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Assessment of prevalence and severity of lower limb varicose veins according to CEAP classification

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Abstract. Chronic venous disease of the lower extremities (CVD) remains one of the most common vascular pathologies, significantly reducing patients' quality of life and requiring a clearly standardised approach to assessing its severity and prevalence. The implementation of the international CEAP (Clinical, Etiological, Anatomical, and Pathophysiological) classification enables systematisation of clinical manifestations and justification of treatment strategies. The aim of this study was to determine the prevalence and severity of CVD based on CEAP clinical classes in patients with chronic venous insufficiency. A total of 139 patients aged 18 to 75 years with CVD at stage C3-C6 were examined. Depending on the treatment performed, patients were divided into three clinical groups. All patients underwent clinical and ultrasound examinations followed by statistical data processing. The most common clinical class was C3, identified in 47.5% of patients, while C4a was found in 28.8%, and severe forms C5-C6 accounted for 10.8% of cases. Women more often had C3-C4a forms, while men were more likely to be diagnosed with C4b-C6. The main risk factors included positive family history (60.4%), sedentary lifestyle (59.7%), occupational exposure in the form of prolonged standing or sitting (49.6%), as well as smoking, obesity, and a history of thrombotic events. No statistically significant differences in clinical severity were observed between the treatment groups. The findings allowed for outlining the epidemiological profile of patients with CVD in the stage of chronic venous insufficiency (CVI), confirm the high prevalence of clinical class C3, and provide an empirical basis for further studies on the effectiveness of various options for combined surgical treatment considering reflux topography and anatomical features of venous pathology. The practical significance of this study lies in enhancing diagnostic and treatment planning through stratification of patients by CEAP clinical class, allowing for more personalised and evidence-based therapeutic decisions

Keywords: chronic venous insufficiency; clinical stages; combined treatment; endovenous ablation; duplex ultrasound; chronic venous disease

Introduction

Chronic venous disease (CVD) of the lower extremities is one of the most common disorders of the peripheral vascular system, characterised by a chronic course, progressive development of venous insufficiency, and a potential risk of complications, including thrombophlebitis, trophic ulcers, and thromboembolic events. According to epidemiological studies, the prevalence of CVD in the general population range between 20% and 40%, with the incidence increasing with age and demonstrating certain gender differences [1]. A. Han [2] cited data from the Framingham Study, which

reported an average two-year incidence rate of varicose veins of 5.2% in women and 3.9% in men.

CVD most often begin to develop at a young age under the influence of various external factors, especially in the presence of a hereditary predisposition to this condition. At present, a positive family history of venous disorders is considered the predominant risk factor in the development of chronic venous pathology. It was reported that 90% of children developed chronic venous insufficiency (CVI) if both parents were affected, and only 20% if both parents were healthy [3].

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Other major factors contributing to the development of venous pathology included patients' lifestyle and medical history [4]. Obesity led to both pathophysiological and pathomorphological changes in the venous wall. J. Patel *et al.* [5] showed that the likelihood of developing CVD increased with rising body mass index (BMI), and patients with higher BMI values demonstrated increased diameter of the great saphenous vein. According to the World Health Organization [6], approximately 31% of the global population aged 15 and above had insufficient physical activity. In Ukrainian patients, a sedentary lifestyle was observed in nearly 45.6% of cases. S. Béliard *et al.* [7] showed that in all age groups and in both sexes (except men aged 18-34), the CEAP (Clinical, Etiological, Anatomical, and Pathophysiological) clinical class was significantly higher in individuals who did not engage in regular physical activity compared to those who did. Smoking was also recognised as a risk factor for CVD due to various interrelated pathophysiological mechanisms, including haemodynamic changes, oxidative stress, inflammation, endothelial dysfunction, and thrombosis.

M. Cui *et al.* [8], based on data from the CIRCS (Circulatory Risk in Communities Study), demonstrated that chronic and intensive smoking was associated with a high prevalence of impaired endothelial function. Musculoskeletal disorders are frequently reported in patients with chronic venous disease and may contribute to symptoms and reduced quality of life. Prolonged standing or sitting, often related to occupational factors, was also capable of provoking the development of CVD. J.H. Park *et al.* [9] showed that Americans spent 55% of their waking hours (7.7 hours per day) in a seated position, whereas Europeans spent 40% of their free time (2.7 hours per day) sitting. A history of thrombotic complications may result in post-thrombotic syndrome (PTS), which leads to venous stenosis, obstruction, or valve damage, causing sustained elevation of venous pressure. S.S. Virani *et al.* [10] reported that PTS affected between 23% and 60% of individuals with deep vein thrombosis. A prior history of thrombotic events is a recognised risk factor for the development of chronic venous insufficiency.

Modern phlebology has relied on the international CEAP classification, which enabled the standardisation of clinical assessment, identification of aetiological factors, determination of the extent of venous involvement, and clarification of the mechanisms underlying disease progression. This system facilitated not only more accurate diagnosis formulation but also the selection of optimal treatment strategies, prediction of disease course, and evaluation of therapeutic efficacy [11]. Despite significant advances in the understanding of varicose vein pathogenesis, its prevalence across different populations has remained insufficiently studied, particularly in the context of lifestyle changes, environmental influences, and socio-economic factors. The lack of generalised epidemiological data regarding the frequency and severity of CVD in different age and social groups highlighted the need for additional population-based research. Therefore, the aim of the present study was to analyse the prevalence and severity of chronic

venous disease according to the CEAP classification in the study population, which allowed for the evaluation of the structural features of the disease, its aetiological and pathophysiological aspects, and contributed to the improvement of diagnostic and therapeutic approaches.

Materials and Methods

The study of patients with CVD of the lower extremities was conducted from 2023 to April 2025 at the Department of Faculty Surgery, Zaporizhzhia State Medical and Pharmaceutical University. Inclusion criteria were: patients with CVD of the lower extremities classified as CEAP clinical classes C3-C6, aged between 18 and 75 years. Exclusion criteria: patients with CVD classified as CEAP classes C0-C2; patients under 18 or over 75 years of age; patients with oncological diseases; patients with autoimmune diseases; patients with diabetes mellitus; patients with liver diseases; absence of signed informed consent for participation in the study. A total of 139 patients (100%) were examined. Among them, 47 (33.81%) were men and 92 (66.19%) were women. All patients were divided into 3 clinical groups with subgroups.

Group 1 (main group): 32 patients (23.02%) who received treatment by endovenous radiofrequency ablation (RFA) of the great and/or small saphenous veins, combined with miniphlebectomy of tributaries and perforating veins.

Group 2 (comparison group): 64 patients:

- Subgroup 2A: 31 patients (22.30%) who underwent endovenous RFA combined with miniphlebectomy of tributaries without ligation of perforating veins;

- Subgroup 2B: 33 patients (23.74%) who underwent endovenous RFA combined with ligation of perforating veins without miniphlebectomy of tributaries.

Group 3 (comparison group): 43 patients (30.94%) who received treatment exclusively by endovenous radiofrequency ablation of the great and/or small saphenous veins.

The average age range of patients was as follows: Group 1 – 47.18 ± 1.95 years; Subgroup 2A – 54.50 ± 2.19 years; Subgroup 2B – 47.18 ± 1.95 years; Group 3 – 50.32 ± 1.81 years. No statistically significant differences in patient age between groups and corresponding subgroups were observed ($p > 0.05$). The examination of patients included a structured anamnesis collection using a standardised questionnaire, clinical evaluation, laboratory testing, and instrumental investigations. Ultrasound examination of the lower limb veins was performed using ultrasound diagnostic systems: "ACUSON Redwood", "ACUSON NX3 Elite", and "ACUSON NX2" manufactured by Siemens Medical Solutions USA, Inc. (USA).

Statistical processing of the obtained data was carried out using the software packages STATIS TICA 13.0, TIBCO Software Inc. (license JPZ804I382130ARCN10-J) and MICROSOFT EXCEL 2013 (license 00331-10000-00001-AA404) [12]. Quantitative indicators were presented as $M \pm m$ (arithmetic mean and standard error of the mean). The study was carried out in compliance with modern bioethical requirements [13], including the requirements of Article 8 of the Law of Ukraine No. 123/96-BP "On

Medical Products” [14], Directive of the European Parliament and of the Council 2001/20/EC [15], Convention for the protection of Human Rights and Dignity of the Human Being with regard to the Application of Biology and Medicine [16], WMA Declaration of Helsinki – Ethical Principles for Medical Research Involving Human Participants [17], recommendations of the World Health Organisation Global Health Ethics [18], provisions of Good Clinical Practice (GCP) [19], and the Order of the Ministry of Health of Ukraine No. 690 [20]. All patients were informed about the risks of conducting the study and publishing materials and signed an informed consent to participate in the study. The authors claim to respect the confidentiality of data and prevent any pressure.

Results and Discussion

An essential part of the study involved the collection and analysis of patients’ medical history and lifestyle-related factors that could influence the progression and severity of CVD. The structured anamnesis included questions about family history of venous pathology, previous thrombotic events, obesity, smoking status, occupational factors such as prolonged standing or sitting, as well as general physical activity level. These data were obtained during patient interviews conducted at the initial stage of clinical evaluation. The aim of this stage was to identify the most common risk factors in the study population and explore their distribution across treatment groups. The results of this analysis are summarised in Table 1.

Table 1. Social and medical history of patients in groups (M ± m)

Indicator	Groups			
	Group 1 (n = 32)	Group 2 (n = 64)		Group 3 (n = 43)
		Subgroup 2A (n = 31)	Subgroup 2B (n = 33)	
Obesity	5 (15.62%)	3 (9.68%)	4 (12.12%)	7 (16.28%)
Smoking	4 (12.50%)	8 (25.81%)	7 (21.21%)	10 (23.26%)
Sedentary lifestyle	19 (59.38%)	21 (67.74%)	17 (51.52%)	26 (60.47%)
Professional factors (prolonged standing or sitting)	15 (46.88%)	16 (51.61%)	15 (45.45%)	23 (53.49%)
Leg trauma	1 (3.13%)	2 (6.45%)	0 (0.00%)	3 (6.98%)
Family history of CVD	16 (50.00%)	20 (64.52%)	20 (60.61%)	28 (65.12%)
Thrombotic history	6 (18.76%)	6 (19.35%)	7 (21.21%)	9 (20.93%)

Source: compiled by the author

According to the obtained results, 60.4% of patients across all groups and subgroups had a positive family history of venous pathology. These findings were consistent with the data of the nationwide Ukrainian study by L.M. Chernukha [21], in which approximately 62% of patients reported a family history of venous diseases. This further confirmed the importance of heredity in the development of CVD.

The second most prevalent risk factor was a sedentary lifestyle, identified in 59.7% of patients. Physical inactivity significantly affects overall health and is recognised as the fourth leading risk factor for global mortality. A sedentary lifestyle not only increases mortality but also substantially reduces the quality of life in patients with CVD. H. Kiloatar *et al.* [22] showed that a low level of physical activity was associated with a reduced quality of life. Moreover, the authors demonstrated that in patients with cardiovascular diseases who maintained moderate physical activity, the intensity of pain during exertion was lower. There is also evidence of the negative impact of sedentary behaviour on vascular health. C. Demiot *et al.* [23] showed that in a study of healthy women, 56 days of head-down bed rest reduced endothelium-dependent vasodilation and increased endothelial cell damage. These vascular alterations could be prevented by aerobic exercise and muscle training. Occupational factors such as prolonged standing or sitting were reported in 49.6% of patients. These findings were nearly consistent with those of a Swiss study, which showed that varicose veins were present in 56% of men

and 55% of women working in the chemical industry [24]. Another 12-year prospective cohort study conducted in Denmark found that prolonged standing increased the risk of hospitalisation for varicose vein treatment [25]. Smoking was recorded in 20.9% of cases. According to the 2023 national survey conducted by the World Health Organization [26], 27.4% of the Ukrainian population were smokers, including 44.0% of men and 13.7% of women. O. Hahad *et al.* [27] reported that cigarette smoke exposure is associated with endothelial dysfunction, primarily characterised by reduced vascular nitric oxide bioavailability due to increased superoxide production in the vascular wall. Thrombotic complications in the medical history of patients with CVD were reported in 20.1% of cases. R.A. Baylis *et al.* [28] showed that post-thrombotic syndrome develops in 23-60% of individuals with deep vein thrombosis (DVT). Furthermore, an epidemiological study based on the UK Biobank cohort found that a history of DVT increased the risk of developing varicose veins, with a hazard ratio (HR) of 2.6 [29]. Following a thrombotic event, affected veins may undergo fibrosis and wall thickening, further disrupting venous flow and contributing to the development of CVI, as well as increasing the risk of recurrent thrombosis [30].

Obesity, as a risk factor for CVD, was reported in 13.7% of patients. According to the World Health Organization (WHO) [31], as of 2022, approximately 890 million adults were living with obesity, which accounted for about

16% of the global adult population. In obese individuals, inflammation extends beyond adipose tissue due to continuous release of pro-inflammatory molecules by adipocytes. Moreover, as adipocytes enlarge, cellular stress due to hypoxia may occur, triggering danger signals and inflammatory mediators that amplify systemic inflammatory responses. In individuals with obesity, free fatty acids and reactive oxygen species activate the inflammatory cascade involving NF- κ B, accompanied by the release of pro-inflammatory cytokines [32].

The gender distribution of patients, presented in Table 2, revealed a predominance of female patients across all

study groups and subgroups, with 66.1% women and 33.9% men, respectively. These data correlate with the results of a study by H. Kim *et al.* [33], which confirmed a higher susceptibility to venous disease among women (73%) compared to men (56%). Researchers suggested that this may be attributed to the specific features of the female hormonal system, as well as the number of pregnancies and deliveries in medical history. M.A. Ortega *et al.* [34] showed that the greater the number of pregnancies, the more likely the development of CVD after the age of 40: up to 40% of women with 1-4 pregnancies and up to 65% of women with 5 or more pregnancies were diagnosed with CVD.

Table 2. Gender distribution in patient groups

Group	Women	Men	Total
1	22 (15.8%)	10 (7.2%)	32 (23%)
2A	22 (15.8%)	9 (6.5%)	31 (22.3%)
2B	20 (14.4%)	13 (9.4%)	33 (23.8%)
3	28 (20.1%)	15 (10.8%)	43 (30.9%)
Total	92 (66.1%)	47 (33.9%)	139 (100%)

Notes: percentages are relative to the full sample (n = 139)

Source: compiled by the author

P. Jain *et al.* [35] reported that systemic use of progestins, both alone and in combination with estrogens, was associated with a significantly reduced frequency of venous procedures for varicose veins in women. The effect was particularly pronounced in those receiving progestin-only therapy, who demonstrated the lowest rates of endovenous ablation, phlebectomy, and sclerotherapy compared to controls. It was also observed that this reduction applied not only to asymptomatic patients but extended to those with complicated forms of the disease, which typically require more active intervention. These findings suggest that systemic hormonal influence may affect the clinical expression and progression of varicose veins, and potentially reduce the likelihood of disease recurrence after treatment.

Furthermore, the influence of sex hormone-binding globulin (SHBG) levels on varicose vein development was investigated. It was shown that serum SHBG levels were positively associated with the risk of varicose veins in both sexes, particularly in women [36].

The severity of clinical manifestations of venous pathology in patients across the groups and subgroups was assessed according to the CEAP classification. The obtained data are presented in Table 3. This classification enabled a structured comparison of the distribution of clinical stages across treatment groups, highlighting both common and less frequent presentations. Such stratification is essential for understanding the burden of disease and for evaluating the appropriateness of applied therapeutic strategies.

Table 3. CEAP clinical class distribution by group

	Group 1 (n = 32)	Subgroup 2A (n = 31)	Subgroup 2B (n = 33)	Group 3 (n = 43)	Total
C3	16 (50%)	14 (45.2%)	18 (54.6%)	18 (41.9%)	66 (47.5%)
C4a	7 (21.9%)	11 (35.4%)	7 (21.1%)	15 (34.9%)	40 (28.8%)
C4b	3 (9.4%)	2 (6.5%)	2 (6.1%)	0 (0%)	7 (5%)
C4c	3 (9.4%)	0 (0%)	4 (12.1%)	4 (9.3%)	11 (7.9%)
C5	1 (3.1%)	1 (3.2%)	2 (6.1%)	2 (4.6%)	6 (4.3%)
C6	2 (6.2%)	3 (9.7%)	0 (0%)	4 (9.3%)	9 (6.5%)
Total	32 (100%)	31 (100%)	33 (100%)	43 (100%)	139 (100%)

Notes: percentages reflect group-specific CEAP class distribution

Source: compiled by the author

Analysis of the data presented in Table 3 revealed that the most frequently observed clinical manifestation across all groups and subgroups was lower limb oedema, corresponding to stage C3 of the CEAP classification, identified

in 47.5% of all patients. Pigmentation and eczema, consistent with stage C4a, were present in 28.8% of cases. The least frequent clinical manifestation was a healed venous ulcer (stage C5), detected in 4.3% of cases. These findings

were consistent with global epidemiological studies, which reported that stages C1-C3 were most frequently observed in clinical practice, while stages C5-C6 occurred less commonly [37]. For example, Z. Krasiński & B. Krasińska [38] showed that varicose veins classified as C2 were present in 25-40% of adults, whereas more advanced stages (C3-C6) were observed in 17-20% of the population. According to a nationwide Ukrainian epidemiological study by L.M. Cher-

nukha [21], the prevalence of CVD by CEAP classification was as follows: C0 – 1.7%, C1-C3 – 77.1%, C5 – 4.2%, and C6 – 3.2%. Analysis using the χ^2 test demonstrated that no statistically significant differences in CEAP class distribution were observed between the groups ($p > 0.05$). The study also investigated the distribution of clinical severity according to CEAP among male and female patients. The data are presented in Table 4.

Table 4. Gender distribution by CEAP clinical class

CEAP	Women	Men	Total
C3	49 (35.3%)	17 (12.2%)	66 (47.5%)
C4a	23 (16.6%)	17 (12.2%)	40 (28.8%)
C4b	5 (3.6%)	2 (1.4%)	7 (5%)
C4c	7 (5%)	4 (2.9%)	11 (7.9%)
C5	3 (2.1%)	3 (2.2%)	6 (4.3%)
C6	5 (3.6%)	4 (2.9%)	9 (6.5%)
Total	92 (66.2%)	47 (33.8%)	139 (100%)

Notes: percentages are relative to the full sample (n = 139)

Source: compiled by the author

Table 4 presents the distribution of 139 patients with chronic venous disease of the lower limbs by sex and CEAP clinical classes. The largest proportion of both women and men fell into class C3: 49 women (35.3%) and 17 men (12.2%). Classes C4a and C4c showed a relatively even gender distribution, with a slight predominance of women. Higher classes (C5 and C6) were less frequent, although the gender distribution remained relatively proportional. Overall, the data indicate a higher prevalence of chronic venous insufficiency among women, particularly at the stage corresponding to class C3 of the CEAP classification. It was found that in both sexes, clinical signs of the disease were most commonly observed at stages C3-C4a. However, the proportion of women was higher than that of men. The fewest women sought medical help for healed venous ulcers (C5), whereas among men, the least common presentation was lipodermatosclerosis (C4b). However, the study by M. Kiguchi *et al.* [39] confirmed that female patients presented with lower CEAP clinical classes at the time of admission compared to males. Although chronic venous diseases were more prevalent among women, men were more likely to present with trophic ulcers. The obtained results confirm that the distribution of CEAP clinical classes among patients with CVD differs by sex, which is consistent with the findings of K.P. Hong [40], who reported a higher prevalence of CEAP class C4 among men. This highlights the importance of considering sex-related clinical features when assessing disease severity and planning treatment. Stratifying patients based on clinical stage and gender may improve individual risk assessment and inform the choice of optimal treatment modality, particularly when determining indications for combined surgical approaches. Moreover, understanding such patterns can enhance early diagnosis and support the development of targeted preventive strategies to limit progression to advanced stages of chronic venous insufficiency.

Conclusions

This study focused on assessing the prevalence and clinical severity of CVD of the lower extremities using the internationally adopted CEAP classification system. A total of 139 patients with CVD at stages C3-C6 were included and analysed. The most frequently observed clinical class was C3, accounting for 47.5% of patients, followed by C4a (28.8%). More advanced forms of the disease (C5-C6) were documented in 10.8% of cases. Female patients comprised the majority of the study population (66.2%) and predominantly presented with C3-C4a stages, whereas male patients were more likely to present with C4b-C6 stages of the disease.

Throughout the study, the most relevant risk factors associated with CVD progression were systematically evaluated. A positive family history was present in 60.4% of patients, confirming its role as the leading risk factor in the development of venous pathology. Other common contributors included sedentary lifestyle (59.7%), occupational exposure in the form of prolonged sitting or standing (49.6%), smoking (20.9%), prior thrombotic events (20.1%), and obesity (13.7%). These findings are consistent with global and Ukrainian epidemiological data and highlight the multifactorial nature of CVD.

The CEAP classification proved to be an effective instrument for the clinical stratification of patients, offering a practical and evidence-based approach to assessing disease severity and guiding the selection of optimal treatment modalities. Its value is particularly evident when determining indications for combined surgical treatment strategies, where clinical stage, anatomical distribution of reflux, and underlying risk factors must be considered together. The study also contributes to a more detailed understanding of the epidemiological profile of patients with CVD in the stage of CVI. These data provide a foundation for structured decision-making and support the

implementation of standardised diagnostic and therapeutic protocols in daily phlebological practice. The empirical findings reinforce the importance of addressing modifiable risk factors, such as lifestyle and occupational habits, alongside timely diagnosis and intervention.

Looking forward, future research should be directed toward a deeper understanding of the pathophysiological mechanisms involved in venous wall remodelling. In particular, the role of matrix metalloproteinases (MMPs) and their tissue inhibitors (TIMPs) in relation to disease progression across different CEAP stages warrants further investigation. Additionally, the effectiveness and justification

of multimodal combined surgical treatment approaches in patients with advanced CVI remains a promising field for continued clinical and translational research.

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Conflict of Interest

None.

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Оцінка поширеності та тяжкості варикозної хвороби нижніх кінцівок за CEAP

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Анотація. Варикозна хвороба нижніх кінцівок (ВХНК) залишається однією з найпоширеніших патологій судинної системи, що суттєво знижує якість життя пацієнтів і потребує чіткого стандартизованого підходу до оцінки її тяжкості та поширеності. Впровадження міжнародної класифікації CEAP (Clinical, Etiological, Anatomical, and Pathophysiological) дозволяє систематизувати клінічні прояви хвороби та обґрунтувати вибір лікувальної тактики. Метою дослідження було визначення поширеності та ступеня тяжкості ВХНК за клінічними класами CEAP у пацієнтів із хронічною венозною недостатністю. Було обстежено 139 пацієнтів віком від 18 до 75 років із ВХНК у стадії C3-C6. Залежно від проведеного лікування пацієнтів розподілено на три клінічні групи. Усі хворі пройшли клінічне та ультразвукове обстеження з подальшою статистичною обробкою результатів. Найчастішим клінічним класом був C3, який виявлено у 47,5 % обстежених, клас C4a встановлено у 28,8 %, а тяжкі форми C5-C6 становили лише 10,8 % випадків. У жінок переважали форми C3-C4a, тоді як у чоловіків частіше діагностували C4b-C6. Серед основних факторів ризику визначено обтяжений сімейний анамнез (60,4 %), малорухливий спосіб життя (59,7 %), професійне навантаження у вигляді тривалого стояння або сидіння (49,6 %), а також куріння, ожиріння й тромботичні ускладнення в анамнезі. Статистично достовірної різниці у ступені клінічної тяжкості захворювання між групами лікування не виявлено. Отримані результати дозволяють окреслити епідеміологічний профіль пацієнтів із ВХНК у стадії хронічної венозної недостатності (ХВН), підтверджують високу поширеність клінічного класу C3 та надають емпіричну основу для подальших досліджень ефективності різних варіантів комбінованого хірургічного лікування з урахуванням топографії рефлюксу та анатомічних особливостей венозної патології. Практичне значення цього дослідження полягає в покращенні діагностичного та лікувального планування шляхом стратифікації пацієнтів за клінічним класом CEAP, що дозволяє приймати більш персоналізовані та науково обґрунтовані терапевтичні рішення

Ключові слова: хронічна венозна недостатність; клінічні стадії; комбіноване лікування; ендовенозна абляція; дуплексне ультразвукове дослідження; хронічне захворювання вен



Educational strategies and an individual approach to developing a responsible attitude towards oral hygiene

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Abstract. Oral hygiene is an important component of overall human health, as its condition directly affects the cardiovascular, endocrine, digestive and other systems of the body. Therefore, the aim of this study was outline effective strategies for establishing and maintaining oral hygiene among adolescents, based on survey data on their oral hygiene habits. An anonymous, face-to-face, cohort, cross-sectional survey of 55 adolescents aged 16-17 years was conducted. The results

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showed that the vast majority of adolescents brush their teeth twice a day and use fluoride toothpaste. However, only 3.6% use electric toothbrushes, despite their potential to improve hygiene habits, and only 40% use dental floss. There were a number of findings that require the attention of dentists to improve the situation: only 59.9% of respondents make preventive visits to the dentist; 38% of teenagers reported bleeding gums; 9% reported bad breath. A comparison of the results of the previous 2021 study with the results presented in this article showed that there are good reasons to believe that some progress has been made in introducing beneficial hygiene habits such as brushing teeth twice a day and using fluoride toothpaste. The results of the study indicate areas in which adolescents and their parents should be informed about the role of the dentist as a mentor, communicator and educator, as the main link in ensuring sustainable oral care and preventing systemic complications

Keywords: prevention of dental diseases; oral health; survey; testing of statistical hypotheses; adolescent hygiene

Introduction

Oral health is an important component of physical, mental, social and economic well-being for both individuals and society. Due to the increasing prevalence of periodontal disease, the growing popularity of fast food and carbonated sweet drinks, as well as a decline in preventive care and a lack of adequate hygiene education among young people, especially adolescents, there is a growing need for a systematic review of approaches to oral care. The formation of sustainable oral care habits in adolescence is critically important, as it is during this period that behavioural patterns are established that affect health throughout life. In this regard, it has become relevant to introduce personalised approaches to oral hygiene education, taking into account individual needs, motivation levels, the availability of hygiene products, and the capabilities of digital technologies. Such approaches should form the basis for improving the effectiveness of preventive dental care.

Numerous studies, in particular the work of N.I. Shovkova *et al.* [1], have emphasised the need to study oral hygiene habits as a prerequisite for the development of personalised approaches to hygiene education. The state of oral hygiene is considered to be a reflection of the overall health of the body. The publication by S.I. Boitsaniuk & M.O. Levkiv [2] states that the basic measures are regular brushing of teeth with a fluoride toothpaste. The modern literature covers a wide range of strategies for the prevention of oral diseases. In particular, the research of O.S. Almajed *et al.* [3] emphasised the role of social determinants of health in the formation of hygienic behaviour. The authors pointed out that educational level and access to medical care significantly affect the level of oral hygiene. The work of L.S. de Albuquerque *et al.* [4] analysed the effectiveness of school hygiene education programmes and emphasised their long-term impact on reducing the incidence of caries. The study by A. Murariu *et al.* [5] emphasised that the use of mobile applications contributes to improving hygienic behaviour among adolescents, especially when combined with individual consultations. These conclusions are supported by data from studies by E. Väyrynen *et al.* [6] and S. Sharma *et al.* [7], which showed that the use of digital platforms for feedback with patients increases their responsibility for the condition of their oral cavity, as well as increases the level of literacy in the field of oral hygiene, improves oral health and, thus, plays a key role in achieving overall health.

Numerous researchers have focused on the educational aspects of oral hygiene in Ukraine. In particular, S.P. Jarova *et al.* [8] pointed out the need to introduce a regional preventive programme for adolescents aimed at improving hygiene and monitoring the condition of the oral cavity, since the main reason for adolescents seeking periodontal care is catarrhal gingivitis, which is associated with poor oral hygiene. The authors noted that awareness remains insufficient and the frequency of preventive visits to the dentist is low. A study by I. Lisetska & M. Rozhko [9] confirmed the negative impact of smoking, both traditional and alternative, on oral hygiene. The data obtained emphasised the importance of systematic educational work by dentists to promote healthy habits and motivation to quit smoking. The publication by V.S. Melnyk *et al.* [10] also emphasised the need to strengthen the motivational component in the dentist's work with patients.

Given the importance of an individual approach in modern dentistry, more and more scientists and professional organisations are emphasising the need to adapt hygiene recommendations to the personal characteristics of each patient. For example, the American Dental Association (ADA) emphasises that no two people are exactly alike, and therefore the approach to oral care must be individualised [11]. Dentists should provide patients with personalised recommendations, taking into account their age, health status, existing diseases, lifestyle and level of motivation. According to C. Gallione *et al.* [12], such recommendations should be based on scientific evidence and take into account the latest data on the effectiveness of hygiene products.

At the same time, the combination of traditional hygiene education methods with modern mobile technologies, as well as the impact of a personalised approach on the level of compliance with hygiene recommendations among adolescents, remains insufficiently studied. The role of active communication by the dentist in this process has also been little studied, taking into account the patient's psychological profile, level of motivation and access to hygiene products. In this regard, the aim of the current study was to determine the level of their awareness of professional oral care and to justify the feasibility of implementing personalised, motivation-oriented hygiene education programmes using modern digital tools. The main tasks were: to conduct a survey of adolescents with an analysis of current hygiene practices; to identify

existing gaps in knowledge and motivation; to formulate recommendations for improving approaches to oral hygiene education in dental clinics and educational events.

Materials and Methods

As part of career guidance events held by the I.Ya. Horbachevsky Ternopil National Medical University of the Ministry of Health of Ukraine for prospective students (senior high school pupils in the city of Ternopil), an anonymous, in-person, cohort, cross-sectional survey was carried out on adolescents aged 16-17 years (Years 10-11 of secondary school), during September 2024 to February 2025. All pupils present at the events were included in the study. A total of 55 adolescents were surveyed, comprising 20 boys and 35 girls. Before participating in the study, all participants were given detailed information about the research goals and signed a consent form to confirm their willingness to take part. Participation in the survey was voluntary. The research was conducted with the informed consent of each individual in accordance with Ethics and data protection [13].

The questionnaire was developed independently by the authors based on an analysis of studies [4, 14]. All questions required a descriptive answer, without predefined answer options. The questionnaire included 11 questions covering the main aspects of oral hygiene and dental care:

- Indicate your gender and age.
- Do you brush your teeth twice a day?
- What type of toothbrush do you use (manual or electric)?
- How often do you replace your toothbrush?
- What brand of toothpaste do you use?
- Do you use mouthwash?
- Do you use dental floss?
- Do you use additional oral hygiene products (interdental brushes, single-tufted brushes, etc.)?
- How often do you visit the dentist for preventive check-ups?
- Have you experienced bleeding gums when brushing your teeth?
- Have you experienced bad breath that is not related to eating?

The results were processed and graphically represented using MS Excel spreadsheets. Descriptive statistics were used to analyse the results of this study [15]. A questionnaire was used to analyse the hygiene habits of adolescents and determine their level of awareness of the forms, methods and means of oral care. This made it possible to identify shortcomings and gaps in the preventive and educational activities of dentists working with adolescent and young adult patients.

Based on the results of the questionnaire, analysis of the data obtained, and a summary of current scientific sources on effective methods of doctor-patient communication, the main problems in the formation of hygiene habits among adolescents were identified. In accordance with these conclusions, a scheme for effective interaction between dentists and patients and a generalised scheme for

oral care were developed, combining preventive and educational approaches to maintaining the dental health of adolescents. The schemes were created based on the analysis of questionnaire data, clinical observations, and current recommendations from leading professional organisations (ADA, FDI). In addition, based on a review of the scientific literature, the possibilities of using digital and mobile technologies to improve the hygiene habits of adolescents were studied. This information was integrated into the doctor-patient interaction scheme as an additional element that enhances the motivational component and promotes the formation of sustainable hygiene habits in adolescents.

Results and Discussion

The survey results showed that 89.09% of schoolchildren brush their teeth twice a day, in the morning and in the evening, although a fairly high percentage – 10.9% – indicated that they brush their teeth only once a day. None of the students indicated that they brush their teeth less than once a day (Fig. 1).

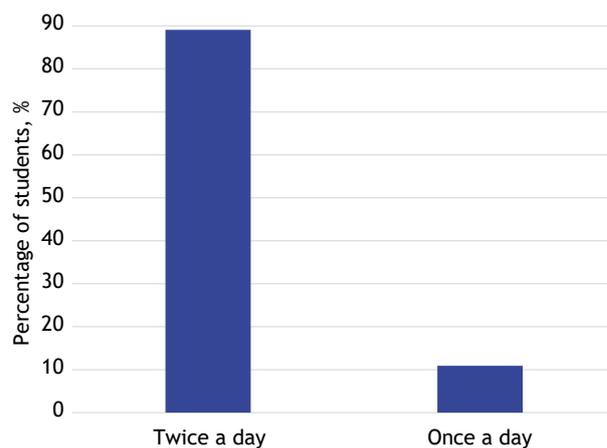


Figure 1. Frequency of tooth brushing
Source: created by the authors

The frequency of toothbrush replacement is important from a hygiene perspective. As the responses showed, the vast majority of adolescents (about 85%) change their toothbrushes regularly and frequently, with almost 42% of all respondents doing so more often than required by oral care standards – more often than every 2 months. Almost a third of teenagers do so every three months (Fig. 2). Only one in seven respondents (14.59%) replace their toothbrush less frequently than recommended by experts. In particular, according to the recommendations of the American Dental Association, manual toothbrushes should be replaced every 3-4 months to ensure effective cleaning of the teeth [16]. The frequent need to change toothbrushes, reported by 41.81% of adolescents, may be the result of improper brushing technique, excessive pressure of the toothbrush on the teeth, or the wrong choice of toothbrush. In this case, the use of an electric toothbrush with a sensor would help.

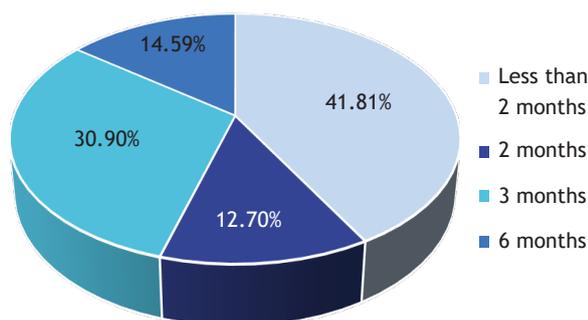


Figure 2. Frequency of toothbrush replacement among survey participants

Source: created by the authors

The survey results showed that the vast majority of respondents use regular toothbrushes, and only 3.63% of them brush their teeth with an electric toothbrush. All respondents also indicated that they use toothpastes containing 1,400 ppm of fluoride, which should provide a good caries-preventive effect. Almost half of the adolescents (43.63%) use mouthwashes, but in their responses they emphasised that they did not study the composition of the products and chose them based on the aroma for “fresh breath” (Fig. 3). In this regard, educational work should be carried out, taking into account that the composition of the rinse is important from a medical point of view, especially for adolescent patients. It should not contain alcohol or parabens, as these have a negative effect on the microflora of the oral cavity and periodontal tissue [17].

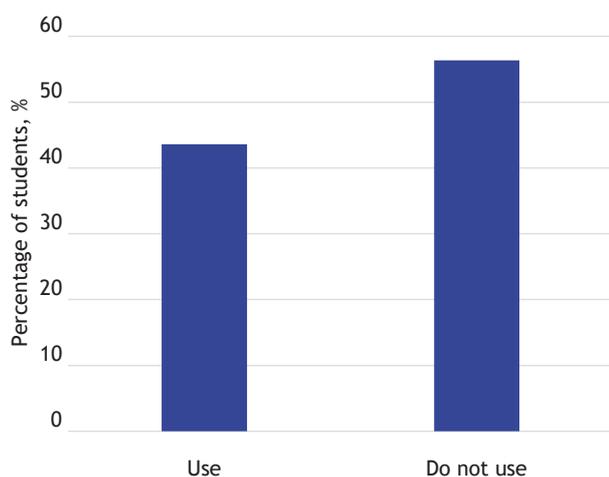


Figure 3. Use of mouthwash by survey participants

Source: created by the authors

As for additional oral hygiene products (dental floss, interdental brushes, single-tufted brushes), the study showed that they are not very popular among adolescents. In particular, less than half of respondents (40%) use dental floss to clean between their teeth (Fig. 4). Only 7.27% of schoolchildren use interdental brushes and single-tufted brushes, and only those who have braces (Fig. 5).

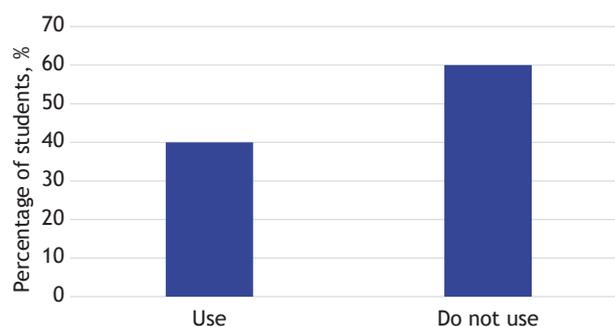


Figure 4. Use of floss

Source: created by the authors

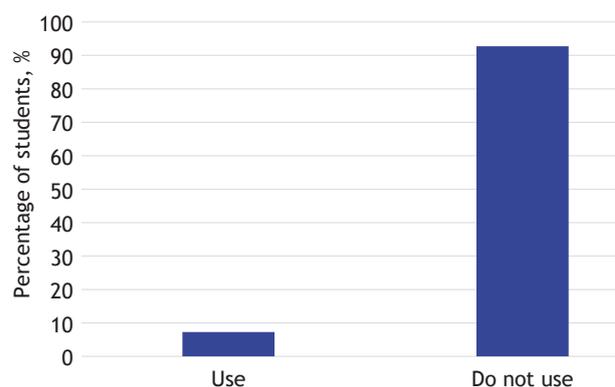


Figure 5. Use of additional oral hygiene products

Source: created by the authors

Such results indicate insufficient promotion of additional preventive measures to prevent the development of caries and periodontal diseases, particularly among school-age youth. At the same time, the survey showed that the majority of respondents undergo regular preventive dental examinations (Fig. 6). In particular, more than a quarter of respondents (27.27%) undergo such examinations twice a year, and 32.72% of students undergo them once a year. At the same time, 40.1% of respondents visit the dentist only when necessary. There is a need for educational work with both adolescents and parents, who need to be made aware of the importance of regular preventive check-ups, professional oral hygiene and the selection of individual oral care products.

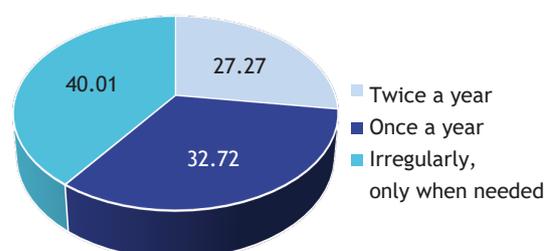


Figure 6. Frequency of preventive dental check-ups according to the survey results, %

Source: created by the authors

Due to the above-mentioned problems, a significant proportion of adolescents reported problems with periodontal tissue (bleeding gums, bad breath). 38.18% of adolescents indicated in the questionnaires that they experience bleeding gums, and 9.09% complained of bad breath (Figs. 7, 8). The high frequency of bleeding gums in adolescents may indicate the presence of an inflammatory process in the periodontal tissues, most often the initial manifestations of gingivitis.

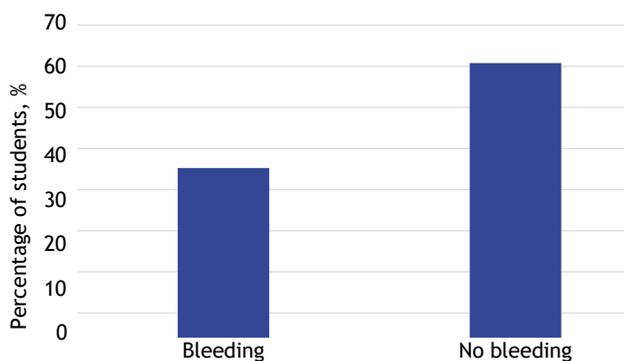


Figure 7. Presence of bleeding gums in respondents

Source: created by the authors

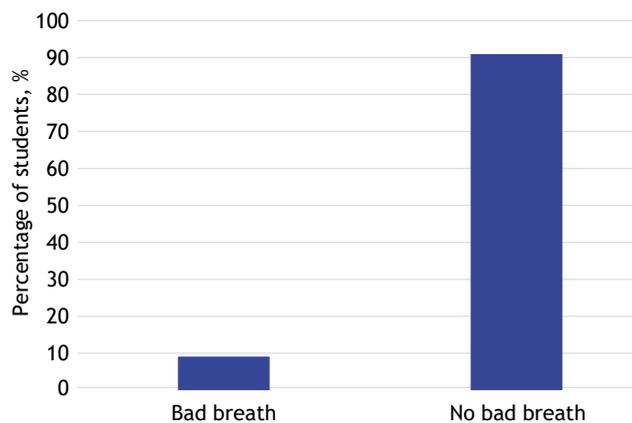


Figure 8. Presence of bad breath in the oral cavity in respondents

Source: created by the authors

Such changes may be caused not only by poor hygiene, but also by pubertal hormonal fluctuations. During puberty, increased sex hormone levels enhance vascularisation and reactivity of gum tissue, leading to the development of pubertal gingivitis even with relatively small amounts of plaque accumulation in the cervical area of the teeth. In addition, the risk of chronic gingivitis also increases in patients undergoing orthodontic treatment, which also occurs mainly in adolescence [18]. If these manifestations of the disease are not addressed and individual oral care is not adjusted, the disease will progress over time. The results obtained in the study indicate the need to raise awareness of dental care rules and the importance of regular visits to the dentist. Therefore, the level of oral hygiene found among

schoolchildren in the city of Ternopil indicates a need for improvement, which emphasises the importance of patient education as a leading factor in the formation and maintenance of healthy hygiene habits.

When analysing the results and comparing them with existing data in the literature, an increase in the level of dental literacy among children can be observed. Thus, the results of a survey of schoolchildren by S.V. Lebedyk & S.O. Konovalenko [19] showed that only about 30% of schoolchildren brush their teeth twice a day, while in the current study the percentage was more than 80%, which may indicate the effectiveness of educational measures. However, the different ages of the samples raise certain reservations, so this difference requires further research. In both cases, the percentage of schoolchildren who use fluoride toothpaste was approximately the same. The results differed slightly with regard to preventive examinations by a dentist. In the current case, 37% of respondents visited once a year, while in the available literature data from previous surveys, this figure was almost 50%. The methodology of this study differs from that of S.V. Lebedyk & S.O. Konovalenko [19], but some questions were the same, in particular, question 2 about the number of brushings per day and question 5 about the choice of toothpaste. The questionnaire for schoolchildren proposed in the current study did not contain questions related to mobile applications. The questionnaire conducted by the aforementioned researchers also included questions related to harmful habits, in particular early smoking and consumption of large amounts of sugar, whereas in the current survey these aspects were not taken into account, although the questionnaire was expanded and included questions about awareness of various hygiene products and the presence of early signs of periodontal disease. Analysing various data from the literature on anonymous surveys of schoolchildren, one can note the importance of this study and the need to create expanded questionnaires that include all questions that affect oral health. At the same time, it is necessary to take a differentiated approach to different age groups of schoolchildren, including various risk factors inherent in different age periods (changing bite, puberty, etc.).

Oral health is important for overall human well-being, as it determines the quality of chewing, speech, appearance, and is associated with the prevention of systemic diseases [20]. Scientific research by O. Denefil *et al.* [21] has shown that diseases of the teeth and gums can have a systemic effect on the cardiovascular, renal, cerebral, and digestive systems, forming a bidirectional pathophysiological link. Oral care is not only the key to a beautiful smile, but also an integral part of overall health. In this context, patient education takes on special significance, as dentists have the opportunity not only to explain the technique of brushing and flossing, but also to discuss the harmful effects of smoking, excessive sugar consumption and other risk factors. In addition, the topic of patient hygiene education is not limited to basic aspects and can cover a wider

range of individual recommendations and approaches to oral care, taking into account the patient's age, health characteristics, lifestyle and level of motivation.

Despite this, there are certain reasons that prevent people from visiting the dentist: fear of dental procedures, lack of time, financial difficulties, and underestimation of the importance of prevention. This requires both educational work and a careful approach to communication, as well as adaptive planning of visits [22]. Every visit to the dentist is extremely important, because it is during the examination that the doctor has the opportunity to teach the patient individual oral hygiene skills, assess the level of existing hygiene competencies, and explain in detail the benefits of professional care. Although this process requires considerable time, patience and a high level of communication skills, the results of such work are worth the effort. An analysis by B. Xiang *et al.* [23] showed that early

intervention in the formation of hygiene habits has a noticeable positive effect on the condition of the oral cavity in the long term. A study by N. Torlińska-Walkowiak *et al.* [24] found that regular visits to the dentist in childhood are associated with a better perception of oral health in adulthood. Patients with oral health problems often seek optimal solutions for the treatment of dental diseases. They rely on their dentists, who not only provide the necessary treatment, but also teach effective oral care and introduce modern methods of prevention.

Since each patient has a unique perception and different learning styles, it is important to take a personalised approach. Dentists can help patients master oral care skills by taking their individual needs into account. This process requires doctors to be accessible, actively listen, observe carefully, ask relevant questions, and adapt their teaching to each patient's specific needs (Fig. 9).

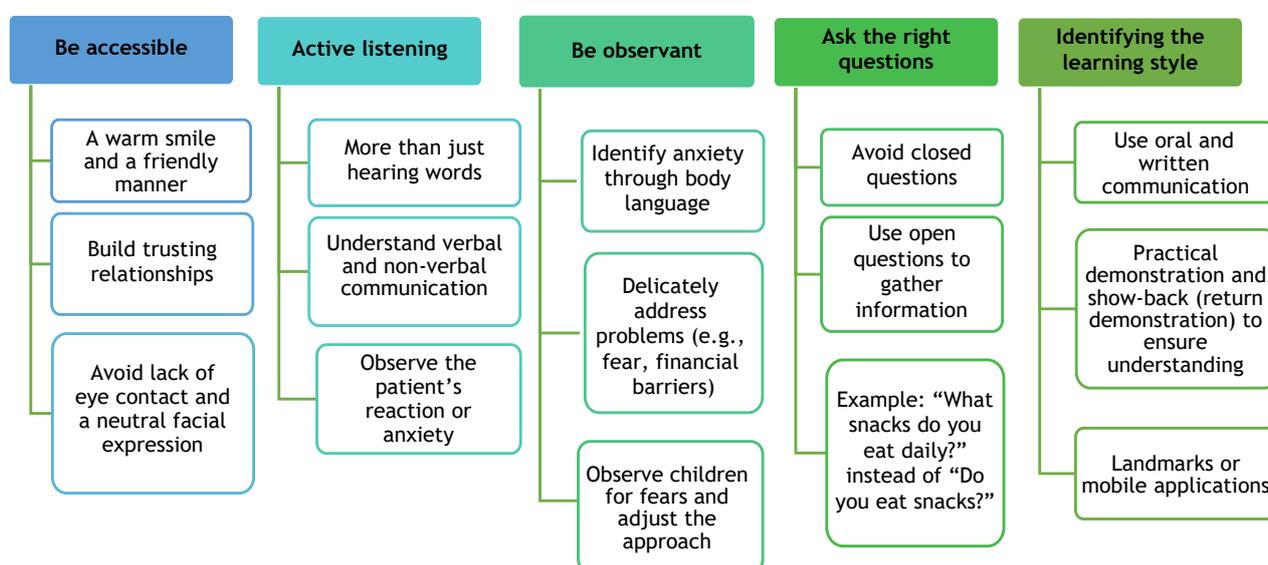


Figure 9. Diagram of effective interaction between dentist and patient

Source: created by the authors based on J.C.Y. Ho *et al.* [25]

As can be seen from the proposed scheme of communication with patients, the dentist must take a highly individual approach to each person, taking into account, first of all, their psycho-emotional state, how open and honest the patient is in their complaints and the reason for their visit to the doctor. This, in turn, will enable the dentist to build a proper dialogue with the patient, which will allow them to provide the patient with competent recommendations on oral hygiene. During regular check-ups, dentists can discuss the main aspects of dental care, such as proper brushing technique, flossing, and healthy diet. For example, the choice of toothpaste is very important for oral hygiene - toothpastes with probiotics that support oral health are especially popular today [26]. It is important to inform patients about the various products available for individual oral hygiene. The modern market offers a wide range of hygiene products [27]:

- manual and electric toothbrushes with different bristle stiffness and pressure sensors [28];
- toothpastes with fluoride, xylitol, enzymes, nano hydroxyapatite [29];
- alcohol-free mouthwashes (for children) or with chlorhexidine [17, 30];
- floss and interdental brushes for different interdental spaces;
- specialised products for patients with braces (single-tufted brushes, irrigators);
- probiotic or enzymatic products to support microflora [31].

These products allow for an individualised approach to care depending on the patient's needs. Regular and proper brushing and a healthy diet improve the condition of teeth and gums and help prevent oral diseases. Based on the results of the study, an oral care regimen was developed that

included recommendations not only for patients but also for dentists (Fig. 10). As can be seen in Figure 10, attention was focused not only on the need for brushing teeth and proper nutrition, but also on the importance of regular visits to the dentist, oral cancer screening, etc. The proposed actions form a closed cycle, emphasising a systematic approach to oral health prevention and maintenance. To effectively convey this information to schoolchildren, it is recommended to use interactive educational strategies based on the principles of active learning and a person-centred approach. In particular, it is worth combining

visual materials (posters, infographics), practical demonstrations (e.g., toothbrushing techniques on models), games (quests, quizzes), and introducing mini-lectures or master classes with the participation of medical professionals. An important tactical step is to create associative thinking, when oral care is perceived not as a routine activity, but as an integral part of overall well-being and a guarantee of self-confidence. It is also important to involve teachers and parents to ensure a triangle of interaction: student – school – family, which allows for the formation of stable hygiene habits.

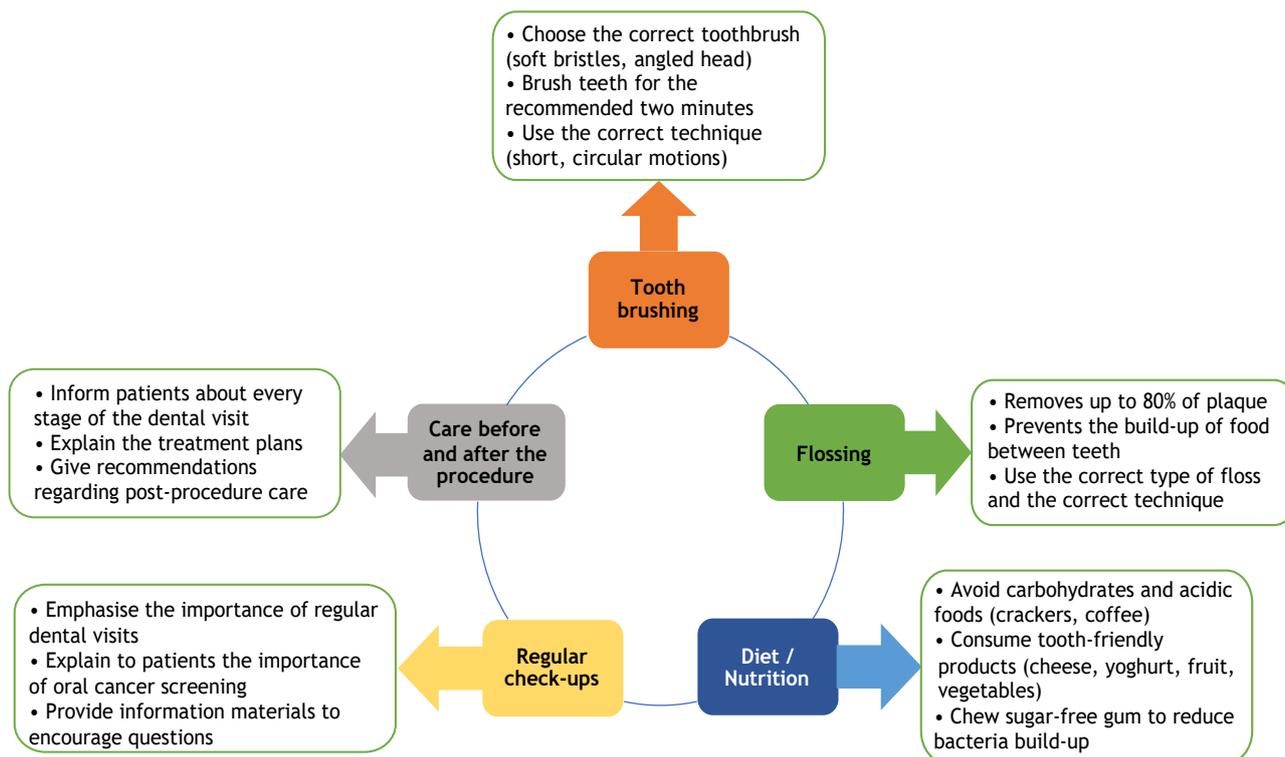


Figure 10. Diagram of basic dental care and oral health maintenance

Source: created by the authors

Modern technological advances have opened up new opportunities for the integration of mobile computing and communication devices into the healthcare system and public health sphere. According to the World Health Organisation (WHO) definition, mobile health, or mHealth, encompasses the use of mobile technologies – including smartphones, personal digital assistants and patient monitoring devices – in the delivery of healthcare and public health interventions. Scientists from the University of Hong Kong have demonstrated the importance of using mobile technologies to maintain oral health in elderly patients [32]. In their research, scientists A. Murariu *et al.* [5] assessed adolescents' awareness and use of various mobile applications related to oral health. For example, applications that track the time and technique of brushing teeth have proven to be effective in young people. These results are confirmed by studies conducted by other scientists. In particular, M. Alkilzy *et*

al. [33] showed in their studies how modern technologies allow the use of smart toothbrushes that connect to mobile applications and provide real-time feedback on brushing technique. A randomised controlled study by J.F.M. Scheerman *et al.* [34] in the Netherlands showed that using the WhiteTeeth mobile application in combination with regular care significantly improves oral hygiene in adolescents with fixed orthodontic appliances. The application provided educational materials and automatic coaching support, which contributed to a reduction in plaque levels. Studies show that mobile applications that track brushing time and technique are effective in improving oral hygiene among young people. They promote good habits, increase motivation and provide feedback, making them a valuable tool in the prevention of dental disease. It is important to take an individualised approach, which allows for the development of prevention programmes that address not only hygiene issues

but also lifestyle in general. This, in turn, will help improve oral hygiene skills and reduce the risk of dental problems.

Conclusions

The study was aimed at analysing the hygiene habits of adolescents, assessing their awareness of professional oral care, and justifying the feasibility of implementing personalised, motivation-oriented oral hygiene education programmes. It was found that the vast majority of adolescents brush their teeth twice a day and use fluoride toothpaste. At the same time, only 3.6% use electric toothbrushes, although recent studies show certain advantages of using modern tools in combination with phone applications. The survey also revealed a number of findings that require the attention of dentists in order to improve the situation. In particular, only 59.9% of respondents make preventive visits to the dentist. The following unsatisfactory facts were revealed during the research: 38% of adolescents reported bleeding gums; 9% reported bad breath. Given this, there is likely a lack of knowledge about the importance of regular visits to the dentist and professional oral hygiene.

Therefore, it can be assumed that the overall level of hygiene awareness and oral care among adolescents in general may be lower than that recorded in the current study, since the survey was conducted during career guidance events at a medical university among respondents who were likely to be more interested in their own health issues. This factor further emphasises the relevance and necessity of implementing targeted educational strategies to develop oral care skills among adolescents from different social groups. Taking into account the results obtained, the authors

propose an educational strategy in the form of an oral care plan containing recommendations for both patients and dentists. It emphasises the need for a comprehensive approach that covers not only the formation of hygiene skills and correction of eating behaviour, but also regular visits to the dentist, including preventive examinations and oral cancer screening. Systematic educational campaigns should be conducted among schoolchildren and their parents to foster a responsible attitude towards oral care from an early age, which, in turn, can form the basis for the prevention of dental diseases in the long term.

Further research should focus on the development, implementation and evaluation of the effectiveness of personalised educational programmes aimed at fostering a responsible attitude towards oral hygiene among adolescents. Particular emphasis should be placed on involving parents in such initiatives, as well as on studying the dynamics of changes in hygiene behaviour as a result of targeted information campaigns.

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Conflict of Interest

None.

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Освітні стратегії та індивідуальний підхід у формуванні відповідального ставлення до гігієни ротової порожнини

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Анотація. Гігієна ротової порожнини є важливою складовою загального здоров'я людини, адже стан її здоров'я безпосередньо впливає на серцево-судинну, ендокринну, травну та інші системи організму. Тому метою даної роботи було окреслити ефективні стратегії формування та підтримки гігієни порожнини рота серед підлітків, базуючись на даних опитування щодо їх звичок підтримання гігієни ротової порожнини. Проведено анонімне, очне, когортне, поперечне анкетування 55 підлітків у віці 16-17 років. Результати показали, що переважна більшість підлітків чистять зуби двічі на день і користуються фторвмісною пастою. При цьому лише 3,6 % застосовують електричні щітки, попри їх потенціал у покращенні гігієнічних звичок, і лише 40 % користуються флосами. Є ряд результатів, які вимагають уваги лікарів-стоматологів для покращення ситуації: профілактичні візити до стоматолога здійснює лише 59,9 % респондентів; 38 % підлітків зазначили кровоточивість ясен; 9 % вказали на неприємний запах із рота. Порівняння результатів попереднього дослідження 2021 року з результатами наведеними у даній статті, показали, що є вагомі підстави вважати, що досягнуто певного прогресу у впровадженні корисних гігієнічних звичок таких як чищення зубів двічі на день, та використання фторвмісних зубних паст. Результати дослідження показують напрямки, у яких слід проводити інформування підлітків та їх батьків про роль стоматолога як наставника, комунікатора й освітянина, як основної ланки у забезпеченні сталого догляду за ротовою порожниною та запобіганні системним ускладненням

Ключові слова: профілактика стоматологічних захворювань; здоров'я порожнини рота; опитування; тестування статистичних гіпотез; гігієна підлітків



Properties of yeast extract in functional nutrition: A review of the literature

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Abstract. Yeast extract, obtained from the intracellular contents of yeast, mainly *Saccharomyces cerevisiae*, is a promising natural ingredient in functional foods. The relevance of its research was due to the growing global demand for sustainable, nutritious and functional components, as well as its ability to improve the taste of products. Yeast extract production often uses agro-industrial waste, such as spent brewer's yeast, making it an environmentally friendly and cost-effective alternative to traditional protein sources. The aim of this study was to systematise and analyse the available scientific evidence on the nutrient profile, functional properties and mechanisms of action of yeast extract and its bioactive components. Methods of analysis and synthesis of scientific literature data were used, covering the results of *in vitro* and *in vivo* studies in animals and clinical trials in humans. The main results showed that yeast extract is an exceptional source of high-quality protein with a complete amino acid profile that surpasses many traditional plant and some animal sources. It is also rich in B vitamins, including B12, and a wide range of minerals, making it valuable for dietary enrichment, especially for vegetarians and vegans. Studies have found that yeast extract contains biologically active compounds such as beta-glucans, mannan-oligosaccharides, nucleotides and glutathione, each of which has proven functional properties. The synergistic action of these components provides a comprehensive health effect that exceeds the effects of individual ingredients. In addition, the ability of yeast extract to enhance umami flavour and mask bitterness is a critically important functional attribute that contributes to consumer acceptance and the effectiveness of functional products. The practical value of the work lies in substantiating the widespread use of yeast extract in functional foods and dietary supplements to improve overall health and well-being, taking into account its safety profile and the need for further research to optimise dosages and bioavailability

Keywords: *Saccharomyces cerevisiae*; beta-glucans; mannan-oligosaccharides; nucleotides; glutathione; immunomodulation

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Introduction

Yeast, single-celled eukaryotic fungi, has been known to mankind for centuries, especially the species *Saccharomyces cerevisiae* (baker's or brewer's yeast), which is key in bread baking and alcoholic beverage production. *Saccharomyces cerevisiae* is an important source of functional food additives. Yeast extract is a natural food ingredient obtained from the intracellular contents of various yeast strains, mainly *Saccharomyces cerevisiae*. Z. Tao *et al.* [1] indicated that its production usually involves autolysis or enzymolysis, processes that break down yeast cell walls to release a rich mixture of soluble components. Various production methods have been developed to obtain yeast extracts with specific properties, including autolysis, plasmolysis, enzymatic hydrolysis, and mechanical disruption, as investigated in the work of F. Demircü *et al.* [2]. Autolysis is the most common method, based on the use of yeast cells' own (endogenous) enzymes, incubating yeast at a temperature of 45-50°C at a controlled pH. According to research by F. Karshoğlu *et al.* [3], one of the key aspects of production is the extraction method. Hydrolysis can be enzymatic (with additional enzymes) or acidic, with the enzymatic approach considered to be gentler. Mechanical methods such as grinding, high-pressure homogenisation or ultrasonic treatment are effective for releasing intracellular components but carry the risk of degrading heat-sensitive compounds.

The resulting extract is a complex matrix containing high concentrations of proteins, peptides and free amino acids (including essential and branched-chain amino acids), B vitamins (B1, B2, B6, B12, folate), various minerals (magnesium, iron, zinc, potassium, phosphorus, calcium), carbohydrates, lipids and nucleic acids [1]. H. Wang *et al.* [4] investigated the properties of yeast extract in their work, namely its ability to impart a savoury, umami taste (due to natural glutamates, 5'-GMP and 5'-IMP, as well as various amino acids and peptides) and modulate bitter tastes in food products, its usefulness goes far beyond its taste qualities. As shown in a study by M. Whatnall *et al.* [5], yeast extracts can significantly improve the taste properties of foods. Its rich and diverse biochemical composition positions it as a powerful functional ingredient capable of providing significant health benefits. As noted by Y. Fu [6], the growing demand for natural and sustainable ingredients has increased interest in yeast extract. An important advantage of yeast extract is its production, which often utilises agro-industrial waste such as spent brewer's yeast. This was pointed out by F.F. Jacob *et al.* [7]. It offers an environmentally friendly and cost-effective alternative to traditional protein sources, in line with the principles of the circular economy, providing valuable nutrients and improving waste treatment. The ability to recycle waste and create a valuable product highlights its strategic importance in modern food production, where sustainability and cost-effectiveness are key factors, as also noted in the work of T. Upcraft *et al.* [8].

With growing demand for natural, functional and sustainable food ingredients, research into yeast extracts and their components is becoming particularly relevant.

Modern research confirms not only the taste but also the significant functional properties of yeast extracts, in particular their potential as a source of proteins, beta-glucans, mannan-oligosaccharides and nucleotides [3]. These properties determine their use in various fields, from dietary supplements to animal feed [1]. For example, a study by R. Pogranichniy *et al.* [9] showed that a probiotic feed supplement based on yeast ("Immunobacterin-D") has a positive effect on the productivity of cows during lactation, confirming the effectiveness of such components in veterinary practice. In addition, the production of yeast extracts from spent yeast contributes to the development of a circular economy and waste reduction [7]. Despite significant achievements, questions remain regarding the optimisation of methods for obtaining yeast extracts to maximise the preservation of biologically active components and the study of their complex effects on the organism. As noted by I. Teimouri *et al.* [10], continuous research is expanding understanding of the properties and applications of yeast extracts.

The aim of the current study was to comprehensively analyse and systematise the latest scientific data on the nutritional profile, functional properties and mechanisms of action of yeast extract, in particular *Saccharomyces cerevisiae*, and its key bioactive components. The objectives of the study were to analyse the chemical composition and nutritional value of yeast extracts, systematise their functional properties, and justify the prospects for using the extract to create functional foods and dietary supplements.

Forty-four peer-reviewed scientific articles were selected for analysis. The search for sources was conducted in the scientometric databases Scopus, Web of Science, PubMed, and the Google Scholar search engine. The inclusion criteria covered publications that highlighted the nutrient profile, production methods, functional properties, mechanisms of action of bioactive components (beta-glucans, mannan-oligosaccharides, nucleotides, glutathione), areas of application, and safety aspects of yeast extract. The search was conducted using the keywords: "yeast extract", "functional food", "*Saccharomyces cerevisiae*", "beta-glucans", "mannan-oligosaccharides", "nucleotides", "glutathione" and "immunomodulation". Particular attention was paid to relevant data, mainly published between 2015 and 2025, covering the results of *in vitro* and *in vivo* studies on animals and clinical trials on humans. The methodology consisted of systematising and comparatively analysing the information obtained. The data was structured into thematic blocks: nutrient composition, detailed consideration of the functional properties of each key bioactive component, practical application in various fields, and potential risks. The synthesis method was used to form generalised conclusions about the complex effect of yeast extract on human health and to identify promising areas for future research.

Nutrient profile of yeast extract

Yeast biomass is a significant natural source of nutrients, rich in protein (including enzymes, peptides and all

essential amino acids), carbohydrates, B vitamins and trace elements, with a low lipid content [1, 2, 10]. It can replace common allergens in food products. Regarding the allergenicity of yeast extract itself, it is important to note that it is generally considered safe and has “generally recognised as safe” (GRAS) status in many countries, including the United States (FDA), as confirmed in the Agency Response Letter [11]. However, scientific studies by X. Zonna *et al.* [12] and B. Sendid *et al.* [13] indicate the possibility of individual hypersensitivity or, more rarely, true allergy to yeast, in particular *Saccharomyces cerevisiae* and its extracts. There have been reported cases of allergic reactions, ranging from gastrointestinal disorders and skin rashes to, in very rare cases, anaphylaxis, are often associated with sensitisation to certain yeast proteins, such as enolase, or with cross-reactivity with other fungi. In addition, yeast extract produced from spent brewer's yeast may contain traces of gluten (from barley), which is an important consideration for individuals with coeliac disease or gluten sensitivity. Although yeast extract is sometimes associated with histamine intolerance, studies show that the extract itself may not contain high levels of histamine and that the problem may be related to other factors or contaminants.

When assessing the body's needs, protein plays a central role in the diet, being a fundamental structural and functional element of cells. Its importance as a nutrient lies in its supply of nitrogen and specific amino acids [6]. Although raw materials and food products are common sources of protein and amino acids, yeast protein biomass demonstrates a potentially higher protein content compared to traditional sources such as plant and animal proteins. G. Martin *et al.* [14] emphasise that the amount of protein in yeast biomass is usually equal to or greater than that in meat or soy protein and exceeds the protein content of milk. Thus, the average protein content in yeast can be 29-65% of dry weight, while in meat it is about 45% and in soybeans 35%. As noted by S. Lee *et al.* [15], this makes yeast extract an important component for overcoming protein deficiency and also highlights the high nutritional value of yeast proteins.

Yeast extracts are an important source of B vitamins, including thiamine (B1), riboflavin (B2), niacin (B3), pantothenic acid (B5), pyridoxine (B6), biotin (B7) and folic acid (B9). The amount of these vitamins may vary depending on the type of yeast and the specifics of production. Some products are additionally enriched with vitamin B12, which is especially valuable for vegetarians and vegans, as this vitamin is mainly found in animal products. B vitamins are critical for energy metabolism, nervous system function and many other physiological functions. Given their water solubility and inability to accumulate, regular consumption of B vitamins with food is essential. In this context, yeast extracts can be a convenient way to provide the body with these important nutrients, especially for certain population groups, according to research by E. Lee *et al.* [16]. The presence of B vitamins, especially B12, and a wide range of minerals indicates that yeast

extract may be a strategic ingredient for fortifying foods and supplements, helping to address common dietary deficiencies in certain population groups.

Yeast extracts contain a wide range of minerals and trace elements, including potassium, sodium, calcium, magnesium, iron, zinc, selenium, copper and phosphorus, as confirmed by research conducted by M. Mirzaei *et al.* [17]. Research by A. Ritala *et al.* [18] shows that yeast biomass is richer in nitrogen and ash than other microorganisms (fungi, algae, bacteria). The ash content is usually 5-10%, varying depending on the cultivation conditions. Thus, the presence of these minerals makes yeast extracts a valuable source of important micronutrients for the body, extending their significance beyond just improving taste.

The approximate nutrient content per 100 g of yeast extract may include: protein 45-70 g, significant amounts of B vitamins (B3 68.2-127.5 mg, B5 4.4-20.2 mg, B6 3.1-55.0 mg, B7 99.0-139.2 mcg, B9 1.4-5.8 mcg, B12 0.03-0.4 mcg) and minerals (potassium 1-2100 mg, sodium 1-3380 mg, magnesium 1.2-180 mg, iron 0.22-4.0 mg, zinc 0.13-4.2 mg, selenium 0.03-27.6 mcg), their amount varies depending on the production conditions and yeast culture [1]. The high protein content, which is transformed into free amino acids and peptides, including a complete set of essential amino acids, makes extracts a valuable nutrient. As T. Linder [19] pointed out in his work, the amino acid profile is similar to that of meat broth, and glutamic acid provides umami flavour. Thus, the lysine content in *Saccharomyces cerevisiae* protein is 65 mg/g, which is higher than in wheat (28 mg/g) and comparable to eggs (63 mg/g). In addition to the main nutrients, the extracts contain biologically active compounds: polypeptides, nucleotides, beta-glucans (with immunomodulatory properties), glutathione (antioxidant), mannans, chitin and ribose, which give them additional functional properties.

Functional properties and mechanisms of action

Yeast extract is a rich source of biologically active components that give it unique functional properties and determine its wide range of potential applications. Each of these components – from complex polysaccharides to essential amino acids and antioxidants – plays a key role in supporting various body systems, as confirmed by numerous scientific studies. Understanding the specific mechanisms of their action at the cellular and systemic levels is fundamental to the development of highly effective functional foods and dietary supplements aimed at improving health and well-being.

Beta-glucans

Beta-glucans are a heterogeneous group of non-starch polysaccharides consisting of D-glucose monomeric units linked by β -glycosidic bonds. Their biological activity depends largely on the specific source, molecular weight, degree of branching, and types of glycosidic bonds. Beta-glucans obtained from yeast, in particular *Saccharomyces cerevisiae*, are characterised by a β -(1.3) backbone

with β -(1.6) side chains. This specific structural conformation is largely responsible for their potent immunomodulatory properties. In contrast, cereal beta-glucans (e.g., from oats and barley) predominantly contain β -(1.3) and β -(1.4) bonds and are mainly associated with metabolic benefits such as cholesterol reduction and glucose regulation. Fractions with higher molecular weight and specific branching frequencies (0.20-0.33) are usually correlated with greater biological activity.

According to studies by E.J. Murphy *et al.* [20] and N.N.M. Habibullah *et al.* [21], understanding the source of beta-glucans is critical to their targeted application. If the product is aimed at supporting immune health, beta-glucans derived from yeast would be the scientifically sound choice. Conversely, for cardiovascular health (lowering cholesterol) or blood glucose control, cereal beta-glucans would be more appropriate. This understanding allows for the creation of highly targeted and effective functional foods.

Yeast beta-glucans are recognised by the immune system as “pathogen-associated molecular patterns” (PAMPs), triggering a strong immune response. As shown in a study by P. Vuscan *et al.* [22], *in vitro* they bind to immune cell receptors (Dectin-1, CR3, TLRs), activating macrophages, NK cells, neutrophils, enhancing phagocytosis and cytokine secretion. Some studies suggest the induction of a “trained immune response.” *In vivo* studies in animals have shown modulation of immune responses, increased resistance to infections, and antibody titres. This was pointed out by M. Maturana *et al.* [23]: in dogs, yeast products increased beneficial intestinal bacteria, which may indirectly affect immunity.

Convincing clinical evidence in humans has confirmed the immunomodulatory effects of yeast beta-glucans. A study conducted by a group of scientists led by K. Zhong *et al.* [24] showed that oral administration, usually at doses of 250 mg daily for at least 4 weeks, reduced the frequency and duration of upper respiratory tract infections (URIs). Research by N.N.M. Habibullah *et al.* [21] also confirmed a reduction in cold symptoms and an improvement in mood and fatigue in athletes. It has been demonstrated that the cell walls of brewer's yeast increase the level of immunoglobulin A (IgA) antibodies (critical for mucosal immunity), prevent a decrease in white blood cell count, increase the activity of natural killer cells, and reduce fatigue in humans. Their 12-week randomised, double-blind, placebo-controlled clinical trial demonstrated the efficacy of yeast beta-glucans (1.3/1.6) at reduced doses (120 mg and 204 mg) on symptoms of respiratory infections, fatigue, immune markers, and gut health in adults experiencing moderate stress. In turn, a study by K. Zhong *et al.* [24] also confirmed the immunomodulatory properties of beta-glucans.

In addition to immune and metabolic effects, yeast beta-glucans also exhibit significant antioxidant, antitumour and antimicrobial properties, as shown in the work of G. Gauterio *et al.* [25]. They function as prebiotics,

promoting the growth of beneficial intestinal bacteria, which has a positive effect on the intestinal microflora and the overall condition of the digestive system. This effect on the intestinal microbiota is important for maintaining overall health. In addition, beta-glucans have been shown to have wound healing potential, which can accelerate regeneration processes by stimulating cell proliferation and collagen synthesis, especially in hard-to-heal ulcers. They also promote the binding of mycotoxins, helping to detoxify the body by adsorbing these harmful substances. These diverse properties highlight the multifunctionality of yeast beta-glucans in supporting health and their potential for use in functional foods and pharmaceuticals.

Mannan-oligosaccharides

Mannan-oligosaccharides (MOS) are low-molecular-weight carbohydrates (mainly composed of mannose) derived from the cell walls of *Saccharomyces cerevisiae*. A distinctive feature of MOS that differentiates them from certain other oligosaccharides is their resistance to digestion by host enzymes in the upper gastrointestinal tract, allowing them to reach the large intestine intact. They act primarily through pathogen agglutination and immunomodulation. *In vitro* studies have shown that MOS promote the growth of *Bifidobacterium* and *Lactobacillus* species and stimulate the production of short-chain fatty acids (SCFAs), as noted by W. Zhao *et al.* [26]. *In vivo* studies in animals have demonstrated that MOS bind to pathogens (*Salmonella*, *E. coli*, *Clostridia*), preventing their adhesion and colonisation, as reported by M. Kamal *et al.* [27]. They also improve intestinal morphology, modulate the gut microbiota (for example, by reducing the *Firmicutes/Bacteroidetes* ratio in mice), alleviate obesity and metabolic syndrome, and lower cholesterol levels.

Although direct clinical data on the effects of mannan-oligosaccharides (MOS) in humans are still emerging, existing studies on postbiotics derived from *Saccharomyces cerevisiae* extracts show significant potential. Results from a randomised pilot trial by I. Pinheiro *et al.* [28] demonstrated that a yeast fermentate (EpiCor) can effectively reduce gastrointestinal discomfort, including bloating and distension, in individuals suffering from constipation. The authors attributed this effect to positive modulation of the gut microbiota, including an increase in beneficial *Bifidobacterium* populations. The mechanisms underlying these changes are partly explained by *in vitro* studies, such as the work of C. Duysburgh *et al.* [29], which demonstrated that a postbiotic derived from *Saccharomyces cerevisiae* alters microbial metabolism in the distal colon, thereby generating immunomodulatory potential. The immunomodulatory action of such postbiotics is further supported by research from N. Kango *et al.* [30], while a study by R. Singh *et al.* [31] found that a yeast-based postbiotic was effective in reducing symptoms of colds and influenza in healthy children, indicating a systemic effect on immune function. Moreover, MOS exhibit pronounced anti-inflammatory properties by modulating intestinal inflammatory responses, as observed in various animal studies [27].

They can suppress the production of pro-inflammatory cytokines and activate anti-inflammatory pathways, thereby supporting the integrity of the intestinal barrier. These oligosaccharides also enhance the immunological functions of animals by stimulating cellular, humoral, and mucosal immunity through interactions with immune cells associated with gut-associated lymphoid tissue (GALT).

Nucleotides

Nucleotides are the fundamental building blocks of deoxyribonucleic acid (DNA) and ribonucleic acid (RNA), making them indispensable for all cellular processes associated with genetic information, including cell division, protein synthesis, and gene expression. Beyond their genetic roles, nucleotides are central to cellular energy metabolism, serving as components of adenosine triphosphate (ATP) – the cell's primary energy currency. They also function as key signalling molecules (for example, cyclic AMP and cyclic GMP) in a variety of intracellular and intercellular signalling pathways, including those that regulate immune responses.

Exogenous intake of nucleotides becomes important during periods of rapid growth, stress, or illness, when endogenous synthesis is insufficient – particularly for immune and gastrointestinal cells, as noted by J. Gene-Morales *et al.* [32]. *In vivo* supplementation with nucleotides supports growth and immunity by promoting the proliferation of T and B lymphocytes, NK cells, and macrophage activity [16]. Given their critical functional roles, the European Commission has approved the use of nucleotides in infant nutrition. Clinical trials have provided compelling evidence of their health benefits. Studies have shown that infants fed formula enriched with nucleotides exhibited higher production of natural killer (NK) cells compared with breastfed infants. In adult women, nucleotide supplementation (1.0 mg/day for four weeks) resulted in a twofold increase in T lymphocytes (CD3+, CD4+, CD8+), indicating an enhancement of cellular immunity [32]. According to A. Singhal *et al.* [33], randomised controlled trials in infants consistently demonstrated that the addition of nucleotides (approximately 31 mg/L) promotes greater weight gain and improved head growth (head circumference) from birth to 8 weeks.

Nucleotides accelerate tissue repair following surgery by playing a key role in cellular regeneration and DNA/RNA synthesis for the restoration of damaged structures. They also support muscle recovery and growth through enhanced protein synthesis, making them beneficial for physically active individuals and those recovering from exercise or injury. Of particular interest is their contribution to neuroprotection and brain development, as nucleotides play a crucial role in the formation of neuronal connections and in processes related to learning and memory. This also suggests potential in mitigating cognitive decline in older adults by supporting nervous system health [32]. Thus, nucleotides are multifunctional compounds that sustain vital physiological processes throughout the human lifespan and across different states of health and activity.

Glutathione

Glutathione (GSH) is a tripeptide (glutamine, glycine, cysteine) and one of the most powerful endogenous antioxidants. It exists in reduced (GSH) and oxidised (GSSG) forms, and the GSH/GSSG ratio is a critical indicator of cellular redox status and a marker of various diseases and ageing processes. It neutralises reactive oxygen and nitrogen species (such as free radicals and hydrogen peroxide), and its deficiency leads to increased oxidative stress, which is associated with the pathophysiology of numerous chronic diseases. J. Richie *et al.* [34] demonstrated that, in addition to directly eliminating free radicals, GSH plays a central role in detoxification processes by conjugating with various electrophiles and maintaining the activity of key antioxidant enzymes such as glutaredoxins and glutathione peroxidases.

Oral supplementation with GSH increases blood GSH levels and reduces markers of oxidative damage in patients with type 2 diabetes, especially in older individuals, where a decrease in HbA1c (a key long-term marker of blood glucose levels) and an increase in fasting insulin, indicating its potential as an adjunctive therapy to traditional antidiabetic treatments, as pointed out by A. Al-Temimi *et al.* [35] in their study. Low GSH levels are closely associated with various liver diseases, including hepatitis, cirrhosis, and metabolically associated fatty liver disease, and it has been shown that in such cases, GSH supplementation improves blood protein, enzyme, and bilirubin levels.

Chronic inflammation, characteristic of autoimmune diseases (e.g., rheumatoid arthritis, lupus), exacerbates oxidative stress. GSH helps alleviate this stress by modulating the immune response and directly protecting cell mitochondria from free radical damage [35]. This helps reduce tissue damage and maintain cellular health in conditions of chronic inflammation. Although direct absorption of intact GSH is limited, oral supplementation has positive results. This is possible due to the absorption of amino acid precursors (especially cysteine), which are necessary for the synthesis of glutathione in cells, as well as the stimulation of endogenous GSH synthesis by the body itself. Thus, even despite the peculiarities of absorption, glutathione supplementation can effectively replenish its stores and support the antioxidant system.

The synergistic action of yeast extract components such as beta-glucans, mannan-oligosaccharides, nucleotides and glutathione provides a comprehensive health effect that exceeds the effects of individual ingredients, as demonstrated by H. Han *et al.* [36]. For example, beta-glucans and MOS work together to support the immune system and gut health, while nucleotides enhance cellular repair and glutathione provides antioxidant protection. This multi-component matrix allows yeast extract to have a more powerful and comprehensive effect on the body than would be possible from isolated compounds.

The use of yeast extract in various industries

The wide range of functional properties of yeast extract determines its versatile application in various fields. Thanks

to its rich biochemical composition and versatility, yeast extract is widely used not only as a food supplement, but also in pharmaceuticals, animal husbandry and agriculture, demonstrating high efficiency in improving product quality and maintaining health. This makes it a strategic component in the development of innovative products that meet modern consumer demand for natural, healthy and functional solutions.

In the food industry, yeast extract is widely used as a flavour enhancer, particularly to impart umami and savoury notes. It also masks unwanted flavours and bitterness, which is particularly valuable when creating products with reduced salt, sugar and fat content, helping product developers maintain flavour appeal, as demonstrated by M. Ciudad-Mulero *et al.* [37], Ş. Yilmaz [38] and A. Alim *et al.* [39]. Yeast extract is used in soups, sauces, snacks, meat and vegetarian products, seasonings, and as a substitute for monosodium glutamate. Due to its nutrient content, it also serves to enrich products with protein, B vitamins and minerals. Its use as a functional ingredient contributes to the creation of products that are not only tasty but also healthy. A well-known example of the widespread use of yeast extract in the food industry is the Australian paste Vegemite, developed in 1922. This thick, dark brown mixture, made from yeast extract supplemented with vegetable extracts and spices, is distinguished by its unique salty, bitter umami taste [5]. This flavour profile is due to the natural presence of significant amounts of free amino acids and nucleotides, which are key components of yeast extract.

Yeast extract is a valuable component in pharmaceuticals and dietary supplements due to its immunomodulatory, anti-inflammatory and antioxidant properties. The beta-glucans and MOS contained in the extract are used to boost immunity, support gut health and prevent infectious diseases [21, 24, 27]. Nucleotides are key to tissue repair, cell growth and immune function support, especially under conditions of stress or rapid growth, making them important for infant formulas and restorative preparations [32, 33]. Glutathione, as a powerful antioxidant, is used to reduce oxidative stress and support detoxification processes in the body [34, 35]. These components make yeast extract attractive for the development of functional products aimed at improving overall well-being, increasing the body's resistance and supporting metabolic health.

In animal husbandry, yeast extract is an effective supplement for improving animal productivity and health. Adding it to feed improves immunity, reduces morbidity and promotes better nutrient absorption. In addition, the presence of proteins, amino acids and B vitamins contributes to better weight gain and overall health of animals. For example, J. Sun *et al.* [40] found that yeast extract improves growth performance and antioxidant capacity in young flounder. This multifaceted effect makes yeast extract a valuable ingredient in the production of feed for farm animals, aquaculture and pets.

Yeast extract is also used in agriculture to improve plant growth and protection. The internal components of

yeast cells are rich in various amino acids that can form complexes with trace elements, improving their bioavailability to plants. Unlike other sources that contain only a few amino acids, yeast extract obtained from certain strains of *Saccharomyces cerevisiae* provides a balanced supply of amino acids in a form that is easily absorbed by plants. A study by M. Vargas Perucca *et al.* [41] has shown that it provides precise nutrition for crops, quickly overcomes nutrient deficiencies, reduces stress from herbicides, maintains yield potential, and protects the soil and the environment. N. Gatti *et al.* [42] investigated the effect of a biostimulant obtained from seaweed and yeast extracts on the secondary metabolism of different apricot varieties and proved that it had a positive effect on the biosynthesis of key biologically active compounds, such as polyphenols, flavonoids, proanthocyanidins and anthocyanins, in both the flesh and skin of apricots. Thus, the multifaceted properties of yeast extract and its bioactive components make it not only an effective nutritional biostimulant, but also an environmentally sustainable solution for optimising crop productivity and increasing their resistance to stress factors.

Risks and limitations of yeast extract use

Yeast extract has a high content of nucleic acids (RNA), which can be metabolised into purines. Excessive consumption of purines can increase blood uric acid levels, which is a risk factor for the development of gout. This is noted by W.S. Jeong *et al.* [43]. However, their study showed that the increase in uric acid levels from yeast extract is less pronounced than from meat or seafood. It should also be noted that the purine content in yeast extracts varies significantly depending on the yeast strains and processing methods. This requires manufacturers to control the nucleic acid content in products and inform consumers, especially those who are prone to gout or hyperuricaemia.

Yeast extract is not generally considered a major allergen. However, in some cases, people with increased sensitivity to yeast or its components may experience allergic reactions. According to EURaSYF, yeast extract is not subject to mandatory labelling as an allergen because it does not contain proteins that cause allergic reactions. It should be distinguished from active yeast. However, when manufacturing products, it is important to consider the individual sensitivity of consumers and the possibility of cross-reactions in rare cases.

Some yeast extracts may contain significant amounts of sodium, which may be a problem for people on a low-sodium diet. However, as noted by Z. Tao *et al.* [1], there are also low-sodium yeast extracts on the market. The use of yeast extract can reduce the overall salt content in foods due to its ability to enhance umami flavour, which can compensate for sodium reduction without compromising taste [38].

Research by H. Li *et al.* [44] showed that the use of yeast extract can cause the excitation of neurogenic and myogenic motor patterns in the large intestine of rats. Interestingly, this effect was similar to that of monosodium glutamate

and inosine monophosphate. Although this study was conducted on animals, it highlights the need for further study of the effects of yeast extract on the human gastrointestinal tract, especially in high doses. Such studies may help to better understand potential side effects or mechanisms of action beyond taste perception.

Yeast extract has “Generally Recognised as Safe” (GRAS) status in the United States, allowing it to be used as a food ingredient without prior FDA approval [11]. In the European Union, its regulatory status depends on its primary function in a food product: it can be classified as a food ingredient with nutritional properties or as a flavouring. If its primary function is to impart or modify taste and/or smell, it falls under EU regulations on flavourings. Importantly, yeast extract obtained by traditional methods is not a food additive but a natural ingredient, which distinguishes it from synthetic flavour enhancers such as monosodium glutamate [39].

Despite certain risks and limitations that have been considered, such as the potential impact on uric acid levels in susceptible individuals, rare allergic reactions, sodium content, or possible effects on gastrointestinal motility at high doses, yeast extract is generally recognised as a safe ingredient. Its natural origin, the possibility of reducing the salt content in products, and its regulatory status as a natural ingredient rather than a food additive underscore its advantages. Therefore, when used responsibly and with consumer information, yeast extract remains a valuable and safe ingredient in various industries.

Conclusions

A review of scientific evidence, covering reliable *in vitro* and *in vivo* studies and increasingly convincing clinical trials in humans, clearly substantiates the significant and growing role of yeast extract and its key bioactive components in functional nutrition. Yeast extract, as a natural, sustainable and nutritious ingredient, provides a unique combination of β -glucans, mannan-oligosaccharides, nucleotides and glutathione. Each of these components provides distinct but often synergistic health benefits, allowing for a more comprehensive and powerful effect on the body than individual ingredients alone. These benefits range from powerful immune modulation and significant improvements in gut health to metabolic regulation and crucial support

for growth and recovery in various physiological states. In particular, studies have shown that β -glucans activate immune cells such as macrophages and NK cells, increasing the body's resistance to infections. Mannan-oligosaccharides have been shown to improve intestinal morphology, modulate its microbiota, and bind pathogens, promoting a healthy digestive system. Nucleotides have been found to be critical for immune cell proliferation and accelerated tissue repair, which is especially valuable during rapid growth and after injury. Glutathione, as a central antioxidant, effectively combats oxidative stress, supporting overall cellular integrity and detoxification processes. Although considerations such as nucleic acid content require careful formulation, the overall profile of yeast extract confirms it as a valuable, multifunctional ingredient for the development of innovative functional products aimed at improving overall human health and well-being.

Despite compelling evidence, several areas require further research to fully unlock the potential of yeast extract in functional nutrition. Further clinical trials in humans are needed to study the full range of benefits for the immune system and other health parameters, namely: determining optimal dosages, studying the bioavailability of exogenous glutathione, gaining a deeper understanding of the molecular mechanisms of structural differences in beta-glucans and their impact on biological activity, and integrating an understanding of the effects of yeast components on metabolism and their immunomodulatory effects. Addressing these issues will enable the development of more targeted and effective functional foods. These research gaps are strategic priorities for future scientific research. Addressing them will not only deepen the understanding of the mechanisms of action of yeast extract, but also enable the development of more targeted, effective and scientifically sound functional foods, contributing to progress in this field.

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Conflict of Interest

None.

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Властивості дріжджового екстракту у функціональному харчуванні: огляд літератури

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Анотація. Дріжджовий екстракт, отриманий з внутрішньоклітинного вмісту дріжджів, переважно *Saccharomyces cerevisiae*, є перспективним природним інгредієнтом у функціональному харчуванні. Актуальність його дослідження зумовлена зростаючим світовим попитом на стійкі, поживні та функціональні компоненти, а також його здатністю покращувати смакові якості продуктів. Виробництво дріжджового екстракту часто використовує агропромислові відходи, такі як відпрацьовані пивні дріжджі, що робить його екологічно чистою та економічно вигідною альтернативою традиційним джерелам білка. Метою цієї роботи було систематизувати та проаналізувати наявні наукові докази щодо нутрієнтного профілю, функціональних властивостей та механізмів дії дріжджового екстракту та його біоактивних компонентів. Було використано методи аналізу та синтезу даних наукової літератури, що охоплювали результати досліджень *in vitro* та *in vivo* на тваринах та клінічних випробувань на людях. Основні результати показали, що дріжджовий екстракт є винятковим джерелом високоякісного білку з повним амінокислотним профілем, який перевершує багато традиційних рослинних та деякі тваринні джерела. Він також багатий на вітаміни групи В, включаючи В12, та широкий спектр мінералів, що робить його цінним для збагачення раціону, особливо для вегетаріанців та веганів. Дослідження виявили, що дріжджовий екстракт містить біологічно активні сполуки, такі як бета-глюкани, манан-олігосахариди, нуклеотиди та глутатіон, кожна з яких має доведені функціональні властивості. Синергічна дія цих компонентів забезпечує комплексний вплив на здоров'я, що перевершує ефекти окремих інгредієнтів. Крім того, здатність дріжджового екстракту посилювати смак умам та маскувати гіркоту є критично важливим функціональним атрибутом, що сприяє прийняттю споживачами та ефективності функціональних продуктів. Практична цінність роботи полягає в обґрунтуванні широкого застосування дріжджового екстракту у функціональних харчових продуктах та дієтичних добавках для покращення загального здоров'я та добробуту, з урахуванням його профілю безпеки та необхідності подальших досліджень для оптимізації дозувань та біодоступності

Ключові слова: *Saccharomyces cerevisiae*; бета-глюкани; манан-олігосахариди; нуклеотиди; глутатіон; імунomodуляція



Virtual and augmented reality in healthcare management mechanisms for maintaining public health: Literature overview

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Abstract. The study aimed to analyse scientific data on the use of virtual and augmented reality technologies in the practical work of doctors. The main results of the study showed that virtual and augmented reality are actively transforming the medical field, offering new opportunities to improve the quality of medical services. In particular, these technologies are effectively used in dentistry for treatment and prosthetics, in ophthalmology for diagnosis and vision training, as well as in psychiatry and psychological assistance for the treatment of phobias, post-traumatic stress disorder (PTSD) and anxiety. In addition, VR and AR technologies have proven effective in the rehabilitation of patients after strokes, traumatic brain injuries, and in the restoration of motor functions after orthopaedic surgery and amputations. Of particular note is the role of VR and AR technologies in planning complex operations, where they can be used by surgeons to pre-model interventions and receive visual cues in real time, reducing the trauma of operations and increasing their effectiveness. In rehabilitation programmes, VR and AR are becoming crucial tools for the physical and cognitive rehabilitation of patients, providing effective methods for restoring motor and cognitive functions. Another relevant aspect is the use of VR and AR for training medical professionals, which can be used to practise in conditions close to real life without risk to patients, thereby improving the level of professional training of doctors. This review not only showed how virtual tools can be used to solve specific problems in medicine, but also encouraged a further analysis of the processes taking place in the healthcare sector under the influence of the latest information and communication developments

Keywords: virtual technologies; non-drug treatment; patient rehabilitation; VR simulators

Introduction

At the beginning of the 21st century, virtual reality (VR) and augmented reality (AR) have become an integral part of the modern digital world, changing approaches to learning, entertainment and professional activities. They create new opportunities for interacting with information, creating intuitive tools for analysis, visualisation and learning. These technologies are substantial in healthcare, where their application improves the quality of diagnosis, treatment, and rehabilitation of patients. Studies demonstrate the high potential of these technologies in medicine. S. Bin *et al.* [1] described in detail the use of VR and AR technologies in various biomedical fields, particularly in surgical practice. For example, when planning operations, VR simulations help surgeons visualise and plan

complex surgical procedures; in minimally invasive surgery, AR technologies are used to superimpose images, such as computed tomography (CT) or magnetic resonance imaging (MRI) data, onto the patient's actual body, which improves the surgeon's orientation during the operation. Scientists have described how VR and AR can be used to train medical students. For example, creating realistic virtual simulations can be used to practice surgical skills or diagnostics without risk to the patient.

The demand for such technologies is growing rapidly. According to a report by Fortune Business Insights [2], the global market for virtual reality in healthcare was worth approximately 4.18 billion USD in 2024. The market is projected to reach 46.37 billion USD by 2032, with a

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compound annual growth rate (CAGR) of 35.1%. This information demonstrates significant market growth, confirming the research relevance and the high demand for these technologies in the medical field.

These technologies are key elements of the digital transformation of healthcare systems. They are used to overcome traditional barriers in the training of medical professionals, communication with patients, and the organisation of treatment processes. Virtual and augmented reality technologies are quite effective in projecting relevant digital information (images, videos, text, graphics) outside of device screens and combining relevant virtual objects with the real environment. For instance, D. Oyekunle *et al.* [3], researching the use of AR and VR in simulation training in clinical education, confirmed that these technologies can be used by medical students and practising specialists to gain a realistic experience of operations and clinical scenarios, reducing the likelihood of errors during real procedures. The study noted that VR/AR improve the quality of diagnosis and treatment, enhances interaction between doctors and patients, and contributes to savings in training costs. Studies showed that VR simulations improve information retention using virtual patients and the reproduction of real-life situations, which can be used for practice at any time. The study of augmented reality has been included in the curricula of most medical specialities. Thus, T. Tene *et al.* [4] conducted a review of the literature on this topic and found a trend toward improved educational outcomes when using VR/AR technologies in the training of future doctors, although it was not statistically significant.

B.W. Munzer *et al.* [5] identified significant potential for AR in three areas: user-environment interfaces, telemedicine and pre-hospital care, as well as medical education and training of medical personnel. The study concluded that AR can improve clinical care in various settings (operating rooms, hospitals, and outpatient clinics) and provide effective training, and that further research in this area is crucial for the development of emergency medicine.

Specific examples of VR and AR use in practice confirm their effectiveness. For instance, these technologies are used for preoperative planning and visualisation. Virtual reality can be used by surgeons to create three-dimensional models of a patient's heart based on CT and MRI scans, which improves awareness of complex anatomy before surgery. J.M. Castellanos *et al.* [6] described how VR was used to plan a complex mitral valve replacement procedure, providing a detailed assessment of the anatomy and preparation for surgery. S.V. Inozemtseva & I.O. Malynina [7] described an example of using the AccuVein AR device, which can be used for real-time visualisation of the patient's venous network, reducing the number of venipuncture attempts by 45%. With these tools, surgeons can plan procedures before making the first incision, and AR diagnostic tools can simulate the patient's condition after surgery.

VR and AR are also actively used for neurorehabilitation and cognitive function improvement. D.D. Georgiev *et al.* [8] emphasised the role of VR in the recovery of patients

after brain injuries, including after surgical interventions. A.Y. Kafes *et al.* [9] demonstrated the effectiveness of a virtual reality-assisted psychological intervention programme for eliminating traumatic symptoms in people who had survived an earthquake. Their study involved 17 people who underwent a five-stage intervention programme using VR technologies at the stages of rethinking, creating a safe place, and developing problem-oriented coping strategies. The results showed a significant increase in post-traumatic growth and social support seeking, as well as a reduction in trauma levels after the earthquake.

Similar results were obtained by R. Cáceres-Matos *et al.* [10] in an evaluation of the use of VR to reduce pain, fear, and anxiety in children and adolescents during invasive procedures (e.g., injections, blood sampling). The use of VR was found to be statistically significantly associated with a reduction in pain intensity, as confirmed by various assessment scales (Wong-Baker Faces Pain Scale, Visual Analogue Scale/Numerical Rating Scale). VR also showed significant effectiveness in reducing anxiety and fear associated with procedures. The effectiveness of virtual reality is explained by its ability to distract patients' attention from pain stimuli through immersion in an interactive virtual environment that activates several senses.

With VR and AR, healthcare professionals have access to innovative training methods that simulate real clinical situations, improving their skills and increasing their level of professional training. Patients, meanwhile, can receive personalised treatment and rehabilitation that was previously unavailable or ineffective. This makes VR and AR technologies not only useful but also necessary in the context of the rapid digital transformation of healthcare. Therefore, the study aimed to analyse scientific data on the potential use of virtual and augmented reality in medical education and clinical practice.

The material for this study included scientific articles published in peer-reviewed medical and technical journals, as well as conference materials related to virtual and augmented reality in medicine. In addition, publications on specialised news websites and blogs dedicated to medical innovations were analysed to identify current trends and practical implementation cases. The search for scientific literature covered the period from 2008 to 2025 and was conducted using the following electronic search engines and databases: Scopus, Web of Science, and Google Scholar. The following keywords and their combinations in English and Ukrainian were used to form search queries: "Virtual reality in healthcare", "Augmented reality in public health", "VR/AR for health management", "Immersive technologies in medicine", "Telemedicine and VR/AR", "Rehabilitation with VR/AR", "Medical training VR/AR", "Mental health VR/AR". The criteria for selecting literature were publications directly related to the application of virtual or augmented reality in any aspect of healthcare; studies containing empirical data, literature reviews, meta-analyses or systematic reviews; articles available in full-text format; publications in English and Ukrainian. After the initial search, more than

100 potentially relevant sources were identified. After careful screening of titles and abstracts, and then full texts, 58 sources that best met the criteria and covered the topic of the work were included in the detailed analysis. The selected sources were analysed according to the following characteristics: application of VR/AR field of use (diagnosis, treatment, rehabilitation, surgery, training, psychological assistance, public health prevention); description of technologies type of technology used (VR, AR), hardware and software, functional capabilities; target audience categories of patients or healthcare professionals for whom the developments are intended; research results quantitative and qualitative indicators of effectiveness, authors' conclusions.

AR/VR in medicine: Opportunities and differences

Virtual and augmented reality are key tools for the digital transformation of modern medicine. Despite their close interconnection, these technologies have fundamental differences in their mechanisms of operation and levels of user immersion. AR involves superimposing digital information (images, videos, text, graphics) onto the physical environment using specialised devices (smartphones, tablets or AR glasses) without breaking the connection with the real world. As noted by V. Volynets [11], one of the main advantages of AR is the ability to integrate digital information with data about the user's surrounding reality in real time. By using this method, medicine gains the ability to visualise physical reality, supplemented or enhanced with computer-generated perceptual data such as images, GPS data, audio or video signals. This integration of digital data with the user's environment in real time is particularly valuable in healthcare for visualising clinical data, supporting decision-making and training.

Virtual reality, on the other hand, creates a fully simulated three-dimensional environment that mimics both physical impact and the user's response to it. With the help of VR devices and 360° visualisation, complete separation from physical reality occurs by blocking signals from the

outside world, and the person is completely immersed in virtual space, which provides the maximum effect of presence, providing the necessary visual, auditory and other sensations. As emphasised by H. Guan *et al.* [12], this approach can be used to practise medical scenarios without risk to the patient and to effectively use simulation technologies in the educational process. The complete isolation from external stimuli contributes to enhanced learning and the reproduction of clinical situations in a safe environment.

Despite their differences, AR and VR complement each other in the context of medical applications. AR maintains a connection with the real environment while enhancing it by providing adaptive information display. It requires less cumbersome equipment than VR, making it convenient for use in surgery, diagnostics, and telemedicine. For instance, the review article by J. Silva *et al.* [13] provided a detailed overview of the literature exploring new and promising areas of application for virtual reality technology in cardiology. In particular, the authors analysed how VR can extend the scope of the entertainment industry and become a powerful tool for medicine. The study highlighted the significant potential of virtual reality for training medical students and interns. The study demonstrated how VR simulations create realistic 3D models of the heart and vascular system, which can be used for the visualisation of complex pathologies such as congenital heart defects or atherosclerosis. This provides practice for future cardiologists of invasive procedures, such as catheterisation or stenting, in a safe virtual environment, significantly improving their skills before working with real patients. Researchers note that VR is an effective tool for improving communication between doctor and patient. Patients can use a VR headset to view a 3D model of a heart, perceive the nature of their disease, and visualise the treatment process. This not only improves awareness but also increases trust in the doctor and promotes greater patient adherence to recommendations. Therefore, increased demand necessitated a review and the formation of new areas of application for VR and AR in healthcare (Table 1).

Table 1. Main areas of application for VR and AR in healthcare

Area	Description
Diagnostics	Use of VR and AR to visualise internal organs, improve diagnostic accuracy and reduce the risk of errors.
Surgery	Simulation of operations in a virtual environment and use of real-time prompts during operations.
Personalised treatment	Adapting medical procedures to individual patient needs using VR and AR.
Rehabilitation	Physical and cognitive rehabilitation of patients using interactive games and virtual exercises.
Educational simulations for healthcare professionals	Training medical personnel in conditions close to real life, using VR and AR to practise emergencies.

Source: compiled by the author based on O. Kovalchuk *et al.* [14]

Due to the rapid development of technology, augmented reality studies have been included in the curricula of many medical specialties [12]. One of the key aspects is their use for visualising the patient's internal organs, which provides medical professionals with a three-dimensional view of anatomical structures and pathological changes.

Such capabilities significantly improve diagnostic accuracy, reduce the risk of errors, and provide a more detailed analysis of the patient's condition [15]. Thus, AR and VR technologies create new opportunities in healthcare, particularly in the areas of personalised treatment, simulation training, clinical training, and improving the patient experience.

Industry applications of AR and VR in medicine: Surgery, dentistry, ophthalmology

The active introduction of virtual and augmented reality into medical practice demonstrates significant potential in highly specialised areas of healthcare. They not only contribute to improving the accuracy of diagnosis and the effectiveness of treatment, but also shape new approaches to surgery, rehabilitation and care for patients with sensory impairments. This section addressed examples of the successful use of AR and VR in surgery, dentistry and ophthalmology, fields where accuracy, visualisation and modelling are critical to the quality of medical care.

In surgery, VR and AR technologies can provide volumetric and surface visualisation of organs and structures of the body, section boundaries, and display information, so they can be used in minimally invasive intra-abdominal surgery. R. Vávra *et al.* [16] provided a review of the literature on the use of augmented reality in surgery. The study demonstrated that surgeons' interest in the use of AR is growing. This technology has the potential to improve the safety and effectiveness of operations. For instance, the use of AR technologies provides intraoperative guidance to surgeons and can quickly identify hidden objects and critical structures: foreign bodies, neoplasms, organs, nerves, veins, vessels, etc. In addition, VR and AR in surgery are becoming crucial tools for planning and performing complex operations. Thanks to these technologies, surgeons can pre-model surgical interventions, practise them in a virtual environment, and receive visual cues during the operation in real time. This minimises the trauma of interventions, reduces the duration of the operation, and improves treatment outcomes.

In addition, these technologies contribute to the improvement of minimally invasive surgery methods, which is particularly relevant in the context of modern requirements for the quality of medical care. Thus, S. Bernhardt *et al.* [17] analysed laparoscopy (minimally invasive surgery), where AR is considered a particularly promising technology. The study authors addressed various aspects, from technical implementations to clinical trials. The study concluded that AR technology can be used by surgeons to superimpose preoperative 3D models of organs, tumours, blood vessels or nerves onto live video images from a laparoscope. This significantly improves the visualisation and awareness of the patient's anatomy, especially in the case of complex structures that are difficult to distinguish on a 2D screen. The studies reviewed in the review showed that AR can help surgeons reduce errors, shorten surgery time, and increase the accuracy of interventions. For example, one study showed that AR navigation can significantly reduce the error of tumour localisation in a phantom model of the liver.

The Remote Interactive Surgery Platform (RISP), which uses Microsoft HoloLens 2 glasses, was described by Y. Kalbas *et al.* [18]. It can be used by a remote consultant to observe the field of view of the operating surgeon and provide advice using 3D annotations, medical images, and voice communication. E.L. Wisotzky *et al.* [19]

described the implementation of a scalable remote solution called TeleSTAR (Telepresence for Surgical Assistance and Training using Augmented Reality). The study explained in detail how the system, which uses a digital surgical microscope, enables surgical training and assistance in the operating theatre. The low-latency of TeleSTAR 3D video transmission, which can be used to observe the same view as the surgeon and use AR tools for annotations and measurements, was noted.

Several software solutions can be used to perform the necessary remote consultations in real time using a standard Internet connection, helping surgeons who are performing the operation. The core concept of these systems is the use of an AR headset (such as Microsoft HoloLens) or cameras installed in the operating theatre to broadcast live video from the surgeon's field of view to a remote consultant. The remote expert can view the operation, overlay annotations, pointers, and 3D models of organs on the image, and provide voice instructions. For example, Y.S. Shpryakhya *et al.* [20], analysing the application of augmented reality technologies in training programmes for surgeons in Ukraine, mentioned the following software solutions and platforms:

- Touch Surgery and Proximie are simulation platforms that combine augmented reality and artificial intelligence technologies with real-time video streaming. They feature a virtual operating theatre where surgeons can virtually "scrub in" (join the operation) to provide expert support and relevant advice. They are used in the United States;
- HoloMed is a local initiative for modelling simple surgical procedures;
- Medivis SurgicalAR is a tool that provides real-time visualisation of anatomical structures;
- Anatomy is a tool designed for interactive anatomy learning;
- Augmedix is a medical student training system developed in Italy.

These platforms make it possible to bridge the gap between medical theory and practice and provide high-quality services in local medical institutions. AR visualisation facilitates the planning of surgical procedures, reducing the duration of operations and patient recovery time. They provide the ability to safely simulate procedures and improve learning of anatomy through interactivity. These platforms make modern education accessible not only in leading medical centres but also in local educational institutions. They help surgeons operate with greater confidence and students learn more effectively, creating conditions for safer and higher-quality medicine. Thus, VR and AR technologies are gradually becoming key tools in modern surgery, providing not only improved visualisation and intraoperative guidance, but also new opportunities for remote consultations and training.

The main area of application for AR technologies in dentistry is maxillofacial surgery and oral surgery. Most often, such technologies are used during specific procedures, in particular, the installation of dental implants, orthognathic surgery, etc. AR technology is also increasingly used

in such areas of dentistry as endodontics, restorative dentistry, and orthodontics. For instance, V. Faus-Matoses *et al.* [21] compared the accuracy of endodontic access formation using an AR device with the traditional technique. The results showed that AR systems can be used to perform this procedure more safely and accurately. D. Dolega-Dolegowski *et al.* [22] described the development of a holographic AR system using HoloLens 2 glasses to study the anatomy of root canals. This demonstrated how AR can be an efficient teaching tool for students. S. Fahim *et al.* [23] described the potential of AR and VR in various fields, including restorative dentistry; in particular, how AR can improve communication with patients by visualising the expected results of treatment (e.g., smile design or prosthetics) directly on the patient's teeth. As noted by E. Roy *et al.* [24], traditional teaching methods in dentistry, which rely on phantom models and mannequins, have certain shortcomings that VR simulators can effectively address. For example, traditional phantom classes cannot always fully reproduce the anatomical features and complexity of real clinical cases. In addition, they do not support real-time tracking of student progress and do not provide instant feedback on the procedures performed. Instead, according to the study, VR simulators can eliminate these shortcomings. They provide training for complex procedures without risking damage to real patient tissue; they can adapt the level of difficulty, ensuring accessibility for students with different levels of training to learn at desired pace; they can automatically analyse student movements, the force of instrument pressure and the accuracy of actions, providing detailed reports for skill improvement. In addition, thanks to haptic feedback, VR simulators can mimic the sensation of tissue resistance, making training as close as possible to a real clinical situation. The authors conclude that the introduction of VR simulators is a substantial step towards improving the quality of dental education. This does not mean a complete abandonment of traditional methods, but VR can significantly complement them, providing further mastery of anatomy and practice of the skills necessary for successful clinical practice.

VR and AR are significant assistance to people with visual impairments. Augmented reality glasses improve the ability to view everyday objects and enhance visual function using 3D recognition software, as demonstrated by M. Iskander *et al.* [25]. Such glasses assist individuals with vision loss and patients with severe visual impairments in locating lost items, recognising people, and easily navigating their surroundings. However, the use of VR and AR in ophthalmology does not replace traditional methods of treatment and rehabilitation but can only be an additional tool for ophthalmologists to improve the quality of medical care. For example, D.L. Fortenbacher *et al.* [26] analysed how VR can be an effective addition to traditional methods of treating visual impairments. In contrast to conventional therapy, VR games and simulations make the process more engaging and motivating for patients, especially children. The publication emphasised the concept of

dichoptic training, which involves showing different images to each eye. This stimulates both eyes to work together, which is key in treating conditions such as amblyopia (lazy eye) and strabismus (crossed eyes). The study highlighted a specific VR system called "Vivid Vision", which uses a virtual reality headset to conduct training. The system is designed to help specialists personalise exercises for each patient and objectively track progress, which is a big advantage over traditional methods.

The use of AR and VR in surgery, dentistry, and ophthalmology demonstrates a high level of effectiveness, safety, and technological feasibility. These innovations not only improve clinical outcomes but also expand the capabilities of physicians in planning, performing, and monitoring medical interventions. Thus, the use of AR/VR is becoming an essential component of modern personalised medicine, contributing to the transformation of the traditional healthcare system.

Virtual and augmented reality in psychiatry

In psychiatry, virtual reality is used to simulate the subjective experiences of patients to increase empathy and awareness on the part of specialists and relatives. A study by E. Vass *et al.* [27] emphasises that VR can be efficient for improving cognitive skills in patients with schizophrenia. Although the study addressed therapy, its findings support the idea that VR can simulate social interactions, which is key to the research of mental states. Their study confirmed that VR interventions can help patients better recognise and interpret emotions, which in turn also contributes to the awareness of their condition by both specialists and loved ones.

VR is also used in exposure therapy to create virtual environments that can simulate real-life situations that cause fear and difficulty for patients. Exposure therapy is one of the most effective methods of treating anxiety disorders, and virtual reality is a safe and controlled way to show patients their fears. For example, I.H. Bell *et al.* [28] noted that VR is a promising technology that can improve assessment and therapy in mental health. It can be used to immerse people in interactive virtual worlds that are completely controlled by the researcher or clinician. This ability is key to the use of VR in both the assessment and treatment of mental disorders. The article also discusses the use of virtual reality to create controlled environments, which is the basic principle of exposure therapy. In this context, VR systems can be used by clinicians to immerse patients in simulated situations to help them overcome phobias, anxiety or post-traumatic stress disorder (PTSD), which is the essence of exposure therapy.

At the same time, meditation programmes that use augmented reality have become efficient in reducing stress and anxiety levels. AR integrates virtual elements into the real world, allocating focus to deep relaxation and meditation techniques in a familiar environment. This approach stimulates psychosocial adaptation and improves overall psycho-emotional state, helping to reduce symptoms of anxiety disorders and alleviate psycho-emotional stress.

This practice is called relaxation therapy. A.I. Iqbal *et al.* [29] confirmed that VR and AR technologies significantly improve the patient experience and the quality of medical education by creating engaging and interactive environments for learning and practice. For instance, VR is used for pain management, anxiety reduction, and surgical simulation. The study also notes that “relaxation and meditation in various VR applications are becoming increasingly common for treating patients at home or in hospitals”. VR can be effective in creating a calm environment and applying relaxation techniques to significantly reduce stress in intensive care units (ICUs). The study also discussed the use of VR for pain relief, which is closely related to relaxation. In particular, the use of VR games has proven effective in reducing acute pain, for example, in patients with burns. The combination of VR with hypnosis (known as virtual hypnosis, or VRH) is also mentioned, which has shown promise in reducing pain and anxiety. Therefore, the authors of the article conclude that VR is efficient for relaxation therapy.

Meditation programmes using augmented reality can create interactive visual and audio stimuli that reduce distractions and increase concentration on relaxation processes. The integration of virtual elements into the real environment helps patients immerse themselves more deeply in meditative practices, which reduce stress and anxiety more efficiently. This technology is particularly relevant for people who are unable to practise traditional meditation due to external factors or concentration difficulties. AR can be used to create customised meditation sessions that increase the effectiveness of treatment, as the programmes are tailored to the user’s personal preferences and needs. For example, R. Jackson *et al.* [30] compared the effect of a mobile AR meditation app with a “point-to-point” distraction technique on 37 participants. The results showed that the group using AR had a more significant anxiety reduction and perceived stress compared to the distraction group. This confirmed that short AR meditation practice can improve aspects of negative mental health.

In addition, virtual reality can be used to treat phobias. The main method of treating phobias is exposure therapy. It involves the patient gradually confronting their fear under the supervision of a therapist. VR makes this process safe, controlled and accessible. In contrast to the real world, where circumstances are unpredictable (for example, it is not always possible to “accidentally” reach a height or be near a spider), in VR simulation, the psychotherapist has complete control over the situation. They can adjust the level of “scariness” of the situation, starting with the least alarming stimuli and gradually increasing them. The patient recognises the safety of the situation, even if the brain reacts to the virtual stimulus as if it were real. This is used to learn emotion and physiological control (heart rate, breathing) without any real threat to health. In addition, the simulation can be repeated as many times as necessary, which is impossible in real life. For example, for a patient with aerophobia (fear of flying), an unlimited number of “virtual

flights” can be created, which accelerates the process of desensitisation (reducing sensitivity to the stimulus).

Numerous studies confirm that VR exposure therapy is as effective as or even more effective than traditional exposure. A study by G. Albakri *et al.* [31] reviewed data from various studies that used virtual and augmented reality technologies to overcome common fears such as acrophobia (fear of heights), arachnophobia (fear of spiders), aerophobia, and claustrophobia (fear of enclosed spaces). The main method discussed in the article is exposure therapy. The authors considered three types of exposure therapy: classical exposure therapy (*in vivo*) involves controlled, gradual contact between the patient and the object of their fear in real life; VR exposure therapy (VRET) uses virtual reality to create a simulated environment, in which patients can interact with their fear in a safe, controlled environment, which can be used to customise and avoid unpredictable factors of the intensity level; AR exposure therapy uses augmented reality, where virtual elements are superimposed on the real environment (e.g., a virtual spider on a real table), which can also be used for control of the process. The study concluded that VR and AR are effective tools for conducting exposure therapy to treat most phobias.

Some medical start-ups propose using VR technologies to help elderly people improve their memory and cognitive functions, facilitate rehabilitation, and increase their social activity. For instance, the research protocol by E. Gambella *et al.* [32] described the evaluation of the effectiveness of a combined approach to the treatment of Alzheimer’s disease. The evaluation addressed the efficiency of an integrated intervention that included computerised cognitive training and aerobic physical exercise using virtual reality, in people with early-stage Alzheimer’s disease, as well as to investigate whether such a combined therapy, combining cognitive and physical exercises, can provide greater stability of cognitive functions, improved mood and quality of life compared to physical exercise alone. The study involved 78 patients with mild Alzheimer’s dementia. The experimental group underwent cognitive training using Brainer software on a tablet and aerobic training using the jDome® BikeAround™ system. This system combines an exercise bike with a dome-shaped projector and Google Street View technology, providing virtual bike rides through places from their memories. The control group underwent cognitive training using Brainer software on a tablet and aerobic training on a standard exercise bike. The intervention consisted of 16 sessions of 60 minutes each, twice a week for 8 weeks. Each session included 30 minutes of cognitive training and 30 minutes of physical exercise. The study believes that their intervention, which combines virtual reality with physical and cognitive exercises, will be effective in combating Alzheimer’s disease, leading to improved cognitive function and quality of life for patients.

Portuguese scientists J. Oliveira *et al.* [33] suggested using appropriate training for people with moderate Alzheimer’s disease, linked to the development of basic skills. Patients with this disease struggle with skills such as

morning hygiene, cooking, going to the shop or pharmacy, etc. However, with the help of modern technology, these patients can train or even “relearn” actions that were once familiar to them. Patients perform all manipulations within the virtual apartment and city.

Post-traumatic stress disorder (PTSD) is a type of nervous disorder that affects millions of people worldwide. This disorder can arise for various reasons, such as war, acute conflict, etc. VR can be used to create specially designed environments that simulate real-life situations, helping patients to gradually confront their fears or traumatic memories in a controlled setting. This approach reduces the intensity of symptoms and helps patients develop coping mechanisms.

Since 1997, the University of Southern California’s Institute for Creative Technologies has been using virtual reality technology to treat PTSD. Various simulations, mainly based on military scenarios, are used to help most veterans successfully overcome the symptoms of the disorder. For instance, O.D. Kothgassner *et al.* [34] evaluated the effectiveness of VRET in comparison with control groups (waiting in line) and active comparators (other treatment methods). The study conducted a literature search that identified nine controlled studies involving 296 participants. The primary outcomes were assessed by the severity of PTSD symptoms, as well as secondary outcomes such as symptoms of depression and anxiety. VRET showed significantly better results in reducing PTSD symptoms and depressive symptoms, indicating that virtual reality therapy is more effective than no treatment. However, no statistically significant difference was found between VRET and other active treatments (e.g., traditional exposure therapy) in reducing PTSD and depression symptoms, suggesting that the effectiveness of VRET is comparable to other recognised therapies.

The experience of Ukrainian scientists also shows positive changes in reducing the symptoms of PTSD and depression when using virtual reality in treatment. For instance, K.A. Kosenko *et al.* [35] studied and summarised modern innovative approaches to the diagnosis, therapy and rehabilitation of patients with post-traumatic stress disorder, especially among military personnel who participated in combat operations. In the context of the ongoing military conflict in Ukraine, this problem is particularly relevant. The study described traditional and innovative methods of treating PTSD. Traditionally, PTSD treatment includes psychotherapeutic approaches such as cognitive behavioural therapy (CBT) and pharmacological intervention. The study emphasised that pharmacological intervention cannot cure PTSD, but it increases the effectiveness of psychotherapy, especially in patients from risk groups. At the same time, the study noted that modern technologies, such as virtual reality, which is used to simulate stressful scenarios, are substantial in treatment, helping patients gradually process traumatic events in a safe, controlled environment.

B.V. Kichak *et al.* [36] investigated the potential of video games and virtual reality technologies as innovative

tools in the treatment and rehabilitation of patients with post-traumatic stress disorder, especially in the context of military conflicts. The study emphasised the need to introduce new, accessible methods to help victims. The study discusses several substantial aspects of the application of gaming technologies:

- controlled exposure VR content developers can create simulated environments that are used to relieve patients of traumatic memories in a safe and controlled setting. This helps to lessen their emotional impact in the future;

- a combination of CBT video games and VR technology should be used as a supplement to traditional methods. This combined approach helps patients overcome negative thoughts, develop coping strategies, and gradually desensitise themselves to triggers;

- regulation of physiological responses: the game format can be used to help patients learn to control physiological responses such as heart rate and breathing, which is particularly useful for managing anxiety and stress associated with PTSD;

- social support – the authors emphasise the importance of communicating with people who have had similar experiences. Multiplayer games and online communities can be used as a platform for creating support networks where patients can help each other and share their thoughts.

The researchers concluded that although game therapy cannot replace traditional approaches such as psychotherapy and medication, its implementation can significantly improve the effectiveness of PTSD treatment. Continuous technological developments and new research open new opportunities for the further application of computer games in this field. Thus, the use of VR for the treatment of anxiety and PTSD has a wide range of advantages, including the creation of a safe and controlled environment for patients, which can be used for exposure therapy without the need for real-life physical situations. Thanks to deep immersion in the virtual environment, patients can gradually adapt to stressful or traumatic situations, which reduces fear and anxiety levels. Virtual reality can also be adjusted by doctors in real time to change the intensity and complexity of situations, which helps tailor treatment to each patient’s individual needs.

Possibilities for using VR and AR during rehabilitation

Rehabilitation is a crucial stage in restoring health after injuries, illnesses, or surgical interventions. Physical and cognitive rehabilitation programmes are designed to restore bodily functions and improve patients’ quality of life. Physical rehabilitation includes a set of exercises that help restore motor functions, increase physical endurance and improve overall well-being. Cognitive rehabilitation focuses on restoring memory, attention, language and cognitive functions that are critical for normal functioning in everyday life. Games that can stimulate both motor and brain activity are essential components of rehabilitation programmes.

The use of games in rehabilitation programmes not only restores physical abilities but also activates cognitive processes, contributing to comprehensive health recovery. Games designed to develop motor skills and brain activity can be used to improve coordination, memory, concentration, and other cognitive functions. For example, K.E. Laver *et al.* [37] studied the effectiveness of virtual reality and interactive video games in the rehabilitation of stroke patients. The authors analysed 72 randomised controlled trials. The study compared groups of patients who received rehabilitation using VR with groups who underwent traditional therapy. The study emphasised that virtual reality has potential, especially as a supplement to standard therapy, to help increase the total rehabilitation time. However, further research is needed to draw more conclusive conclusions and to clearly identify which types of VR interventions are most effective and for which patient groups. In turn, N. Ahmadpour *et al.* [38] examined the potential of VR as a non-pharmacological treatment for acute and chronic pain. The study argued that virtual reality is an effective complementary or even alternative method of pain relief that does not require medication. Its effect is based on distracting the patient's attention from pain sensations by immersing them in an immersive virtual environment. In their opinion, VR demonstrates high effectiveness in cases of acute pain arising during medical procedures. For example, burn wound care (VR games such as SnowWorld can be used to distract patients from pain during dressing changes), dental procedures, and pre- and post-operative procedures (VR helps reduce anxiety and pain). The study also believes that VR has substantial potential for treating chronic pain.

Rehabilitation is not only a medical but also a social process that includes supporting patients in restoring their ties with society, family and workplace. Successful rehabilitation requires an interdisciplinary approach that involves various specialists, including doctors, physiotherapists, psychologists and social workers. A substantial aspect is an individual approach to each patient, considering their physical condition, psychological characteristics, age factors, and social conditions. Psychological support and motivation of patients are essential for achieving high rehabilitation results, as without proper emotional support, the recovery process can be significantly slowed down. In this context, the role of cognitive rehabilitation, which contributes to the improvement of intellectual abilities and neuropsychological functions, cannot be overestimated. Programmes that address memory, language skills, and cognitive abilities help patients adapt to changes caused by disease or injury, which is crucial for their social functioning.

As such, H. Bateni *et al.* [39] considered virtual reality as an innovative and promising tool for rehabilitation. This technology can create immersive and motivating environments that help patients do physical exercises, which can be boring in traditional settings. The cited studies confirm that VR improves motor function, balance, and

coordination. In addition to treatment, VR is also considered a valuable diagnostic tool. With VR systems, therapists can objectively assess a patient's movements and functionality in a controlled virtual environment; measure key indicators such as reaction time, movement accuracy and range of motion, which is difficult in traditional clinical practice; create realistic scenarios to assess how a patient responds to different situations, which is relevant for determining fall risks and planning rehabilitation. The study discusses the use of VR in the rehabilitation of patients with various conditions, including Parkinson's disease, stroke, and other neuromuscular disorders. The study emphasised that VR can be beneficial for patients who have lost the ability to perform certain tasks independently, as the virtual environment facilitates safe and fear-free training.

V.V. Kormiltsev & A.M. Chyhyrnskyi [40] systematised the experience of foreign studies on the use of virtual reality technologies in physical therapy for patients after an acute cerebrovascular accident (CVA), or stroke. The study believes that the use of VR in physical therapy for patients after ACIS has led to statistically significant improvements. Improvements in upper limb motor function, range of motion, muscle strength, and independence in daily activities were noted, and VR training has a positive effect on patients' ability to walk. VR-based rehabilitation also has a positive effect on neural plasticity. This includes improved interhemispheric balance, enhanced cortical connectivity, and activation of areas in the frontal cortex, which correlates with improved behaviour. The study noted that VR systems are divided into specialised and commercial game consoles that can be adapted for clinical practice. In Ukraine, there are also VR trainers, such as VR NOW, which are designed based on clinical experience to restore movement and overcome complications.

T. Rutledge *et al.* [41] described the development and initial results of research on the use of VR for the treatment of phantom limb pain. Phantom limb pain (PLP) is a common and debilitating condition that is difficult to treat. It occurs in people who have undergone amputation and is felt as pain in the missing part of the body. The study developed a new VR programme to help reduce PLE and conducted a pilot study to assess its viability, i.e. its feasibility and safety. Ten patients with lower limb amputations who suffered from phantom pain participated in the experiment. The VR intervention was based on the principle of mirror therapy, but instead of a physical mirror, a virtual reflection was used. Patients saw a virtual version of their missing leg moving along with their healthy leg. Participants underwent 10 sessions of VR therapy over 5 weeks. This study showed a positive trend towards a reduction in the intensity of phantom pain in most participants.

The gaming methods used in rehabilitation can include both traditional board games that stimulate cognitive activity and interactive computer programmes that use virtual exercises and tasks to train various mental and physical functions. The use of such methods improves motor skills, perception and concentration, which contributes to

the restoration of nervous system functions and facilitates the adaptation of patients to new living conditions [42]. In turn, the integration of such games into a comprehensive

rehabilitation programme reduces stress levels, promoting psycho-emotional recovery [43], which is a substantial component of successful rehabilitation (Table 2).

Table 2. The role of VR and AR in rehabilitation

Type of rehabilitation	Description
Physical rehabilitation	Exercises to restore motor functions and improve endurance.
Cognitive rehabilitation	Exercises to restore memory, attention, language and cognitive functions.
Motor functions development games	Use of interactive games to improve coordination and motor function development.
Cognitive activity games	Stimulation of cognitive processes through games to improve concentration and memory.

Source: compiled by the author based on L. Atukunda [44]

It is worth noting that the use of VR in the rehabilitation of patients with cerebral palsy (CP) demonstrates a high level of effectiveness. The main clinical manifestations of this disease are movement disorders (paresis, paralysis), impaired muscle tone, and poor coordination of movements. The main goal of rehabilitation therapy for patients with CP is to correct these motor disorders. Thus, D.K. Ravi *et al.* [45] provided evidence of the effectiveness of VR rehabilitation in improving sensory and motor skills in children with CP. The analysis covered 31 studies with a total of 369 participants. The study showed that VR rehabilitation is a promising intervention for improving balance and overall motor development in children and adolescents with CP. The authors emphasised that virtual reality, especially in the form of games, increases children's motivation and engagement in therapy, which is a key factor in achieving better results. This makes the rehabilitation process more enjoyable and less monotonous.

Notably, scientists have convincingly demonstrated the potential of virtual reality and computer games in the rehabilitation of patients with cerebral palsy (CP). For instance, an experimental study by F.R.C. Machado *et al.* [46] found that the targeted use of computer games as a therapeutic tool significantly increases activity and improves the functionality of the upper limbs in children with paretic CP. This indicates the promise of interactive approaches in the restoration of motor functions. In addition, S.S. Korney *et al.* [47] emphasise that virtual reality is a valuable technique for expanding the range of motor tasks for the upper limbs. It can be effectively used in both clinical and home settings, as well as in educational institutions, providing flexibility and accessibility of rehabilitation. In general, as shown by the research of J.H. Do *et al.* [48], interactive virtual reality programmes have proven effective in improving hand dexterity and coordination in children diagnosed with hemiplegic CP, creating new opportunities for their adaptation and improving their quality of life.

Although the main application of virtual reality in rehabilitation is the correction of motor disorders, its potential is not limited to this. Immersion in immersive virtual environments also demonstrates high effectiveness in relieving pain syndrome, which creates new prospects for non-drug treatment. An example of this is the development of a VR product with an analgesic effect. G. Hoffman *et al.* [49] described an experiment in which patients

with burns were immersed in a virtual winter wonderland, where they had the opportunity to shoot snowballs at snowmen. According to the data obtained, this significantly reduced pain during dressing changes and was more effective than opioid analgesics.

H. Deng *et al.* [50] also confirmed the distraction theory. The study used near-infrared functional spectroscopy to assess brain activity and found that VR reduces pain perception by modulating cortical processing of pain signals. When the brain is busy processing visual and cognitive tasks in a virtual environment, it has fewer resources to process pain impulses. R. Gopalan *et al.* [51] confirmed that distraction was the most effective mechanism for pain relief using VR, which was proven in 86.9% of the studies they examined. According to these scientists, VR outperforms other non-pharmacological methods (such as watching television) due to its high immersiveness, which completely captures the patient's attention. The review indicated that VR offers an innovative way to manage acute pain while minimising the side effects and risks associated with traditional pharmacological approaches, such as nausea, addiction or even overdose.

In conclusion, VR and AR are key innovative instruments of modern rehabilitation programmes, as they offer an effective complement to traditional therapy methods. These technologies help restore physical and cognitive functions after strokes, injuries, neuromuscular disorders, and cerebral palsy. Due to their immersive nature, VR technologies provide high patient motivation and increase their engagement in training, which is critical for achieving positive results. In addition, VR is effectively used as a non-pharmacological means of pain relief, as it distracts the brain from pain sensations. Studies also confirm that VR systems are valuable diagnostic tools that can be used for objective assessment of patients' conditions, contributing to comprehensive health recovery and social adaptation.

Features of training medical professionals to work with VR and AR

The process of training medical professionals using VR is crucial. For example, A. Alaraj *et al.* [52] described the development and evaluation of the usefulness of a new virtual reality simulator with tactile feedback for training neurosurgeons to clip aneurysms. The study created a simulator for clipping aneurysms of the middle cerebral artery using

the ImmersiveTouch platform, which provides realistic 3D images and tactile sensations, simulating mechanical impact on virtual tissues. A study involving scientists from three institutions (the University of Illinois at Chicago, the University of Chicago, Weill Cornell Medical College, USA), showed that the simulator is a useful tool for preparing for real operations, improving knowledge of anatomy and assisting in the planning of surgical approaches. As a result, a virtual reality room was created at Weill Cornell Medical College (New York, USA), where simulators for surgeons were installed. The system was equipped not only with the appropriate graphics headset but also with tactile feedback devices. Doctors could feel the mechanical impact on the relevant organs of the “patient”. With the help of such a simulator, it is possible to acquire the necessary skills for successful operations at a much lower cost. The work also highlighted the potential of such VR systems to improve patient safety and the effectiveness of neurosurgical training.

D. Mistry *et al.* [53] emphasised that VR provides unique learning opportunities, offering students and healthcare professionals an immersive, safe and controlled environment for practising their skills. Therefore, it is possible to train without risk to real patients and increase the confidence of future specialists. The study covered a wide range of VR applications, including clinical skills training (the ability to practise diagnostic procedures, manipulations and communication with patients), surgical training (the ability to practise complex surgical procedures, improving motor skills and decision-making), studying anatomy and physiology (interactive 3D models for further awareness of the human body), interpersonal skills and empathy (the ability to simulate complex scenarios of interaction with patients and develop empathy). The study highlighted existing barriers and challenges to the implementation of VR in medical education. These include the high cost of equipment, the need for specialised content, possible motion sickness in users, and the need to integrate VR programmes into existing curricula. Future directions for the development of VR technologies and their potential for further transformation of medical education were also analysed, including hardware improvements, the development of more realistic simulations, and wider accessibility.

C. Cao & R.J. Cerfolio [54] addressed the use of virtual and augmented reality to improve surgical education and planning. The study investigated the use of VR simulators for practising surgical skills, including visualisation of anatomy, planning access trajectories, and simulating complex procedures. This improves the skills of novice and experienced surgeons in a safe and controlled virtual environment. The study discussed the possibilities of AR overlaying digital information onto the real world, which can be used for more intuitive learning, such as displaying anatomical structures or step-by-step instructions during simulation. The study emphasised that VR and AR can be used by surgeons to visualise complex patient anatomy in 3D, based on real medical images (e.g., CT, MRI).

This improves analysis of the pathology, planning of the optimal surgical approach, and prediction of possible complications. AR and VR technologies can also be used to “rehearse” the operation, which can be used by surgeons virtually practice all stages of the procedure, increasing the accuracy and efficiency of the actual operation.

S. Patil *et al.* [55] analysed the effectiveness of devices with tactile (haptic) feedback in the preclinical training of dental students. The study conducted a systematic search of several large databases (PubMed, Embase, Web of Science, Scopus) and found that tactile devices significantly improve the psychomotor and manual skills of dental students. The use of such devices increases students’ confidence in performing procedures. Tactile feedback systems help develop more precise movements and a greater awareness of how instruments interact with tissues, which is fundamental to dental practice. Tactile feedback makes simulation more realistic and immersive, which contributes to more effective learning. The study noted that these simulators let students repeat procedures many times and get instant feedback, which significantly reduces the number of mistakes in real-life situations.

In 2008-2009, a series of studies on virtual reality simulation and local anaesthesia was conducted at the University of Aachen (Germany). For example, a study by S. Ullrich *et al.* [56] described a virtual reality-based medical training application for local anaesthesia procedures, which includes simulation of electrical impulse transmission to activate the motor response of nerves. O. Grottko *et al.* [57] developed a VR simulator for local anaesthesia that considers the individual anatomy of the patient, which is relevant for realistic training.

Educational simulations for healthcare professionals are essential tools for improving qualifications and practical skills in conditions that are close to real life. The use of virtual environments can be used for practice of healthcare professionals in a variety of situations that require quick and accurate decisions, without risk to patients. Such simulations can be used by medical staff to improve their skills in managing emergencies, developing the ability to adapt quickly under stressful conditions [1, 44]. Such training in virtual reality can provide experience that is difficult or even impossible to obtain in real-life situations due to the rarity of certain emergencies or limitations in training resources. They also help reduce stress levels during real incidents, as medical professionals can deal with potentially traumatic situations in a safe environment, which significantly increases their confidence in their actions [4, 3].

Thus, the integration of virtual simulations into training programmes for medical professionals, particularly in emergencies, achieves high training effectiveness. This approach maintains high-quality medical services even when practical experience in real-life situations is limited or insufficiently available. A key aspect is that virtual simulations can be used for training not only technical skills, but also cognitive and emotional responses to stressful situations, which are necessary for quick decision-making in

extreme conditions. Training through virtual simulations has great potential to improve the quality of medical practice, particularly in emergencies where accuracy and speed of action are relevant. It maintains skills at a high level and prepares medical professionals for any challenges in the real world.

Benefits and drawbacks of using VR and AR in medicine

The introduction of virtual and augmented reality technologies into medicine faces several challenges and limitations, among which financial costs, technical limitations, and ethical issues are substantial. Thus, the financial costs of introducing VR and AR into medical practice can be significant. The cost of technological equipment, software, and training medical staff to use these tools effectively requires significant investment. Most medical institutions, especially in countries with limited financial resources, may face difficulties in securing the necessary funding to implement such technologies.

In addition, the high hardware requirements for VR and AR, the need to constantly update equipment to support new software versions and improve technologies can be a barrier to the widespread use of these technologies in medical institutions. Furthermore, ensuring proper compatibility with existing medical systems and databases can also require significant technical effort. Systems must not only be functional but also safe for patients, which requires thorough testing and verification. Insufficient accuracy, data errors, or delays in real-time can have substantial consequences, increasing the risk of using these technologies.

Ethical issues related to the use of VR and AR in medical practice are a crucial part of this process. In particular, the use of these technologies for patient treatment, research, or training may raise questions about the security and confidentiality of patients' personal data. It is necessary to determine in which cases the use of VR/AR is ethically justified, whether these technologies can be relied upon in the treatment process, and what potential risks exist for patients who require special attention in terms of psycho-emotional impact. In addition, the issue of technology accessibility for the general population is also necessary. On the one hand, the use of VR and AR can improve the quality of medical services and make them more accessible, especially for patients in remote or hard-to-reach regions. However, on the other hand, the high cost of such technologies may create inequality in access to modern medical services. This could lead to a gap between patients who can afford VR/AR treatment and those who cannot.

In addition to the aspects listed above, there are other challenges that need to be addressed when implementing VR and AR in medical practice. One of these is the need for medical professionals to adapt to new technologies. This requires significant efforts in staff training, as the use of modern technologies requires specific knowledge and skills. In addition, training must be integrated into existing medical programmes, which can be difficult due to changes in educational standards and programme materials [3, 58].

Another aspect is patient acceptance of new technologies. Not all patients are ready to accept and trust treatment or diagnostic methods based on virtual or augmented realities. This is true for older people or those with limited experience with technology. Problems with trust in new treatment methods can lead to delays in the implementation of such innovations.

Conclusions

Virtual and augmented reality are actively changing the medical field, offering fundamentally new and unprecedented opportunities to improve the quality of medical services at all stages, from diagnosis to rehabilitation. Their use has led to significant improvements in the diagnosis, treatment and rehabilitation of patients, creating new horizons for personalised medicine and increasing the effectiveness of therapeutic interventions. The key role of VR and AR technologies in planning complex surgical operations should be highlighted. These innovative systems can be used not only to pre-model interventions with high accuracy, but also to receive visual cues and holographic projections in real time, directly during the operation. This significantly reduces the trauma of operations, minimises the risk of errors and significantly increases their overall effectiveness and safety for the patient. The ability to study the patient's anatomical features in detail in 3D format before the operation can be used for the development of an optimal strategy and preparation for any unexpected situations.

In rehabilitation programmes, VR and AR are becoming crucial tools for the physical and cognitive rehabilitation of patients. These technologies provide effective methods for restoring motor and cognitive functions by offering patients interactive and engaging exercises. Thanks to gamification and simulations integrated into these technologies, patients are actively encouraged to engage in daily training and recovery, which is relevant not only from a medical but also from a social point of view, as it promotes faster reintegration of patients into society by increasing their motivation and self-esteem.

The use of VR and AR to support mental health deserves special attention. Modern technologies can create safe and fully controlled virtual environments for treating various disorders, including anxiety disorders, phobias, and PTSD. Thanks to virtual reality exposure therapy, patients can gradually adapt to stressful situations, overcoming their fears and anxiety in a safe environment, which reduces anxiety levels and improves overall emotional well-being.

Another relevant aspect is the use of these technologies for training and improving the skills of medical professionals. They can be used for training in conditions that are as close as possible to real clinical situations, but without any risk to real patients. This applies to both learning new surgical techniques and practising skills for interacting with patients and making quick decisions in crises. Thus, VR/AR significantly improve the level of professional training and competence of doctors and all medical personnel, which is a guarantee of high-quality medical services in the future.

At the same time, augmented/virtual reality requires further study by scientists, researchers, experimenters, and inventors, because the fast-paced world of modern post-information space on a global scale will only accelerate its progress, and the world of new technologies will continue to develop at the fastest possible pace. Particular attention should be paid to the development of adaptive VR and AR interfaces for different age groups and people with special needs, the assessment of the long-term impact of their use on cognitive functions and psychological state, as well as the study of the ethical aspects of data collection and use in these technologies to ensure user privacy and security. Equally crucial is the improvement of methods for

integrating virtual/augmented reality with existing medical information systems and the development of standards for data exchange, which will ensure the effective implementation of these technologies in healthcare practice.

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Віртуальна та доповнена реальність в механізмах управління охорони здоров'я щодо підтримання громадського здоров'я: огляд літератури

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Анотація. Метою даного дослідження було проведення аналізу наукових відомостей щодо використання віртуальних технологій та технологій доповненої реальності в практичній діяльності лікарів. Основні результати дослідження показали, що віртуальна та доповнена реальність активно трансформують медичну сферу, пропонуючи нові можливості для покращення якості надання медичних послуг. Зокрема, ці технології ефективно застосовуються в стоматології для лікування і протезування, в офтальмології – для діагностики та тренування зору, а також в психіатрії та психологічній допомозі – для терапії фобій, посттравматичних стресових розладів (ПТСР) та боротьби з тривогою. Крім того, технології VR та AR довели свою ефективність в реабілітації пацієнтів після інсультів, черепно-мозкових травм, а також при відновленні рухових функцій після ортопедичних операцій та ампутацій. Особливо слід виділити роль VR та AR технологій у плануванні складних операцій, де вони дозволяють хірургам попередньо моделювати втручання та отримувати візуальні підказки в реальному часі, знижуючи травматичність операцій і підвищуючи їх ефективність. У реабілітаційних програмах VR та AR стають незамінними інструментами для фізичної та когнітивної реабілітації пацієнтів, забезпечуючи ефективні методи відновлення рухових і пізнавальних функцій. Важливим аспектом є також використання VR та AR для навчання медичних працівників, що дозволяє тренуватися в умовах, наближених до реальних, без ризику для пацієнтів, тим самим підвищуючи рівень професійної підготовки лікарів. Проведений огляд не тільки показав, як віртуальні інструменти можна використовувати для розв'язання конкретних проблем у медицині, а й спонукає до глибшого проникнення у сутність процесів, які відбуваються в сфері охорони здоров'я під впливом новітніх інформаційно-комунікаційних розробок

Ключові слова: : віртуальні технології; немедикаментозне лікування; реабілітація пацієнтів; VR-тренажери

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