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Carotid revascularization improves cognition in patients with carotid stenosis

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Patients with atherosclerosis in the carotid arteries are at risk of ischemic stroke and cognitive decline due to emboli and chronic hypoperfusion of brain tissue. Revascularization procedures improve cerebral hemodynamics, which has some effect on cognitive function. Some authors suggest that the presence of stenosis in the carotid arteries is an independent factor influencing cognitive decline. The aim of this study was to investigate the relationship between the degree of stenosis of a stented carotid artery and attentional performance in individuals with carotid atherosclerosis. A prospective longitudinal study was conducted at a single center involving patients during cardiology hospitalization (T-1) and 1 year after hospital admission (T-2) for invasive treatment of carotid stenosis. The attention D2 test by R. Brickenkamp was used. The study showed that a critical degree of internal carotid artery stenosis is associated with poorer attentional performance in individuals undergoing carotid artery stenting. However, the ability to concentrate improved one year after the procedure in all groups of patients who underwent carotid artery stenting, regardless of the degree of internal carotid artery stenosis. It was also found that the side of the vasoconstriction (right/left) in patients with atherosclerosis in the carotid arteries has no influence on cognitive functions in relation to attention.

Keywords Cognitive functions, Attention, Carotid artery stenosis, Carotid artery stenting, D2 test of attention

According to current medical knowledge, patients with atherosclerosis in the carotid arteries are at risk of ischemic stroke and cognitive deterioration associated with embolism and chronic hypoperfusion of brain tissue[1–4]. Revascularization procedures improve cerebral hemodynamics and thus, to some extent, cognitive function[2,5–9]. Some authors consider that the presence of stenosis in the carotid arteries is a factor independent of other variables that affects cognitive deterioration, especially in cases of severe stenosis[7]. Other researchers see no relationship between the degree of carotid stenosis and neurocognitive function, although they confirm cognitive impairment in functions such as executive function, word production, verbal and visual memory, and motor speed, supporting the hypothesis that the degree of carotid stenosis is independent of cognitive function deterioration in people with atherosclerosis[10]. Recent data suggest that compensatory changes in specific brain regions related to functional connectivity (FC) play an important role in improving cognitive performance after stent implantation[8]. Similar to patients with coronary artery disease, patients with carotid atherosclerosis are more likely than the general population to suffer from depressive and anxiety symptoms, which often require pharmacological treatment. Emotional disorders occur in 1 in 3 people within a year of the stroke[11].

Attention is a special form of cognitive function and consists of several parameters. In this study, it is understood as a type of selection, where its main component - concentration - is the constant selection of stimuli leading to the achievement of a specific goal, i.e. the subject's ability to quickly and appropriately analyze relevant stimuli by selecting out irrelevant stimuli[12]. The second aspect of attention is perceptual ability, i.e. the ability to perceive and distinguish features of stimuli. Another aspect is impulsivity, i.e. the tendency to make "false alarms",

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in contrast to inattention, which refers to "errors of omission"[13]. Currently, various aspects of attention can be assessed with modern computerized tests whose psychometric properties are of interest to neuropsychologists[14].

The aim of this study was to investigate the relationship between the degree of carotid artery stenosis after stenting and attentional function in individuals with carotid atherosclerosis.

Attention was assessed before and 12 months after stenting. This study is part of a larger project, and some of the results have already been published.

Methods.

The study was conducted in accordance with the local laws of the Republic of Poland and the European Union, but also with the Declaration of Helsinki and Good Clinical Practice rules and was approved by the Bioethics Committee of the Medical University of Silesia, the local authority responsible for authorizing such studies. Approval number – NN-6501-132/07. Informed consent was obtained from all subjects and no legal guardians as there was no minors or incapacitated persons enrolled in the study.

A prospective longitudinal study was conducted at the Silesian Center for Heart Diseases in Poland, in which patients were included during inpatient treatment in the cardiology department (T-1) and one year after hospitalization (T-2) for invasive treatment of carotid artery stenosis. The first time point (T-1) is the time of the first assessment of the attention parameter in people who are candidates for carotid artery stenting and who fall in the period before the procedure. Usually the next day after admission to the cardiology department in the morning or afternoon hours. The second time point (T-2) falls in the period of 12 months after stent implantation and corresponds to the second measurement of attentional function efficiency.

One criterion for symptomatology was an ischemic stroke and/or transient ischemic attack (TIA) within the last six months. During the procedure, all patients were treated with a distal neuroprotection system in the form of filters to prevent embolism. The study team consisted of psychiatrists, an interventional cardiologist and psychologists. The same experienced clinical psychologist assessed and interpreted the results of the cognitive function tests at both the first (T1) and second (T2) time points of the study.

The study enrolled subjects over the age of 18 who consented to the project, were eligible for carotid artery angioplasty, and had no cognitive impairment that would prevent them from completing the test. Inclusion criteria: Age over 18 years, informed written consent to participate in the study, fulfilment of the criteria for qualification for carotid artery angioplasty, no cognitive impairment to an extent that would prevent the test from being performed. The burden of additional somatic diseases and mental disorders was not an exclusion criterion. Patients who were dependent on alcohol and other psychoactive substances and had severe cognitive impairment were excluded from the study. Due to the small number of symptomatic subjects, subjects were not divided into symptomatic and asymptomatic groups. Two groups were distinguished and analyzed based on the percentage of internal carotid artery (ICA) stenosis. The degree of stenosis of the carotid artery on Doppler examination was assessed according to the NASCET criteria (North American Symptomatic Carotid Endarterectomy Trial). The first group comprised those with stenosis $\leq 90\%$ (group 0), while the second group comprised those with critical carotid stenosis, as mean $> 90\%$ (group 1). These groups were analyzed with regard to the function of the attention parameters. In cases where both carotid arteries were affected by atherosclerosis visualized by Doppler ultrasound, only the artery selected for revascularization was considered. Bilateral narrowing of the carotid artery was found in 11 patients. Angioplasty with stent implantation was always performed on the artery with the larger, hemodynamically significant stenosis if the change in the other vessel was hemodynamically insignificant. In cases where both changes were hemodynamically significant, the artery with the larger stenosis or the artery responsible for the acute neurological episode was stented.

As already mentioned, the Brickenkamp's Test of Attention was used in a Polish adaptation by Elzbieta Dajek (2003), whose objectivity, reliability and accuracy have been confirmed in numerous research papers[12,13,15]. It has very high internal consistency coefficients and high stability, which were determined in German studies, and confirms relationships with other tests for measuring attention. It measures concentration, working speed and accuracy and can be used in neuropsychological and psychiatric research to study individuals with CNS (Central Nervous System) damage. According to the definition of attention on which the idea of this test is based, the subject must concentrate on external visual stimuli. The D2 test assesses: speed (the amount of material processed in time), quality (accuracy by assessing the errors made) and perseverance (behavior while working). The degree of concentration depends on all three variables. The test takes less than 10 min and consists of crossing out the letters d with two strokes arranged between the letters p and d with one, two, three or four strokes in various combinations in 14 number sequences of 47 characters each. The test participant should take 20 s to cross out the specified letters in a sequence. The following indicators are calculated as suggested by the test developers: WZ- the working speed of the test taker (the total number of letters worked out); B- the sum of all errors, %B- the percentage of errors made, i.e. an indicator of the accuracy of the work; GP - the limits of the result range, it provides information about the subject's constant or changing way of working; WZ-B- the indicator of the general perceptual ability, which results from the difference between the number of analyzed letters (WZ) and the number of all errors (B); ZK - the indicator of the ability to concentrate (the sum of the number of correctly crossed out letters minus the number of all errors). Poor marks and omissions are treated as errors. The measures WZ, %B and ZK reflect attention qualities such as capacity, accuracy and efficiency respectively. The measures WZ, WZ-B and ZK are normally distributed in the population[13]. In contrast to the ZK index, which has the advantage of being resistant to falsification, the WZ-B index is characterized by its susceptibility to falsification, i.e. the possibility that it could be falsified by a test subject who does not follow the test instructions.

In 2020, a revised version of the D2 test (D2-R) was developed in Poland, in which an instructive worksheet was added, the number of characters per line was increased and the calculation of indicators was simplified[16]. In the present study on attention parameters, the earlier version of the test was used, which was also used in other studies[17–19]. The D2 test has also been used to study attention parameters in individuals under acute stress and in athletes[20,21].

In addition, sociodemographic data were collected using the author's questionnaire, and selected clinical parameters, including the percentage of stenosis of the artery in which a stent was inserted, were obtained from the patients' discharge paperwork data.

Statistical analysis

The data was processed using the computer programs Excel 2016 and Statistica version 13.3. The normality of the distributions was assessed using the Shapiro-Wilk test. Due to the lack of normal distributions for some of the variables and the small size of the study group, non-parametric statistics were used for the calculations. Comparison of results between groups separated by percentage of carotid stenosis was performed using the Mann-Whitney U test. On the other hand, comparison of the results in the study group between the measurements before and after carotid artery stenting was performed using the Wilcoxon paired rank order test. $\alpha \leq 0.05$ was used as the statistical significance level.

Results

The neuropsychological study included 56 patients who were eligible for carotid artery stenting (CAS). The study group comprised 37 men and 19 women. The average age of the patients was 63.55 ± 9.03 (SD) years. Of the study group, 50 patients participated in an attentional function study with the D2 test, and 30 patients also participated in a follow-up examination one year after carotid artery stenting. The sociodemographic characteristics of the study group are shown in Table 1. Two people did not provide all sociodemographic data, so they are not included in Table 1.

Patients eligible for carotid artery stenting were compared on parameters describing the efficiency of their attention before the procedure. The group was divided according to the percentage of carotid artery stenosis. A group of patients with stenosis ≤ 90% ($n = 29$) was categorised as group 0 and a group of patients with stenosis > 90% ($n = 21$) as group 1. Comparisons were made using the non-parametric Mann-Whitney U test. The test revealed statistically significant differences for three attention parameters: B, B5-10 and B1 (Table 2). In all three cases, the group of patients with arterial stenosis > 90% scored higher, indicating that these patients had poorer attentional performance compared to patients with arterial stenosis ≤ 90%. These differences are shown in Figs. 1, 2 and 3.

		≤ 90% (*N* = 29)		> 90% (*N* = 25)	
Sociodemographic feature	**Category**	**n**	**% of N**	**n**	**% of N**
Education	Basic	7	24	5	20
	Professional	4	14	9	36
	Medium	12	41	7	28
	Higher	6	21	4	16
Marital status	Married	14	48,3	14	56
	Widower/widowed	5	17,2	1	4
	Single	1	3,45	2	8
	Other	9	31,05	8	32
Work situation	Employed	1	3,45	2	8
	Retired	19	65,5	15	60
	Not working	1	3,45	0	0
	Other	8	27,6	8	32
Coronary artery disease (CAD)	Yes	18	62	15	60
	Not	11	38	10	40
Previous stroke	Yes	8	27,6	8	32
	Not	21	72,4	17	68
Previous TIA	Yes	0	0	1	4
	Not	29	100	24	96
Previous cancer	Yes	2	6,9	1	4
	Not	27	93,1	24	96
Percutaneous coronary intervention (prePCI)	Yes	10	34,5	6	24
	Not	19	65,5	19	76
Coronary artery bypass grafting (preCABG)	Yes	4	14	3	12
	Not	25	86	22	88
Carotid artery stenosis %	> 90%	0	0	25	100
	≤ 90%	29	100	0	0
Stented artery	Rights	20	69	16	64
	Left	9	31	9	36

Table 1. Sociodemographic characteristics of the study group.

Variable	Stenosis ≤ 90% (*n* = 29)			Stenosis > 90% (*n* = 21)			Z	*p*
	median	Q1-Q3		median	Q1-Q3			
WZ	348	318	400	388	297	424	1,071	0,284
B	30	11	44	43	22	65	2,173	0,030*
%B	9	4	12	10	8	19	1,749	0,080
WZ-B	325	288	354	337	264	374	0,305	0,761
ZK	112	92	139	110	81	129	−0,551	0,582
GP	14	10	21	16	10	22	0,414	0,679
B1-4	9	4	12	10	4	18	1,075	0,282
B5-10	9	5	20	19	14	29	2,459	0,014*
B11-14	8	4	12	13	5	21	1,861	0,063
B1	25	10	39	40	19	54	2,232	0,026*
B2	1	0	5	3	2	6	1,918	0,055

Table 2. Comparison of the results of the D2 attention test between patients with stenosis ≤ 90% and patients with stenosis > 90% (Mann-Whitney U test). *Statistically significant, WZ - working speed, B - sum of all errors, %B - the percentage of errors, WZ-B - general perceptual ability, ZK - ability to concentrate, GP – indicator of the subject's constant or changing way of working, B1-4 - errors from the first part of the tasks (lines 1–4), B5-10- errors from the middle part of the tasks (lines 5–10), B11-14 - errors from the last part of the tasks (lines 11–14), B1 - errors of omission, B2 - number of incorrectly crossed out letters.

We also analyzed the changes in attentional parameters in the group of patients with carotid stenosis, considering the measurement of this cognitive function before and one year after carotid stenting ($N = 30$). The analysis was performed using the Wilcoxon paired rank order test (Table 3). The test revealed a significant change - in the ability to concentrate (ZK). The results show that this parameter improved in the study group after carotid artery stenting (Fig. 4).

No differences in cognitive performance in terms of attention were found depending on which side of the stenosed vessel (right/left) the stenting was performed. The absence of these is shown in Table 4.

Discussion

Most published scientific reports to date suggest that carotid revascularization improves cognitive abilities in patients with carotid atherosclerosis[9,22]. However, this patient population has received insufficient research attention, in contrast to patients with coronary atherosclerosis, on whose emotional and cognitive functioning many valuable articles have been published. Moreover, data on depressive and anxiety symptoms and cognitive functioning in patients with cardiovascular disease (CVD) are usually found together in the same articles. Therefore, the present discussion is based on an analysis of the results of papers that consider both neurocognitive impairment and emotional disturbances in patients with carotid stenosis.

Although knowledge of the mechanisms linking cardiovascular disease to mental disorders is increasing, patients with carotid atherosclerosis remain a poorly studied population in terms of comorbid psychopathological symptoms and cognitive functioning compared with patients with coronary atherosclerosis and after ischemic stroke. As a result, the emotional disorders and cognitive dysfunctions occurring in this patient group are underestimated, which has an impact on the course of the underlying disease and the patients' quality of life. The active involvement of cardiologists, psychiatrists and neurologists in the diagnosis and treatment process would contribute to a better understanding of the psychopathology of patients with cardiovascular disease and enable the development of evidence-based treatment strategies[23].

In a study published two years ago, nearly 12% of patients who underwent carotid artery stenting had significant anxiety symptoms and more than 14% had significant symptoms of depression[24]. Other researchers report similar data, but in relation to the heart failure patient population – 14% for depression and 18.6% for anxiety[25].

Cognitive impairment is common in patients with coronary heart disease and is associated with higher levels of psychological distress, depressive symptoms and anxiety, anger and hostility. On the other hand, poorer memory and executive function can also lead to mental health problems[26]. Patients with New York Heart Association (NYHA) class II-IV heart failure are more likely to have cognitive impairment, anxiety and depressive symptoms, with patients with NYHA class III/IV heart failure having higher levels of cognitive decline[27]. Patients with ischemic stroke have poorer cognitive function in all domains compared to healthy individuals. In the long-term follow-up, a significant improvement was only observed in executive function tasks, although participants performed better in all domains. The high levels of anxiety and depression in these patients did not correlate with cognitive performance[28].

These results are somewhat similar to those of our previous study, in which we observed improvements in basic and complex cognitive functions one year after stenting, demonstrating the positive effect of CAS surgery on patients' functioning during long-term follow-up[9]. Most reports have reported improvement in cognitive function after carotid revascularization in patients with cognitive impairment, regardless of the method (CAS - carotid artery stenting and CEA - carotid endarterectomy), which is reflected in the functional connectivity (FC)

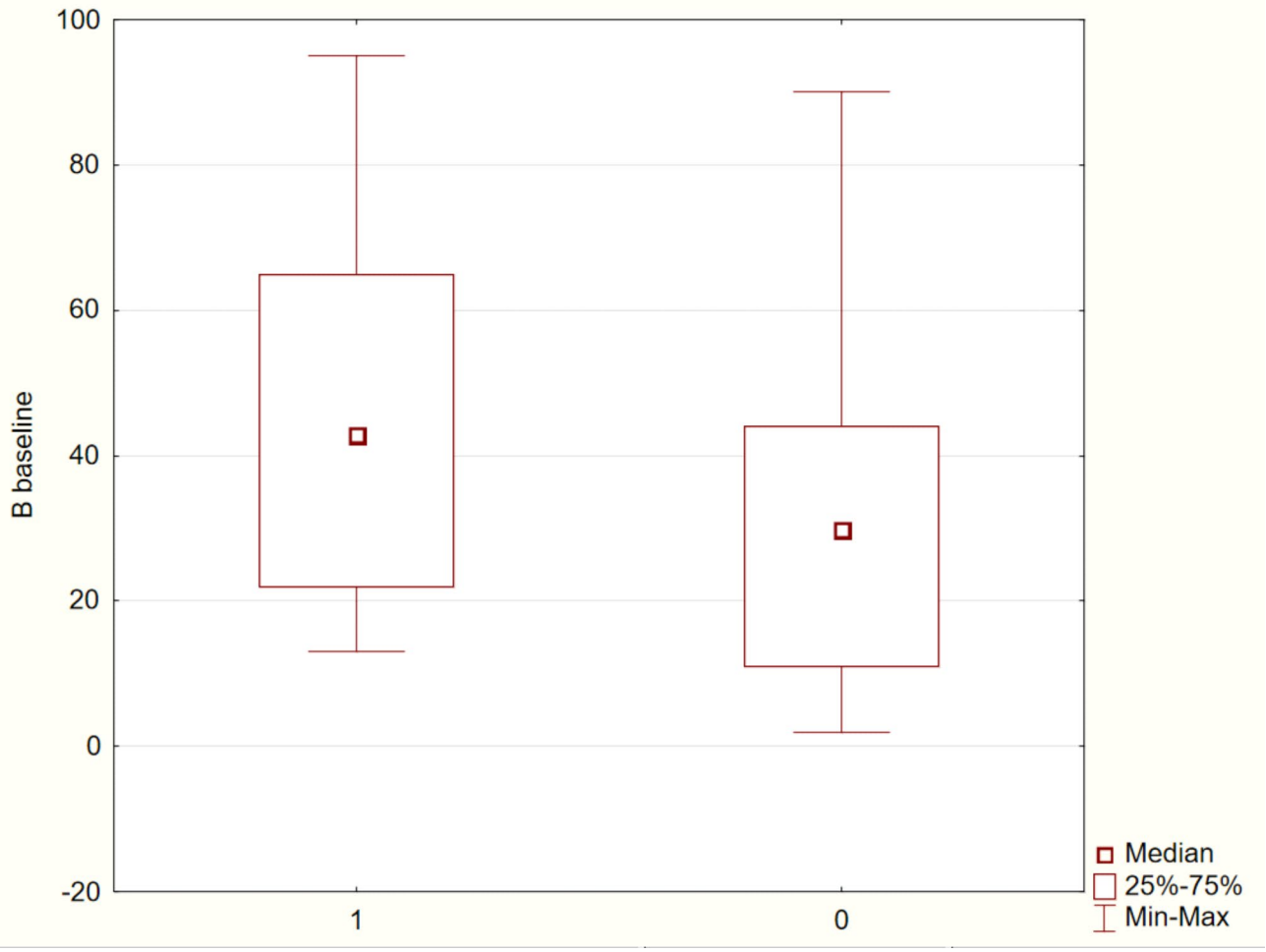

Fig. 1. Comparison of B parameter from the D2 attention test between patients with stenosis ≤ 90% and patients with stenosis > 90%. Note: 1 - patients with stenosis > 90%; 0 - patients with stenosis ≤ 90%, B baseline-sum of all errors before carotid artery stenting.

of the brain in the default mode network (DMN)[3,4]. It has been shown that patients with depressive symptoms after ischemic stroke have increased default mode network (DMN) connectivity to certain structures in the left hemisphere of the brain, which may indicate an alternative pathway for the development of depression, such as brain network dysfunction, which is commonly known to result from regional structural damage due to stroke[29]. In a similar project to ours, we examined the prevalence of cognitive and emotional impairment one year after a first-time minor stroke in younger adults and found that 67% of patients had difficulties in at least one cognitive domain, 43% had emotional disturbances, 28% had cognitive and emotional impairments, and only 18% of patients showed no abnormalities in emotions and cognitive functioning[30]. Protective factors against cognitive deterioration one year after the stroke were found to be female gender, a higher level of education, employment in the post-stroke period, a higher physical health index in relation to quality of life and the use of diabetes therapy. High scores on the HADS-A and HADS-D (Hospital Anxiety and Depression Scale) were independent predictors of a significant deficit in the MMSE (Mini-Mental State Examination)[31]. After a one-year follow-up of people who had suffered a minor stroke for the first time, it was found that younger age, several subsequent strokes and retirement from work were independent predictors of cognitive impairment in functions such as psychomotor speed, attention, executive and visuospatial function and memory. Women showed a higher level of depressive and anxiety symptoms[32]. A training program conducted by nursing staff significantly reduced cognitive impairment, anxiety and depression in patients after an acute ischemic stroke after one year[33]. The location of the ischemic stroke does not predict the occurrence of affective disorders 3 months after the stroke and is not related to the presence of depressive and anxiety symptoms measured with the HADS scale, while it determines cognitive outcome in specific domains. Disorders of language function, abstract thinking and delayed memory were more frequently associated with left hemisphere damage. Bilateral lesions after stroke have been associated with impairments in visuospatial and executive functions, naming, attention and orientation[34]. Differences in cognitive improvement depending on the CAS intervention site were observed by Japanese researchers. People with severe, right-sided ICA stenosis achieved higher IQ scores, as measured by the Wechsler Adult Intelligence Scale III (WAIS-III) scale, after CAS than before the intervention, and verbal IQ also increased after the intervention in the left ICA[35]. The Austrian researchers also observed differences

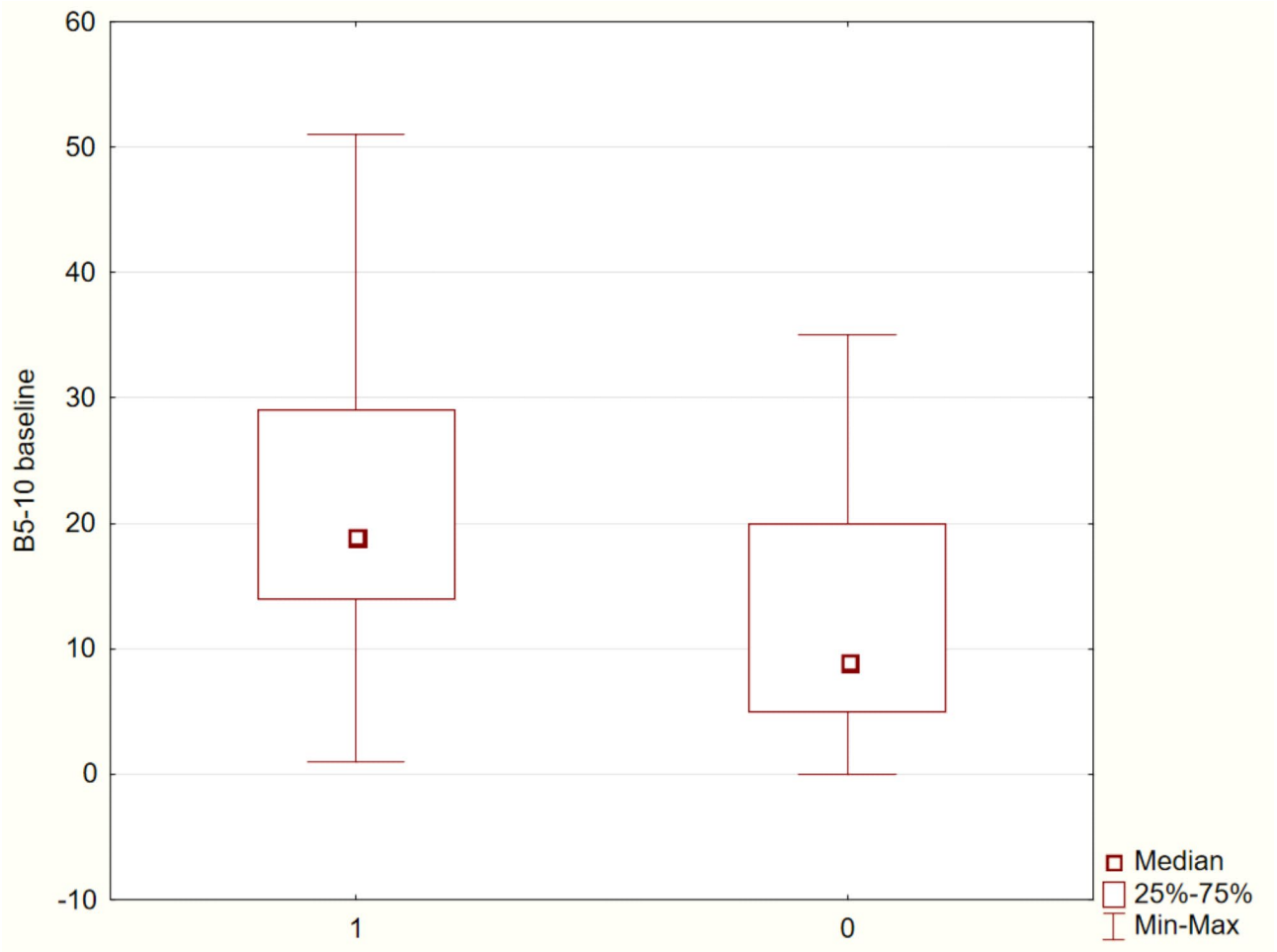

Fig. 2. Comparison of B5-10 parameter from the D2 attention test between patients with stenosis ≤ 90% and patients with stenosis > 90%. Note: 1 - patients with stenosis > 90%; 0 - patients with stenosis ≤ 90%, B5-10 baseline - errors from the middle part of the tasks (lines 5–10) before carotid artery stenting.

in neurocognitive improvement after CAS depending on which side the intervention was performed on. After excluding individuals with extreme test results (the floor and ceiling effect), they obtained an improvement in global cognition (MMSE) and verbal episodic memory in the group with left-sided ICA stenosis and an improvement in divided attention in patients with right-sided ICA stenosis[36]. This was the only study available to us that found a difference in the effect of the side of the arterial stenosis that underwent stenting on attentional function. In another study, symptomatic bilateral stenosis was associated with poorer processing speed. Cognitive processes and anxiety were independent of the degree and side of vascular stenosis (right or left ICA). Women, those with higher education, ambidexterity, and with treated hypercholesterolemia were variables associated with less cognitive impairment[10]. In the our study, there was also no association between the side of the narrowed artery and the attention parameters studied.

No scientific papers were found describing the relationship between the degree of stented carotid stenosis and neurocognitive function. In our study, a higher degree of stented internal carotid artery stenosis, expressed as a percentage, was associated with poorer accuracy in the attentional process. This could indicate a more severe impairment of blood supply to the dorsolateral prefrontal region and the dorsolateral anterior cingulate cortex in patients with critical carotid stenosis, in contrast to patients with less severe atherosclerotic lesions in the carotid arteries. These structures are associated with attentional processes.

Recent data report a strong positive association between cognitive decline in all assessed domains and depressive symptoms in stroke patients at six months. Interestingly, a similar association was not observed for anxiety symptoms. Only apraxia was found to be a factor associated with post-stroke anxiety. Spatial attention, executive function, language processing, memory, number processing, praxis - all of these areas were found to be important factors in the profile of cognitive impairment associated with post-stroke depression. However, the results of this study cannot serve as a basis for a model relationship between depression/anxiety and cognitive impairment in stroke patients, as it was found that controlling for depressive symptoms abolished significant associations between cognitive impairment and anxiety 6 months post-stroke. Therefore, the authors hypothesized that a bidirectional relationship might exist between these factors[37]. The relationships between psychiatric symptoms and cognitive performance after stroke are not yet clear. Even in relatively well-

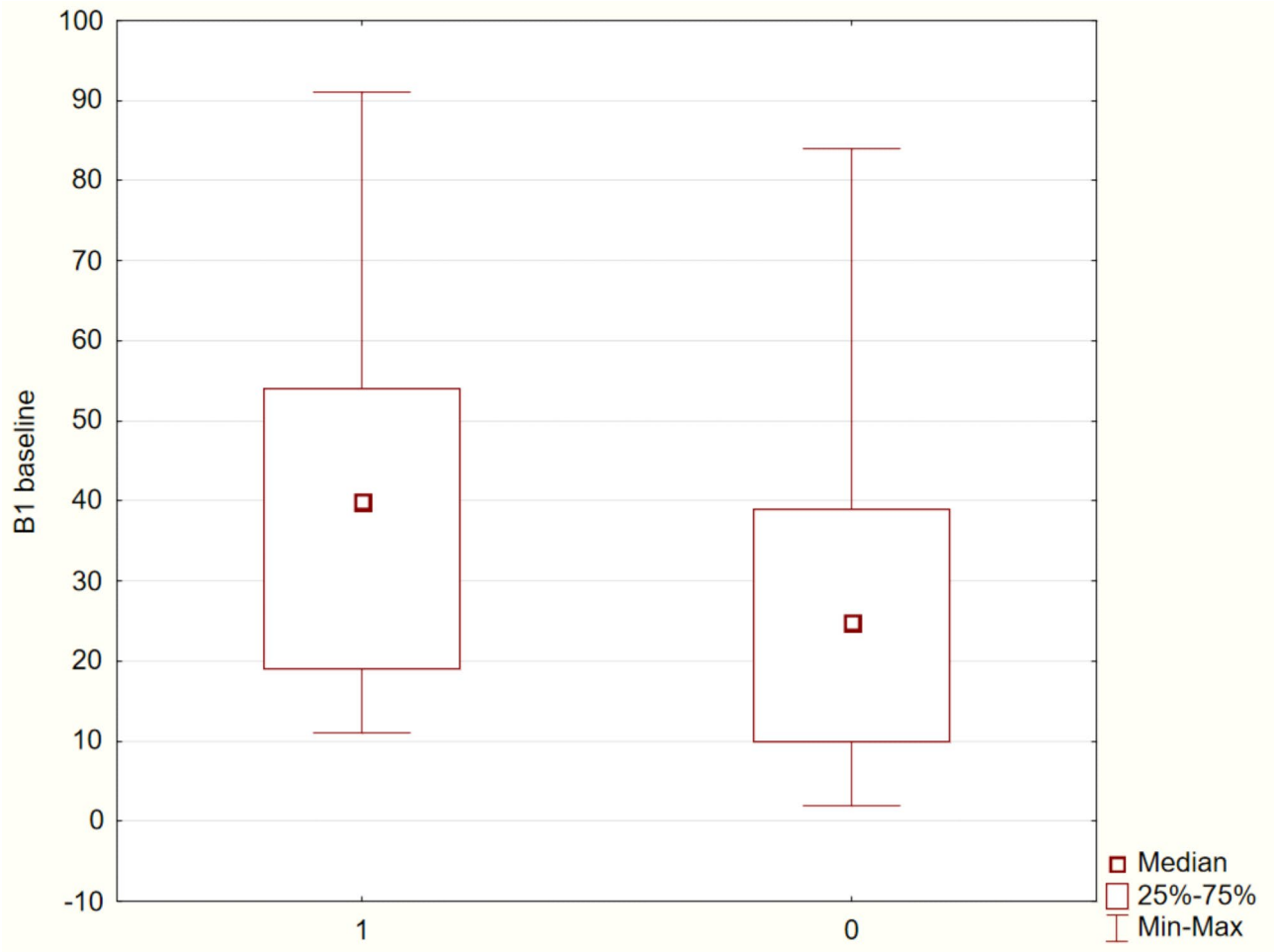

Fig. 3. Comparison of B1 parameter from the D2 attention test between patients with stenosis ≤ 90% and patients with stenosis > 90%. Note: 1 - patients with stenosis > 90%; 0 - patients with stenosis ≤ 90%, B1 baseline- errors of omission before carotid artery stenting.

functioning patients, depressive symptoms are associated with poorer memory. The various psychopathological symptoms are more closely related to self-reported cognitive deficits than to the results obtained on structured neuropsychological tests. The authors of the project described here advocate screening for self-reported cognitive difficulties, which may help to identify not only patients with cognitive impairment but also those in need of psychological support[38]. The results of an analysis by Japanese researchers suggest the stress threshold hypothesis, according to which stroke-related changes may increase susceptibility to stress and cause mood disorders[39].

Higher cognitive reserve (CR) correlates positively with lower cognitive impairment as measured by the Montreal Cognitive Assessment (MoCA) scale after stroke[40]. Cognitive reserve can be defined as the brain's ability to perform cognitive tasks as a result of existing cognitive or compensatory processes, and studies have shown that people with higher cognitive reserve perform better in situations with neurodegenerative damage[41,42].

Researchers from Norway observed a small but significant improvement in cognitive performance between 3 and 12 months in patients after a mild stroke. Nevertheless, they described the prevalence of mild cognitive impairment one year after the stroke as high. The most important factors contributing to the maintenance of cognitive deterioration were high blood pressure and smoking. The prevalence of depressive symptoms also increased between the second and third time points (3–12 months), while there was no increase in anxiety symptoms[43]. The results of the described study partly overlap with ours, particularly with regard to the improvement in alertness one year after carotid artery stenting, regardless of the degree of vasoconstriction. However, in the present project, no post-stroke patients were studied, although 13 of all subjects were classified as symptomatic patients. Symptomatic and asymptomatic patients did not differ in the intensity of depression, but the intensity of anxiety was higher in symptomatic patients before carotid stenting[24].

In another study, 25.6% of patients with heart failure had an abnormal score on the MoCA scale that did not change during the entire follow-up period, i.e. 6–12 months after hospital discharge. Those with a higher baseline score on this scale were better able to cope with their somatic disease. Throughout the follow-up period, there was also no improvement in HADS scale scores for those with a baseline score below normal. Interestingly, this was independent of MoCA scale scores[25].

Variable	Before stenting			After stenting			Z	*p*
	median	Q1-Q3		median	Q1-Q3			
WZ	354	317	412	375	301	416	1,568	0,117
B	35	15	51	27	18	51	0,137	0,891
%B	9	5	15	7	4	13	0,705	0,481
WZ-B	324	268	371	320	259	381	1,831	0,067
ZK	111	87	134	114	98	144	1,964	0,049*
GP	14	10	21	14	12	19	0,278	0,781
B1-4	10	4	14	8	3	13	0,854	0,393
B5-10	16	7	22	13	5	21	0,031	0,975
B11-14	10	4	16	9	3	16	0,041	0,967
B1	29	13	45	24	14	45	0,186	0,852
B2	3	1	6	2	1	5	0,483	0,629

Table 3. Comparison of the results of the D2 attention test in patients with carotid artery stenosis before and one year after stenting (Wilcoxon test). *Statistically significant, WZ - working speed, B - sum of all errors, %B - the percentage of errors, WZ-B - general perceptual ability, ZK - ability to concentrate, GP – indicator of the subject's constant or changing way of working, B1-4 - errors from the first part of the tasks (lines 1–4), B5-10- errors from the middle part of the tasks (lines 5–10), B11-14 - errors from the last part of the tasks (lines 11–14), B1 - errors of omission, B2 - number of incorrectly crossed out letters.

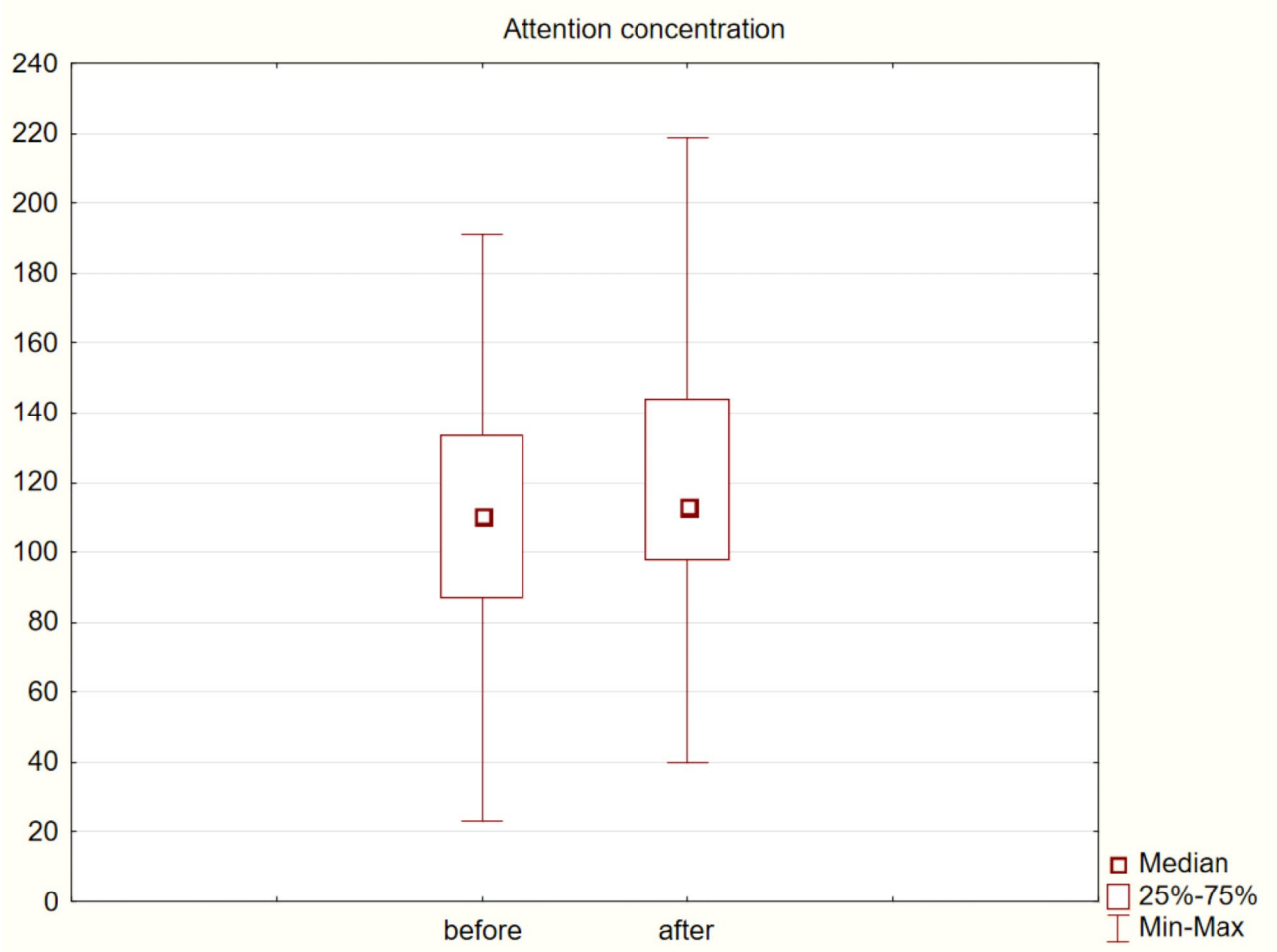

Fig. 4. Comparison of attention concentration from the D2 attention test before and after carotid artery stenting. Note: before - concentration of attention before carotid artery stenting; after - concentration of attention after carotid artery stenting.

Variable	Right stenosed vessel			Left stenosed vessel			Z	p
	Median	Q1-Q3		Median	Q1-Q3			
WZ	368	318	414	353	307	395	−0,385	0,700
B	37	14	50	30	18	53	0,021	0,983
%B	10	5	15	9	6	13	0,010	0,992
WZ-B	328	268	372	313	267	368	−0,489	0,625
ZK	118	84	134	110	79	137	−0,375	0,708
GP	14	10	20	16	11	23	0,824	0,410
B1-4	9	4	13	11	4	14	0,136	0,892
B5-10	18	6	22	14	9	22	−0,031	0,975
B11-14	10	4	16	10	5	17	0,406	0,685
B1	30	12	42	27	16	51	0,572	0,567
B2	3	1	7	2	0	4	−1,765	0,078

Table 4. Comparison of the results of the D2 attention test in patients with carotid artery stenosis taking into consideration the stenosed vessel (right/left) (Mann-Whitney U test). *Statistically significant, WZ - working speed, B - sum of all errors, %B - the percentage of errors, WZ-B - general perceptual ability, ZK - ability to concentrate, GP – indicator of the subject's constant or changing way of working, B1-4 - errors from the first part of the tasks (lines 1–4), B5-10- errors from the middle part of the tasks (lines 5–10), B11-14 - errors from the last part of the tasks (lines 11–14), B1 - errors of omission, B2 - number of incorrectly crossed out letters.

Asymptomatic carotid artery stenosis (ACS) can also lead to cognitive decline. The authors of the cited review and other researchers argue that clinicians should consider a high risk of cognitive impairment as an indication for carotid revascularization in asymptomatic patients with carotid stenosis[44,45]. In addition, the now historical term "asymptomatic carotid stenosis" needs to be redefined, which according to the 1991 definition means the presence of 50 narrowing of the vessel lumen in the absence of a stroke or TIA in the preceding six months[46]. Cognitive deterioration could be considered a "symptom" and thus represent a new indication for revascularization measures in these patients. However, modern methods for assessing neurocognitive and cerebrovascular reserve (CVR) and longitudinal ultrasound examinations of carotid plaque progression are required for risk stratification of patients with ACS[44]. These are the challenges of the future, not only from a medical but also from a socioeconomic point of view, as the prevalence of carotid disease increases with age. In men under 50, it is 0.1%, while in men over 80 it reaches 3%. When vascular risk factors are added, the possibility of age-related carotid disease increases many times over[45]. In a study published in 2023, no improvement in cognitive function was observed in men over 80 years of age after carotid surgery, in contrast to a younger patient population. According to this report, younger patients with carotid atherosclerosis benefit from revascularization interventions that protect them from cognitive decline. Both the authors of this study and the present report advocate further research to identify an appropriate patient population that may optimally benefit from treatment of carotid atherosclerosis[47].

Limitations of the study.

The main limitation of the work presented here is the small number of study participants with a low proportion of women. However, it should be noted that few previously published articles on the population of patients with atherosclerosis of the carotid arteries include a larger number of subjects. Furthermore, the number of papers addressing the neurocognitive and emotional functioning of patients with carotid stenosis is not increasing. Therefore, the authors of the present study are aware of both the extent of the difficulties in obtaining material for the study and the importance of the project they are carrying out from a long-term and socioeconomic point of view. The attention test we used now appears in a newer form, but it is more than doubtful that this small correction could influence our results. In the future, we would like to extend the methodology to test different cognitive functions, using modern suggestions for comprehensive care and management of patients with carotid atherosclerosis.

Conclusions

1. A critical degree of internal carotid artery stenosis is associated with poorer attentional performance in individuals undergoing carotid artery stenting.
2. The ability to concentrate improves one year after the procedure in the entire group of patients undergoing internal carotid artery stenting, regardless of the degree of stenosis of the internal carotid artery.
3. The side of the vessel stenosis (right/left) has no influence on cognitive performance in terms of attention in patients with atherosclerosis in the carotid arteries.

Data availability

All data on the basis of which the manuscript was created are available from the first author.

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References

1. Lattanzi, S. et al. Neurocognitive functioning andcerebrovascular reactivity after carotid endarterectomy. *Neurology* **90**(4), e307–e315 (2018).
2. Marshall, R. S. et al. Carotid revascularization and medical management for asymptomatic carotid stenosis—hemodynamics (CREST-H): Study design and rationale. *Int. J. Stroke* **13**(9), 985–991 (2018).
3. Succar, B. & Zhou, W. Does carotid intervention improve cognitive function? *Adv. Surg.* **57**(1), 267–277 (2023).
4. Kohta, M. et al. Effects of carotid revascularization on cognitive function and brain functional connectivity in carotid stenosis patients with cognitive impairment: A pilot study. *J. Neurosurg.* **139**(4), 1010–1017 (2023).
5. Huang, K. L. et al. The correlation of asymmetrical functional connectivity with cognition and reperfusion in carotid stenosis patients. *Neuroimage Clin.* **20**, 476–484 (2018).
6. Neuvonen, E. et al. Late-life personality traits, cognitive impairment, and mortality in a population-based cohort. *Int. J. Geriatr. Psychiatry*(9), 989–999 (2020).
7. Virues-Ortega, J. et al. Spanish epidemiological studies on Ageing Group. A protective personal factor against disability and dependence in the elderly: An ordinal regression analysis with nine geographically—defined samples from Spain. *BMC Geriatr.* **17**(1), 42 (2017).
8. Pucite, E. et al. Changes in cognition, depression and quality of life after carotid stenosis treatment. *Curr. Neurovasc. Res.* **16**(1), 47–62 (2019).
9. Piegza, M. et al. Cognitive functions after carotid artery stenting-1-year follow-up study. *J. Clin. Med.* **11**(11), 3019 (2022).
10. Everts, R. et al. Cognitive and emotional effects of carotid stenosis. *Swiss. Med. Wkly.* **144**, w13970 (2014).
11. Chun, H. Y., Ford, A., Kutlubaev, M. A., Almeida, O. P. & Mead, G. E. Depression, anxiety, and suicide after stroke: A narrative review of the best available evidence. *Stroke* **53**(4), 1402–1410 (2022).
12. Brickenkamp, R. *Handbuch apparativer Verfahreninder Psychologie* 195 (Hogrefe, 1986).
13. Brickenkamp, R. *Test d2. Test Badania Uwagi. Podręcznik* (ERDA, 2003).
14. Langner, R. et al. Evaluation of the reliability and validity of computerized tests of attention. *PLoS One* **18**(1), e0281196 (2023).
15. Brickenkamp, R. *Auferksamkeits-Belastungs-Test (Test d2)* 1 edn. (Hogrefe, 1962).
16. Bac, I. & Stańczak, J. Zrewidowana wersja testu do badania uwagi i koncentracji. Polska adaptacja. Podręcznik. Pracownia Testów Psychologicznych. Warszawa (2020).
17. Stanisławska-Kubiak, M. et al. An analysis of cognitive functioning of children and youth with type 1 diabetes (T1DM) in the context of glycemic control. *Eur. Rev. Med. Pharmacol. Sci.*(11), 3453–3460. (2018).
18. Piasecki, B., Stanisławska-Kubiak, M., Strzelecki, W. & Mojs, E. Attention and memory impairments in pediatric patients with cystic fibrosis and inflammatory bowel disease in comparison to healthy controls. *J. Investig. Med.* **65**(7), 1062–1067 (2017).
19. Pawełczyk, T. et al. Zaburzenia procesów poznawczych obserwowane u pacjentów z przewlekłym zapaleniem wątroby typu C w trakcie terapii pegylowanym interferonem alfa i rybawiryną [Cognitive disturbances observed in chronic hepatitis C patients during pegylated interferon alpha and Ribavirin therapy]. *Psychiatr Pol.* **42**(6), 925–941 (2008).
20. Degroote, C. et al. Acute stress improves concentration performance. *Exp. Psychol.* **67**(2), 88–98 (2020).
21. Hammami, A. et al. It is time to play: Acute effects of soccer and sprint exercise on attentional performance, mood, and enjoyment in untrained male adolescents. *Am. J. Mens Health* **17**(5), 15579883231209202 (2023).
22. Piegza, M., Więckiewicz, G., Wierzba, D. & Piegza, J. Cognitive functions in patients after carotid artery revascularization—A narrative review. *Brain Sci.* **11**(10), 1307 (2021).
23. Schnabel, R. B. et al. Heart and brain interactions: Pathophysiology and management of cardio-psycho-neurological disorders. *Herz* **46**(2), 138–149 (2021).
24. Piegza, M. et al. Symptoms of anxiety and depression and sense of coherence in patients undergoing carotid artery stenting. *Int. J. Environ. Res. Public. Health* **19**(19), 12222 (2022).
25. Rigueira, J. et al. Heart and brain interactions in heart failure: Cognition, depression, anxiety, and related outcomes. *Rev. Port Cardiol. (Engl. Ed.)* **40**(8), 547–555 (2021).
26. Moazzami, K. et al. Association between symptoms of psychological distress and cognitive functioning among adults with coronary artery disease. *Stress Health* **37**(3), 538–546 (2021).
27. Sargent, L. et al. Influence of physiological and psychological factors on cognitive dysfunction in heart failure patients. *Appl. Nurs. Res.* **56**, 151375 (2020).
28. Ebaid, D. et al. Mood and cognitive trajectories over the first year after mild ischemic stroke. *J. Stroke Cerebrovasc. Dis.* **31**(4), 106323 (2022).
29. Vicentini, J. E. et al. Depression and anxiety symptoms are associated to disruption of default mode network in subacute ischemic stroke. *Brain Imaging Behav.* **11**(6), 1571–1580 (2017).
30. Vlachos, G. et al. Cognitive and emotional symptoms in patients with first-ever mild stroke: The syndrome of hidden impairments. *J. Rehabil. Med.* **53**(1), jrm00135 (2021).
31. Boutros, C. F. et al. Factors associated with cognitive impairment at 3, 6, and 12 months after the first stroke among Lebanese survivors. *Brain Behav.* **13**(1), e2837 (2023).
32. Vlachos, G. et al. Predictors of cognitive and emotional symptoms 12 months after first-ever mild stroke. *Neuropsychol. Rehabil.* **33**(4), 662–679 (2023).
33. Zhang, L., Zhang, T. & Sun, Y. A newly designed intensive caregiver education program reduces cognitive impairment, anxiety, and depression in patients with acute ischemic stroke. *Braz. J. Med. Biol. Res.* **52**(9), e8533 (2019).
34. Sagnier, S. et al. The influence of Stroke Location on Cognitive and Mood Impairment. A voxel-based lesion-symptom mapping study. *J. Stroke Cerebrovasc. Dis.* **28**(5), 1236–1242 (2019).
35. Ishihara, H. et al. Cognitive outcome differences on the side of carotid artery stenting. *J. Vasc. Surg.* **57**(1), 125–130 (2013).
36. Scherr, M. et al. Ignoring floor and ceiling effects may underestimate the effect of carotid artery stenting on cognitive performance. *J. Neurointerv. Surg.* **8**(7), 747–751 (2016).
37. Williams, O. A. & Demeyere, N. Association of depression and anxiety with cognitive impairment 6 months after stroke. *Neurology* **96**(15), e1966–e1974 (2021).
38. Kliem, E. et al. The relationship of psychiatric symptoms with performance-based and self-reported cognitive function after ischemic stroke. *J. Int. Neuropsychol. Soc.* **28**(1), 35–47 (2022).
39. Hama, S. et al. Relationships between motor and cognitive functions and subsequent post-stroke mood disorders revealed by machine learning analysis. *Sci. Rep.* **10**(1), 19571 (2020).
40. Abdullah, A. H., Sharip, S., Rahman, A. H. A. & Bakar, L. Cognitive reserve in stroke patients. *Psych. J.* **10**(3), 444–452 (2021).
41. Bettcher, B. M. et al. Dynamic change of cognitive reserve: Associations with changes in brain, cognition, and diagnosis. *Neurobiol. Aging* **83**, 95–104 (2019).
42. Pettigrew, C. & Soldan, A. Defining Cognitive Reserve and implications for cognitive aging. *Curr. Neurol. Neurosci. Rep.* **19**(1), 1 (2019).
43. Morsund, Å. H. et al. The development of cognitive and emotional impairment after a minor stroke: A longitudinal study. *Acta Neurol. Scand.* **140**(4), 281–289 (2019).

44. Bhandari, A. et al. Evaluating the influence of altered cerebral hemodynamics on cognitive performance in asymptomatic carotid artery stenosis: A systematic review. *J. Vasc. Surg.* **S0741-5214**(23), 01924-9 (2023).
45. Lineback, C. M., Stamm, B., Sorond, F. & Caprio, F. Z. Carotid disease, cognition, and aging: Time to redefine asymptomatic disease? *Geroscience* **45**(2), 719–725 (2023).
46. North American Symptomatic Carotid Endarterectomy Trial Collaborators. Beneficial effect of carotid endarterectomy in symptomatic patients with high-grade carotid stenosis. *N. Engl. J. Med.* **325**, 445–453 (1991).
47. Succar, B. et al. Cognitive effects of carotid revascularization in octogenarians. *Surgery* **174**(4), 1078–1082 (2023).

Author contributions

Magdalena Piegza - originator of the research project, creator of the methodology, investigator, wrote the main manuscript text, Paweł Dębski - prepared figures and tables, assessed test results, Gniewko Więckiewicz - investigator, wrote the main manuscript text, Joanna Smolarczyk - investigator, prepared figures and tables, Izabela Jaworska - chief psychologist in the team, investigator, assessed test results, Jacek Piegza - originator of the research project, invasive cardiologist, investigator.All authors reviewed the manuscript.

Declarations

Competing interests

The authors declare no competing interests.

Additional information

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