from dangerous fire factors is 0.15 minutes. The number of runs carried out by one pair of employees (acting as rescuers) should be determined based on the data from Table 4 during the transportation of patients down the stairs from different floors.

CONCLUSIONS

A large scale work was undertaken aimed to research fire safety of hospital patients. The study results permitted to diagnose the most important issue of this problem – evacuation and rescue of people with physical disabilities. The percentage of patients with precise disabilities was established for various hospital departments and the most unfavorable ones (neurological and surgical) were chosen for further research. Undertaken experiments with patients of these departments permitted to establish parameters of their movement in a flow that made possible to calculate this process more precisely.
An attention was also paid to the problems of evacuation of immobile people as well. Physical abilities of staff carrying out the stretchers, their travel speed along different route type and analytical relations for prediction of evacuation time of immobile patients were discussed.
A described research helps to focus on the main problems of hospital contingent evacuation and might facilitated to find proper engineering solutions for their fire safety.

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