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The impact of surgical intervention on statographic parameters of patients with diabetic foot syndrome

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Abstract

Taking into account that the prevalence of diabetes mellitus continues to increase worldwide, secondary complications associated with this endocrine disorder are becoming increasingly common. Disruption of glucose homeostasis and hyperglycemia lead to the activation of several pathological metabolic pathways, contributing to the development of vascular insufficiency and neurodegenerative processes in the lower limbs. These processes are the causes of a condition known as diabetic foot syndrome (DFS), which requires special attention and meticulous treatment. Complications in the form of trophic ulcers of the lower limbs are one of the serious consequences of diabetes mellitus (DM) since they often lead to severe medical and social problems, including high rates of limb amputations. The purpose of the research is to investigate the redistribution of plantar pressure depending on the volume of surgical intervention in patients with diabetic foot syndrome (DFS) by measuring individual statographic parameters. The analysis of a series of parameters from statographic studies in patients with diabetic foot syndrome undergoing various volumes of surgical interventions has allowed for a comprehensive understanding of the features of vertical standing of these patients. In the course of the research, it has been revealed that as the support area of the operated foot decreases, there is an increase in body oscillation in both the sagittal and frontal planes relative to the support area. It has been proven that in cases with a normal support area of the foot, the relative body oscillation decreases.

KEYWORDS

diabetic foot syndrome (DFS), diabetes mellitus, biomechanics of the foot, statography, treatment method

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1. INTRODUCTION

The formation of ulcers and purulent complications in patients with diabetic foot syndrome (DFS) is the main cause of lower limb amputation at various levels. The scope of foot surgeries can range from surgical treatment of a purulent focus to resection of a single phalanx of the toe or the forefoot. After such surgical interventions, the load on the remaining part of the foot changes not only on the contralateral



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limb but also on the position of the body in the frontal and sagittal planes. Changes in the vertical position of the body lead to alterations in the biomechanics not only of the operated foot but also of the healthy foot, resulting in the emergence of overloaded areas with increased pressure on soft tissues, which is one of the main causes of trophic ulcer formation.

2. LITERATURE REVIEW

Scientific literature sources convincingly indicate that among all causes of limb amputations at various levels, destructive processes on the foot in patients with diabetes mellitus account for 40-70% of cases [1]. S.V. Bolgarskaia [2] argues that this more commonly occurs in patients with a neuro ischemic form since the extent of tissue damage on the foot is not dependent on the duration of diabetes mellitus in this category of patients. Targeted studies conducted by Danilov, Karpinska, and Belov [3] have established that one of the main reasons causing ulcerative and purulent-inflammatory lesions of the foot tissues is abnormal elevation of pressure on individual areas of the toes and metatarsals due to various types of deformities.

The conclusions of scientific investigations by Vasiliuk [4] indicate that in 6-30% of patients who have undergone surgery for purulent-inflammatory complications of diabetic foot syndrome (DFS), the need for minor amputations on the same foot arises in the subsequent 1-3 years. Even within one year, the frequency of interventions on the contralateral limb increases to 12%, and within five years, it reaches 28-50%.

The influence of body deviations on the supportability of lower limbs is studied using the method of statography, which is widely applied in orthopaedics, sports, rehabilitation, and other fields [5,6]. The study of patients' standing features using stabilography has been recognized as one of the effective methods for various types of joint, spinal, and vestibular apparatus pathologies [7,8].

In Japan, the statography method has been incorporated into the standards of examination for patients with vestibular disorder [9]. M. Yamamoto *et al.* argued that international standardization of stabilometry is mandatory for confirming the exchange of important results. Scientists believe that stabilometry is a useful tool for examining patients with functional disorders of the vestibular apparatus.

In the last ten years, there have been very few publications on the use of stabilography in the treatment of patients with diabetic foot syndrome (DFS). In particular, researcher A. Rundo [10] studies plantar pressure in patients who have un-

dergone foot surgery to identify areas of overload on the operated limb. The scientist emphasizes that peripheral neuropathy combined with repetitive foot trauma and peripheral vascular disease are the main etiological factors in the development of foot ulcers.

Researchers V. Filipenko *et al.* [11] have studied the potential of rehabilitation therapy programs that would determine the regimen, dosage, and intensity of regeneration exercises for the studied category of patients, depending on the initial level of functionality of the musculoskeletal system as a whole and the specifics of the postoperative recovery period. S.M. Vasilyuk *et al.* [4] studied the redistribution of plantar pressure on the operated foot in patients with diabetic foot syndrome (DFS). A.U. Haviretskyi [12] investigated the features of plantar pressure redistribution in patients with diabetic foot syndrome (DFS) on the operated limb to justify the use of immobilizing offloading bandages. Upon analyzing domestic and foreign literature, no data was found regarding how the load on the foot changes on the non-operated limb in such cases. There is no data on how the load on the feet changes depending on the patient's ability to maintain a vertical body position, which characterizes their stability.

The issue of changes in the biomechanics of the foot, the criteria for which would form the basis for the prevention of trophic disorders in patients who have undergone "minor" amputations, is poorly covered in the scientific literature. The reasons explaining the depth of the spread of purulent foci on the foot in patients with a mixed form of diabetic foot syndrome remain unclear.

Thus, the review of the scientific literature suggests that a significant number of "saving" surgical interventions on foot is currently not decreasing but increasing due to patients suffering from a mixed form of diabetic foot syndrome. The distribution of plantar pressure changes in these patients after surgery, both on the operated and non-operated limb. There is no data on how statographic indicators change in patients with DFS with double-support and single-support standing, depending on the volume of surgical intervention on the foot.

3. AIM

The purpose of the research is to study the redistribution of plantar pressure, depending on the extent of surgical intervention in patients with SDS, by measuring individual indicators of statogramma. In order to achieve the purpose outlined, it is necessary to solve the following tasks:

1. to study the influence of the surgery volume on the redistribution of plantar pressure in patients with SDS in double-supported standing.
2. to study the influence of the surgery volume on the redistribution of plantar pressure in patients with SDS in single-supported standing.

4. MATERIALS AND METHODS

A total of 106 patients with type 2 diabetes mellitus for a period of 5 to 12 years were included in the research. There were 52 (49,1%) men and 54 (50,9%) women aged from 52 to 79 years among them. According to the Decree of the Ministry of Health of Ukraine № 574 dated August 5, 2009, the severity of the course of diabetes mellitus is divided into mild, medium and severe forms. Out of 106 patients, 31 (30%) patients had a medium degree of severity of the disease, and 75 (70%) patients had a severe one.

Depending on the scope of surgical intervention, the patients were categorized into six groups. A separate control group included six patients with moderate to severe type 2 diabetes mellitus who did not undergo surgical interventions.

The necessary indicators were determined according to the standard method of statographic examination – standing on two legs and standing with predominant support on the right and left lower limb in patients of the control group, as well as on the operated and non-operated limb in patients of groups 2-7. Each examination was conducted for 25 s.

Data collected during any study or clinical trial can be analyzed to identify patterns and various factors. Duncan's multiple range test identifies pairs of means (at least three) that differ from each other. Therefore, the reason for conducting Duncan's test is the need to determine which specific samples differ significantly from others.

The following parameters of the statogramma were evaluated:

- the total center of mass (TCM) for double-supported (S1) and single-supported standing on the right foot (S2) and left foot (S3) ;
- coefficient of the geometry of the centre of mass spot for double-supported standing (G1) and single-supported standing on the right and left foot (G2, G3), respectively;
- the magnitude of the displacement of the mathematical expectation (MA) of the TCM in the case of preferential standing on one leg from the MA of the TCM of double-supported standing in the frontal plane (R) or the displacement in standing with support on the affected (RXb) and healthy (RXz) limb.

The study of the features of the vertical position of patients in the sagittal and frontal planes that underwent surgical interventions for SDS was carried out on the device "Statograph" in the biomechanics laboratory of the SE "Sytenko Institute of Spine and Joint Pathology National Academy of Medical Sciences of Ukraine".

Permission to conduct the study required written consent from the participants. The study was conducted during the autumn-winter period over the course of 3 months.

5. RESULTS

The foot typically carries out three biomechanical tasks for the human body: propulsion, balancing, and sensory functions. Irreversible alterations in the structure of the bone and joint apparatus occur in cases of developed "diabetic foot syndrome", which leads to changes in its functions and redistribution of plantar load in certain areas. In addition, different surgical interventions are performed on the foot in patients with various complications of SDS. In this case, the plantar load is changed not only on the operated limb but also on the contralateral limb. In addition, the redistribution of plantar load is influenced by the sagittal and frontal oscillation of the human body in the upright position [13,14].

Depending on the volume of surgical intervention, the patients were categorized into six groups (Table 1). A separate control group included six patients with moderate and severe type 2 DM who had no surgical interventions, as presented in Table 1.

Table 1. Distribution of patients by groups depending on the scope of surgical intervention.
Source: Developed by the author.

No of the group	Scope of surgical intervention	Number of patients, %
1	non-operative (control)	6 (5,6%)
2	surgical treatment of the purulent focus	8 (7,5%)
3	1/2 finger amputation (any finger)	12 (11,3%)
4	amputation of 1 toe with metatarsal head bone	18 (17%)
5	amputation of the V toe with the metatarsal head bone	29 (27%)
6	amputation of II-IV toes with the metatarsal head bones	11 (10,4%)
7	forefoot amputation	22 (20,7%)
	Total	106 (100%)

A flowchart of the distribution of volunteer patients is shown in Figure 1.

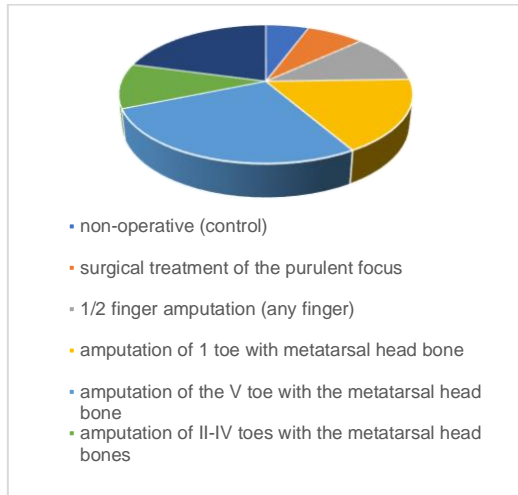


Figure 1. Flowchart of Distributing Volunteer Patients, %.

The results of the TCM projection areas obtained after statistical processing are presented in Table 2.

Table 2. Results of TCM projection areas. Source: Developed by the author.

Parameters of areas	Gr	M±SD, mm ²	Min÷max
S1 (area of the TCM in double-supported standing)	1	417,7±39,3	394,0÷463,0
	2	421,0±19,9	409,0÷444,0
	3	480,0±63,6	435,0÷525,0
	4	657,0±91,9	592,0÷722,0
	5	494,5±120,0	391,0÷630,0
	6	497,0±31,1	475,0÷519,0
	7	725,0±219,2	570,0÷880,0
S2 (area of the TCM with support on the affected leg)	1	504,7±151,2	336,0÷628,0
	2	657,0±81,2	600,0÷750,0
	3	662,5±31,8	640,0÷685,0
	4	857,0±272,9	664,0÷1050,0
	5	729,0±383,7	435,0÷1290,0
	6	639,0±188,1	506,0÷772,0
	7	642,0±144,2	540,0÷744,0
S3 (area of the TCM with the support on the healthy leg)	1	617,3±211,3	378,0÷778,0
	2	481,3±97,3	380,0÷574,0
	3	649,5±389,6	374,0÷925,0
	4	661,0±120,2	576,0÷746,0
	6	758,0±374,8	493,0÷1023,0
	5	574,5±301,1	276,0÷882,0
	7	772,5±74,2	720,0÷825,0

As can be seen from the presented results, a statistically significant difference in TCM area between the two groups was observed only in

double-supported standing: in the control group, the smallest TCM spot area was 417,7±39,3 mm², and the largest was in the group of patients with forefoot amputation 725,0±219,2 mm² (F=3,175, p=0,046). For this indicator, an analysis of variance with Duncan's post hoc test was performed, resulting in the following distribution of area between groups (Table 3).

Table 3. Analysis of variance for the area of DCM in a double-supported standing position. Source: Developed by the author.

Groups	Subsets for α = 0,05		
	1	2	3
1	417,7		
2	421,0		
3		480,0	
5		494,5	
6		497,0	
4			657,0
7			725,0
St. significance between elements of subsets	0,438	0,097	0,469

As can be seen from the presented results, as a result of the analysis, three homogeneous subgroups were obtained – the areas of TCM in double-supported standing, which differ from each other at the level of (α = 0.05). The TCM area of the control group (417,7±39,3 mm²) was not statistically different (h=0,438) from the TCM area of patients with foot surgery (421,0±19,9 mm²); at the same time, the area of TCM of these two groups is statistically different from the patients of groups 3 (480,0±63,6 mm²), 5 (494,5±120,0 mm²) and 6 (497,0±31,1) (amputation of ½ toe, amputation of 5 toe, and amputation of 2-4 toes) and also from the subgroup of groups 4 (657,0±91,9 mm²) and 7 (725,0±219,2 mm²) (amputation of 1 toe and forefoot).

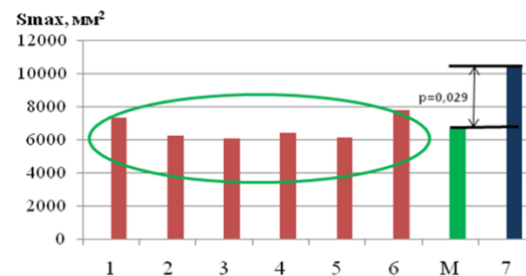


Figure 2. Diagram of the comparison of the total areas of the statogramma in the patients under study by the patient group. Source: Developed by author.

Analysis of the magnitude of the TCM projec-

tion area with preferential support on the non-operated foot did not reveal any particular differences between the groups ($F=0.410, p=0.857$). However, this indicator is slightly higher in group 7 of the patients. The mean value of maximum areas of groups 1-6 was ($6597,3 \pm 2200,0 \text{ mm}^2$) and group 7 was ($10467,5 \pm 1173,1 \text{ mm}^2$), and this difference is statistically significant ($t=-2,4; p=0,029$). This pattern is clearly presented in Figure 2.

The analysis of the average maximum area of statogrammas did not reveal any significant differences in this parameter between the groups, despite the insignificant excess of the average area of statogrammas in group 7. The dispersion analysis of the area ratio S% also revealed no statistical differences between the groups ($F=1.039; p=0.451$).

Thus, the analysis of the examined indicators and their relations has shown that conventional surgical interventions on foot without removal of its fragments do not affect the bearing capacity and stability, both in double-supported standing and with preferential support on one limb. However, retractive surgeries, especially amputation of a significant portion of the foot, result in altered standing patterns.

The parameters of the statogramma range in the frontal plane with support on the operated foot and support on the healthy foot were studied (Table 4).

Table 4. Dynamics of the statogramma in the frontal plane with support on the affected (a) and healthy (h) limbs.
Source: Developed by the author

Gr		Mean	Std. deviation	
1	RX a	64,7	20,2	t=0,609 p=0,604
	RX h	57,7	1,0	
2	RX a	63,8	13,4	t=0,470 p=0,685
	RX h	59,5	11,0	
3	RX a	61,1	5,4	t=0,610 p=0,651
	RX h	53,6	12,0	
4	RX a	40,2	8,6	t=-10,917 p=0,058
	RX h	53,3	10,3	
5	RX a	53,2	13,6	t=4,908 p=0,016
	RX h	39,3	9,9	
6	RX a	50,1	5,4	t=-0,643 p=0,636
	RX h	56,7	20,1	
7	RX a	50,3	17,1	t=-0,317 p=0,804
	RX h	59,0	21,4	

Analysis of the statogramma range with preferred support on one limb revealed a statistically significant difference in group 5 of the patients who underwent amputation of the fifth toe with the metatarsal bone. In this group, the range of the statogramma in the frontal plane with support on the affected leg ($53,2 \pm 13,6$) is statistically significantly

larger ($t=4,908; p=0,016$) than with support on the healthy leg ($39,3 \pm 9,9$).

Group 4 of the patients who underwent amputation of the 1st toe with metatarsal bone is also drawing attention. In this group, the range of the statogramma when supporting the affected limb in the frontal plane is smaller ($40,2 \pm 8,6$) than for the healthy limb ($53,3 \pm 10,3$). And although the difference is not significant ($t=-10,917; p=0,058$), it is quite close to it.

A comparison was made of the proportion of body weight load on the affected and healthy foot, as well as the coefficient of load asymmetry. The results of the analysis are presented in Table 5.

Table 5. Results of the analysis of the proportion of foot loads (%).
Source: Developed by the author.

Group	Load on the lower limb	Mean	Stat. deviation	St. significance of differences
1	Right	50,4	2,5	t=0,327 p=0,775
	Left	49,5	2,5	
2	Affected	43,2	5,0	t=-2,378 p=0,141
	Healthy	56,8	5,0	
3	Affected	49,9	0,7	t=-0,207 p=0,870
	Healthy	50,1	0,7	
4	Affected	47,0	1,4	t=-3,000 p=0,205
	Healthy	53,0	1,4	
5	Affected	44,4	3,8	t=-2,982 p=0,058
	Healthy	55,6	3,8	
6	Affected	49,0	1,1	t=-1,396 p=0,396
	Healthy	51,0	1,1	
7	Affected	40,5	0,7	t=-19,000 p=0,033
	Healthy	59,5	0,7	

The Table shows that a statistically significant difference in comparison to control ($t=-19,000; p=0,033$) of loads is observed only in group 7 of the patients with forefoot amputation. The difference is not reliable in the other groups. Duncan's post hoc test applied to the obtained data revealed three homogeneous groups according to this coefficient, as presented in Table 6.

The first subgroup included only group 7 of the patients who underwent amputation of the anterior segment. The second subgroup included patients with surgical treatment of purulent foci, as well as with amputation of the first and fifth toes with the head of the metatarsal bone. The third group included patients with half-finger amputation, amputation of 2-4 fingers, and the control group. All subgroups differed from each other, with a probability of 95%.

The analysis of a number of parameters of statographic studies in patients with diabetic feet with different volumes of surgical interventions

made it possible to obtain complete information about the features of upright standing of these patients.

Table 6. Dispersion analysis of the coefficient of asymmetry of loads on the feet.

Source: Developed by the author.

ps	Subsets for $\alpha = 0,05$		
	1	2	3
1	0,69		
2		0,77	
3		0,84	
5		0,88	
6			0,93
4			0,96
7			0,98
St. significance between elements of subsets	0,105	0,079	0,107

The scope of surgical intervention on the foot reliably affects the patient's stability; that is, the more extensive the surgical intervention, the larger the projection area of the TCM on the plane. It should be noted that surgical treatment of the foot wound in group 2 of the patients did not lead to a significant increase in the area of the TCM projection compared to the same index in group 1 of the patients who did not undergo any interventions on the foot ($p=0,438$). Amputation of $\frac{1}{2}$ of any toe, the fifth toe and 2-4 toes of the foot leads to a significant ($\alpha=0,05$) increase in the projection area of the TCM. Amputation of the first toe with metatarsal bone and amputation of the forefoot further increases the TCM projection area, the values of which are significantly different from the first and second groups.

One of the important indicators is the load on the operated and healthy foot. It was revealed that patients with forefoot amputation (group 7) had significantly ($p<0,05$) less load on the affected foot. The calculated asymmetry coefficient revealed a statistically significant difference ($F=3,476$; $p=0,035$) with the increase of this index on the non-operated limb. At the same time, an increase in the area of TCM projection in group 4 of the patients compared to the control was revealed. However, there was no increase in the area of TCM projection on the operated leg in patients with anterior amputation in one-supported standing. This can be explained by the fact that as the support area of the operated foot decreases, the body oscillation in the sagittal and frontal planes increases in relation to the support area. In cases with normal foot support areas, the relative body oscillation decreases.

6. DISCUSSION

In contemporary scientific circles, the possibilities of alternative approaches to treating DFS are actively discussed. In particular, O. Al-Dadah, L. Shepstone, and S. Donell [15] emphasize the issue of ulcer formation and purulent complications in patients with diabetic foot syndrome, highlighting the need for therapeutic support for surgical interventions in the treatment of DFS.

Scientists G. Nunes *et al.* [16], in the process of verifying whether kinesiology taping, applied to the ankles of healthy individuals as a preventive intervention and those with ankle injuries, outperforms sham or alternative interventions regarding ankle function, emphasize that as the support area of the injured foot decreases, body sway in the sagittal and frontal planes relative to the support area increases, which resonates with the findings of this study.

Meanwhile, S. López-de-Celis [17] and V. Najafi, R. Mishra [18] state that the main cause of lower limb amputations at various levels. Scientists summarize some of the latest innovations in three specific areas, including technologies that support triage of high-risk patients, technologies that support on-site medical care, and technologies that expand self-care capabilities. Researchers propose decentralizing care for people with foot diseases through innovations in digital health, smart wearable devices, telemedicine technologies, and the "hospital at home" model. These technologies are seen as optimal for improving the remote treatment of diabetic foot ulcers, effectively differentiating those who need monitoring in outpatient or inpatient clinics, and providing urgent home care. The authors' conclusions are synergistic with the results of the current study.

The volume of operations performed, according to E. Navarro-Flores and O. Cauli [19], on the foot can range from surgical debridement of an affected area to resection of a single toe phalanx or the forefoot. Scientists insist that various aspects related to DFS, such as physical changes, psychological complaints, and even disorders and socio-economic difficulties, can affect the quality of life of these patients. Researchers emphasize that individuals with DFS should always have access to medical services aimed at reducing inequality, as well as ongoing medical education, promotion, and support for psychological and socio-economic issues to improve the quality of life.

In the future, a number of researchers [20,21,22] argue that after such surgical interventions, the load changes not only on the remaining part of the foot but also on the contralateral limb. To partially alleviate the situation, N. Korada *et al.*

concluded that the use of custom insoles can significantly reduce peak plantar pressure. When designing the insoles, scientists suggest considering parameters such as contour insoles with shape pressure and load position, which in synergy can significantly reduce peak plantar pressure. The conclusions of the scientists serve as a vivid example of the practical implementation of scientific research in the concept of DFS problems.

Some scientists, in particular, G. Chemello *et al.* [23], explore the potential of modern digital technologies in the treatment of DFS, emphasizing that artificial intelligence (AI) methodologies seem sufficient today to address aspects such as timely screening to detect the risk of foot ulcers (or worse, amputation) based on appropriate sensor technologies.

Meanwhile, M. Monteiro-Soares *et al.* [24] focus on the body's position in the frontal and sagittal planes. Scientists evaluate existing diabetic foot ulcer classification systems to determine which should be recommended for a specific clinical goal. Classification systems, according to the authors, aim to predict lower limb amputation in patients with active diabetic foot ulcers.

G. Ruemenapf, S. Morbac, and M. Sigl [25] argue that changes in the vertical position of the body lead to changes in the biomechanics not only of the operated but also of the healthy foot and the appearance of overload zones with increased pressure on the soft tissues, which is one of the main causes of trophic ulcers. The results of the scientists' research complement the conclusions of this study.

7. CONCLUSION

Complications in the form of trophic ulcers of the lower extremities are one of the serious consequences of diabetes mellitus since they often lead to severe medical and social problems, up to and including high limb amputations. The research examined the redistribution of plantar pressure as a function of surgical intervention volume in SDS patients by measuring selected statogramma parameters.

The analysis of a number of parameters of statographic studies in patients with diabetic feet with different volumes of surgical interventions made it possible to obtain complete information about the features of upright standing of these patients. In the course of the research, it has been found that as the foot support area of the operated foot decreases, the body oscillation increases in the sagittal and frontal planes in relation to the support area. It has been proved that in cases with normal foot support areas, the relative body oscillation decreases.

Change of body position in both planes in patients operated because of SDS increases the plantar load on the non-operated foot with increased pressure on soft tissues, which is one of the reasons for the formation of trophic ulcers on the non-operated limb.

The distribution of TCM on the operated foot in single-supported standing is in direct correlation with the volume of surgical intervention. For maintaining a stable upright posture, the major part of the TCM in double-supported standing is distributed on the non-operated limb, which leads to an increase in soft tissue overload zones in the limb.

The prospect of further studies is foreseen in the direction of establishing the reasons explaining the depth of spread of purulent foci on the foot in patients with mixed forms of SDS.

CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

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